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Flora and vegetation of the Banded Iron Formations of the Yilgarn Craton: Gullewa.

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ABSTRACT

The flora and floristic communities are described for the Buddadoo Range, Edamurta Range, Mugga Mugga Hill and Murdaburia Hill, in the Gullewa region of Midwest Western Australia. This area is geologically varied, and includes landforms of Archaean banded iron formation, mafics (metabasalt, dolerite and gabbro) and colluvial deposits of Cainozoic sediments. Fifty 20 x 20m² permanent vegetation quadrats were strategically located over these varied landforms to cover the toposequence of floristic communities. A total of 235 taxa (species, subspecies, varieties and forms) and three hybrids were identified from these quadrats. Five taxa of conservation significance were collected, four of these being first records for the survey area and one (*Dodonaea amplisemina*) being a range extension of c. 100km. Range extensions were found for an additional three taxa. No endemic taxa were collected, although *Acacia subsessilis* is considered to be a near-endemic.

Classification analysis of perennial floristic data (presence/ absence) resolved seven floristic communities (types and subtypes). The primary division in the classification distinguished communities from low, relatively saline depressions and mafic landforms to those associated with ridges of banded iron formation and lateritic pediments and breakaways. Further divisions within these major groupings distinguished between upland communities and those from depositional parts of the landscape. A strong association was found between floristic composition and underlying geomorphology, and soil chemistry.

Mining and exploration tenements effectively cover the entire extent of banded iron formation and mafic landforms within the Gullewa survey area, and there are no areas within the Gullewa survey region that currently occur within conservation reserves. A century of mining and grazing has impacted on the semi-arid vegetation of the ranges and hills, and there are few signs of restoration attempts at the older mine sites. Given the increase in mining and exploration activity within the Gullewa area, industry has a duty to follow best practices in order to minimise environmental impacts.

Keywords: BIF, banded ironstone, ranges. floristic communities, Yilgarn

INTRODUCTION

The Yilgarn Craton of Western Australia is a sizeable area of Archaean bedrock that harbours a series of metamorphosed volcanic and sedimentary mineral belts embedded in granitoids. Known locally as greenstones, these mineralisation belts consist of metasedimentary rocks, notably banded iron formation (BIF), and mafic and ultramafic metavolcanic rocks. These greenstone belts outcrop as isolated ranges and hills above surrounding plains of weathered Cainozoic sediments. They are highly prospective for base and precious metals, and have been exploited for mineral resources for over a century. It is expected that the recent resurgence in the iron ore industry in the Midwest of Western Australia will see an unprecedented level of exploration and mining activity target these BIF landforms of the Yilgarn Craton (Department of Industry and Resources 2007). Given current deficiencies in the knowledge on the biota of these ranges, there is a need to survey the biodiversity of such prospective areas for conservation planning and management purposes (Department of Environment and Conservation 2007).

A series of quadrat-based botanical surveys is in progress, and is producing a regional overview of the flora and floristic communities on banded iron formations of the northern Yilgarn Craton (Department of Environment and Conservation 2007; Gibson 2004a, 2004b; Gibson & Lyons 1998a, 1998b, 2001a, 2001b; Gibson *et al.* 2007; Markey & Dillon 2008a, 2008b; Meissner & Caruso 2008a, 2008b, 2008c). These detailed surveys extensively sample individual ranges and can resolve fine-scale patterns in floristic communities (as defined by their species composition,) which previous regional surveys have not addressed. Such surveys of individual ranges in the northern Murchison and Eastern Goldfields have found that floristic communities vary within a landform as a function of topographic position, geological substrate and associated edaphic factors (Gibson 2004a, 2004b; Gibson & Lyons 1998a, 1998b, 2001a, 2001b; Gibson *et al.* 1997; Markey & Dillon 2008a, 2008b; Meissner & Caruso 2008b, 2008c). Like other rocky peaks and outcrops in semi arid – arid Australia (Butler & Fenham 2008; van Etten & Fox 2004; Hopper *et al.* 1997), these surveys are finding the flora of isolated banded iron formations of the Yilgarn to be insular in character. The floristic communities on these isolated peaks also differ in composition to the surrounding lowland matrix, and recent surveys are finding significant differences among individual ranges and a distinct north-south transition within the Yilgarn region (Gibson *et al.* 2007; Gibson 2004a; Gibson & Lyons 1998b; Markey & Dillon 2008a). Some of these floristic communities appear to be restricted to particular ranges, and even are restricted to parts within a landform (Markey & Dillon 2008a;, Meissner & Caruso 2008b, 2008c). In addition to high α and β diversity, banded iron formations of the Yilgarn Craton harbour rare, unusual and endemic taxa, and that many of these ranges have high conservation values (Gibson *et al.* 2007).

This current paper is part of this ongoing regional survey of vegetation communities on banded iron formations of the northern Yilgarn Craton, intended to cover over 25 ranges or regions within a five year period (Gibson *et al.* 2007; Department of Environment and Conservation 2007). This particular paper aims to compile a flora list and describe floristic communities on greenstone landforms within the Gullewa survey region, in the Midwest of Western Australia. In doing so, this survey aims to redress the current paucity in botanical knowledge for a number of BIF and mafic volcanic landforms found within this area.

Study Site

This survey targeted the vegetation communities on hills and ridges of BIF and greenstones within the Gullewa region, c. 45km south-west of Yalgoo and c. 80km east of Mullewa, in the Midwest region of Western Australia (Fig. 1). The survey area is named after the historical mining centre of Gullewa, and refers to a rectangular area extending 30km east-west, 35km north-south and extends over a latitudinal range of 28.50 – 28.82 °S and longitudinal range of 116.22 – 116.52 °E. The study area extends over the Barnong, Mellenbye and Bannawarra pastoral stations, all located within the shire of Yalgoo.

The predominant industries in the Yalgoo region are pastoralism and mining, and the entire survey area and much of the wider region is covered by pastoral leases. As with all rangelands, the native vegetation is left for grazing and the study area has escaped the extensive clearing of vegetation that has occurred in the adjacent northern wheatbelt, the eastern margin of which is 12km south-west of the Gullewa survey area. The pastoral leases in the Gullewa region are among the first established in the Midwest region, having been established during the 1870's and 1880's (Hennig 1998a). Mellenbye and Bannawarra are active sheep stations, while Barnong was recently purchased by the Department of Conservation and Environment for future inclusion in the conservation estate.

Gold discoveries in the late 19th century lead to the rapid establishment of towns and gold mining centres in the Yalgoo and Murchison region (Beard 1976a, Hennig 1998a). The Yalgoo Goldfields were declared in 1895 (Hennig 1998a), and Gullewa was one of several mining centres in the southern extent of these goldfields. Since 1900, the level of gold production and other mining activities in the region has fluctuated greatly. There has been a recent resurgence in interest in the Gullewa region, and many of the hills and ranges within the survey area have been indicated as prospective for gold, copper, vanadium and iron-ore deposits (Cornelius *et al.* 2007; Flint *et al.* 2000; Muhling & Low 1977). Intensive exploration targeting BIF landforms for haematite and magnetite deposits is currently underway throughout the Gullewa survey area.

Climate

The climate of the Gullewa study is described as semi arid (Leighton 1998) or extra-dry Mediterranean to semi-desert: Mediterranean (Beard 1976a, 1990). The area experiences cool -mild, and wet winters and hot, dry summers and an irregular and variable rainfall that falls mostly in winter (Beard 1976a; Leighton 1998). The nearest rainfall recording station to the survey area is Barnong Station, where the median annual rainfall is 265 mm (Leighton 1998). There is a gradient of increasing aridity over the Yalgoo region in a west-east direction, as the average annual rainfall declines from 334 mm at Morowa to 256 mm at Yalgoo (Australian Bureau of Meteorology 1908–). For Yalgoo, the average summer and winter daily maxima are 36.3°C and 19.1°C respectively (Australian Bureau of Meteorology 1908–). Annual evaporation across the region (c. 2800 mm pa), greatly exceeds annual rainfall (Australian Bureau of Meteorology 1908–; Leighton 1998).

Geology

The survey region falls within the Murchison Domain of Youanmi Terrane, within the north-western part of the Yilgarn Craton (Cassidy *et al.* 2006), and the geology of the Gullewa area is described and mapped within the Yalgoo 1:250 000 geological sheet (Muhling & Low 1977). As with much of the Youanmi Terrane, the Yalgoo landscape is dominated by undulating plains of Cainozoic sediments which overlie the Archaean bedrock (2.7 – 3.0 Ga) of the Yilgarn Craton (Cassidy *et al.* 2006). These are dissected by extensive drainage systems, and the general landscape is one of low overall topographical relief (Johnson 1998; Muhling & Low 1977). Only a small proportion of this area is of significant elevation, where rises, hills and ridges of exposed, erosion resistant outcops of bedrock project

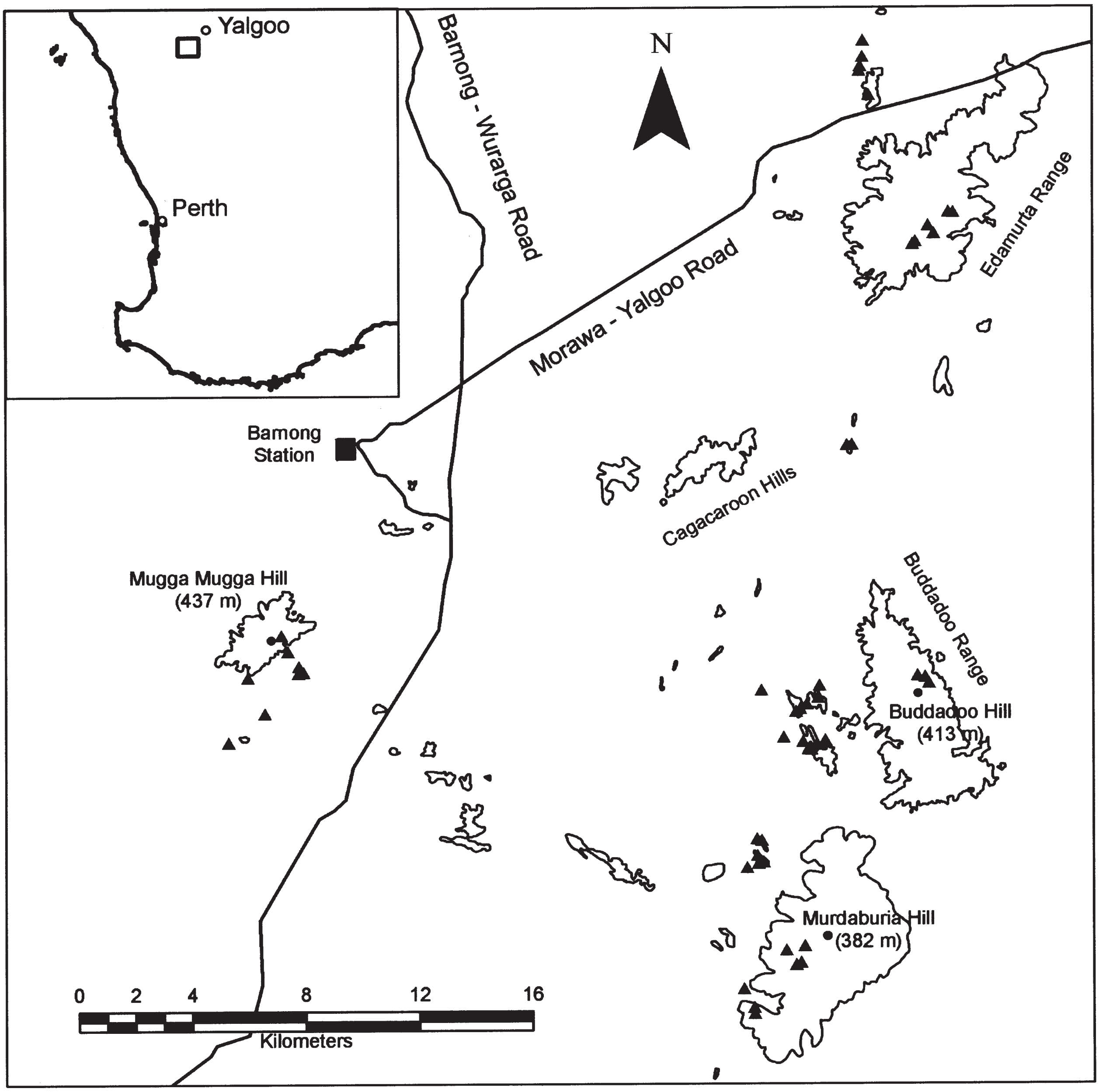

Figure 1. Location of the Gullewa survey area within the Midwest region of Western Australia (inset). The ranges and hills of the Gullewa survey area have been outlined at the 300-350m contour and significant landmarks are labelled. The distribution of the 50 floristic quadrats across the survey area is marked by triangles

above the peneplains of sediments. From lowlands at an altitude of 270m above sea level (ASL), the relative elevations of these landforms range from rises, breakaways and low hills (9–30m in height) to hills and ridges (30–150m in height). Mugga Mugga (436m ASL) and Buddadoo (413m ASL) are the only hills within the study area that exceed an altitude of 400m. The main ranges and hills located within the Gullewa survey area are the Cagacaroon, Mugga Mugga and Murdaburia Hills, and the Buddadoo, Edamurta and Murdalyou Ranges. These landforms are all surface expressions of the Gullewa greenstone belt (Flint *et al.* 2000).

As with the greater Yalgoo region, the underlying bedrock consists of greenstone belts of deformed, metamorphosed igneous and sedimentary rocks embedded within the gneissic granitoids of the northern Yilgarn craton (Muhling & Low 1977; Payne & Pringle 1998). These belts consist of complexes of mafic, ultramafic and felsic intrusive and volcanic rocks, and BIF and associated metasedimentary rocks. They form prominent ranges and, in the case of BIF, generally north-south trending, narrow strike ridges (Cornelius *et al.* 2007; Johnson 1998; Muhling & Low 1977). Magnetite and haematite deposits will be associated with these greenstone belts (Cornelius *et al.* 2007.) Extensive deposits of colluvium from eroded bedrock accumulate around the slopes, pediments and plains around these landforms, from scree on steeper slopes to stony mantles on lower gradients. Likewise, alluvial deposits will accrue in drainage lines and outwashes around the ranges (Johnson 1998; Payne & Pringle 1998). Soils of the rocky uplands of these landforms are typically skeletal or shallow (< 50cm), stony and acidic (pH ≤ 5.1) silty clay loams and sandy loam rudosols, which progress into shallow, stony red earths, ferruginous gravels and red clayey sands on the depositional slopes and outwashes (Hennig 1998b).

Payne and Pringle (1998) used the Land System concept of Mabbutt *et al.* (1963), to classify land systems for the greater Paynes Find-Yalgoo-Sandstone region. Within the Gullewa survey area, four land systems apply to the hills and rises; the Gabanintha Land System (prominent hills and ridges of greenstones, basalts and banded iron formation), the Tallering Land System (prominent hills and ridges of banded iron formation, dolerite and sedimentary rocks), the Watson Land System (lower hills, rises and gravely plains of sedimentary rocks, some schists and felsic volcanics) and the Violet land system (undulating plains, with stony and gravely mantles, on the flanks of greenstone ranges).

Vegetation

The study area is located within the Tallering Interim Biogeographic Regionalisation of Australia (IBRA) subbioregion which is at the south-western limit of the Yalgoo IBRA bioregion and immediately north of the Avon Wheatbelt IBRA bioregion (Environment Australia 2000; Thackway & Creswell 1995). The Yalgoo bioregion is considered an interzone and is intermediate in nature between the arid Eremaean and mesic, species-rich South-West Provinces (Beard 1976a, 1990; Environment Australia 2000; Thackway & Creswell 1995). The structural vegetation communities of the Yalgoo subregion have been mapped on a broad scale by Beard (1976a) as part of a larger 1:1 000 000 scale vegetation survey of the Murchison region. The general communities consist of tall *A. aneura* shrublands on the plains, scrub of *Acacia ramulosa* and *Acacia acuminata* (= *Acacia burkittii*) on BIF and greenstone hills and *Acacia sclerosperma* and *Acacia eremaea* over *Atriplex* spp. and *Maireana* spp. on flats. *A. aneura* is replaced by other dominant *Acacia* species in the far south-west of the region, and there are scattered trees of *Callitris* and *Eucalyptus* in the valleys (Beard 1976a). Although Beard (1976b) has mapped and described range-specific vegetation systems at a smaller scale (1:250 000) to the south of the survey area, such mapping was not extended to the Gullewa survey region.

The most recent vegetation survey which has covered the Gullewa survey area is that of Pringle (1998), where Gullewa is inclusive of a larger rangeland inventory for the Paynes Find – Yalgoo – Sandstone region, which was mapped on scales of 1:250 000 and 1:500 000. Pringle (1998) adapted floristic classifications from previous rangeland surveys to describe a large number of regional vegetation communities (termed 'habitats'). Within each Land System are several vegetation communities, each of which occupies a distinct part of the landform toposequence in a manner akin to the 'catenary sequence' of the Vegetation Systems of Beard (1976a, 1976b, 1990). There are four land systems (primarily the Gabanintha and Tallering, but also the Watson and Wiluna land systems) mapped for the hills and ranges in the Gullewa survey area, which contain a total of 16 communities (Mabbutt *el al.* 1963; Payne *et al.* 1998). However, these communities are broadly described and are not specific to any particular range or to any single land system in the wider Midwest region. A detailed, quadrat-based survey of BIF ranges immediately south-east of the Gullewa survey area identified eight floristic community types, of which some were restricted to parts of range-specific communities (Markey & Dillon 2008a).

METHODS

Fifty 20 x 20m^2 permanent vegetation quadrats were established over the survey area during a two week period that commenced in late September 2006 (Fig. 1). These were established on the slopes and pediments of Mugga Mugga Hill (mafics, felsics, weathered metasedimentaries and laterites), the undulating pediments and breakaways around Murdaburia Hill (laterites, weathered metasedimentaries and BIF), on the Buddadoo Range (BIF, magnetite and haematite, Buddadoo Gabbro), on the eastern edge of Cagacaroon Hills (metamorphosed basalt) and on the Edamurta Range (metamorphosed medium grained dolerite, muscovite schist and seams of haematite) (Muhling & Low 1977). Quadrats were placed strategically on landforms to cover the extent of the toposequence of vegetation communities on ranges and hills; from hillcrests and slopes, to pediments and plains of colluvium and alluvial outwash. This methodology has been used to survey other ranges in Western Australia (Gibson 2004a, 2004b) and is consistent with the previous survey on adjacent central Tallering Land System (Markey & Dillon 2008a). Quadrats were established only in what could be estimated to be the least disturbed vegetation in the area, thereby avoiding recently burnt, heavily grazed, cleared and mined areas. However grazing was an unavoidable factor in much of the study area, and all sites were impacted to an appreciable degree.

Quadrats were marked with a steel fence post at each corner, photographed and the location and altitude recorded using a GPS (Garmin 76). For each quadrat, the presence, cover classes and growth form for all vascular plant species was recorded, and the vegetation structure described according to McDonald *et al.* (1998). Material was collected for verification at the Western Australian Herbarium, where representative vouchers have been lodged. A number of environmental attributes were recorded for each plot (Table 1). For each quadrat, 20 samples from the uppermost 10cm of topsoil were collected over the area of the quadrat and pooled for chemical analysis. Prior to analysis, soils were sieved (2 mm) and soil chemical composition was assayed at the Chemistry Centre of Western Australia (Table 1).

Classification and semi-strong hybrid multidimensional scaling (SSH MDS) ordination analyses were conducted on a site by species data matrix of presence / absence information. Pattern analysis on floristic data was conducted using PATN (V3.03) (Belbin 1989). The Bray-Curtis coefficient was used to generate a dissimilarity matrix for both the classification and ordination analyses. A site and species classification was generated using agglomerative, hierarchical clustering using the flexible 'Unweighted Pair Group Method with Arithmetic mean' (UPGMA) algorithm, with the β value set at -0.1 (Belbin 1992; Sneath & Sokal 1973).

Preliminary analyses were conducted on a site by species data matrix consisting of 218 taxa from 50 quadrats, from which two quadrats were found to be outliers and were subsequently omitted from this dataset. A further 11 annual and 37 perennial singleton taxa (species known from a single quadrat) were considered for omission from the dataset to be consistent and comparative with previous surveys on Western Australian BIF and greenstone ranges (Gibson 2004a, 2004b; Markey & Dillon 2008a, 2008b; Meissner & Caruso 2008b, 2008c). Singleton taxa contribute little additional information to the analyses, and, unlike perennials, the distribution and abundance of annual taxa is a response to rainfall in the preceding months (Mott 1972, 1973). Site association matrices (Bray-Curtis measure of dissimilarity) of floristic data were compared using the '2 Stage' algorithm in Primer (Clark & Gorley 2006) using the Spearman rank to determine the degree of correlation between datasets following the exclusion of annuals and / or singletons. This found a 94% correlation between the original data matrix with all taxa and the shared perennial dataset used in final analyses. And subsequent analyses found that perennial singletons and annuals had little overall effect on community classification, and these sets of taxa were omitted from the dataset prior to final analysis.

A sorted two-way table was generated from the final site and species classifications, which cross-referenced site groups with species groups. Indicator species analysis (Dufrêne & Legendre 1997) was employed to find significant indicator species characteristic of each floristic community type, using the INDVAL routine in the PC-Ord statistical package (McCune & Mefford 1999). A Monte Carlo permutation (MCAO) test, using 10 000 simulations, was used to test for the significance of these indicator species (McCune & Mefford 1999).

Three dimensional semi-strong hybrid (nonmetric) multidimensional scaling (SSH MDS) was used to ordinate sites using presence / absence data of floristic composition (Belbin 1991), using 1000 random starts and 50 iterations. Principal Component Correlation (PCC) (also known as rotational correlation analysis) was run in PATN as a form of simultaneous multiple linear regression of the extrinsic environmental parameters with the site ordination. A MCAO test, using 10000 iterations, evaluated the significance of these correlation coefficients (Belbin 1991). Significant vectors ($p < 0.05$), oriented on axis of best fit, were superimposed on to the site ordination. The Spearman rank correlation coefficient was used to examine relationships among site environmental attributes, and the Kruskal-Wallis nonparametric analysis of variance tested for differences in these environmental parameters among floristic community types, followed by Dunns' posthoc multiple comparisons (Zar 1984). Parameter values were not transformed except for aspect, where values were converted from degrees to radians and then transformed by a sine and cosine function. This produced linear values between -1 and 1, for the respective east-west and north-south orientations.

Nomenclature follows Packowska and Chapman (2000), with recent taxonomic updates and species distributions being obtained from the Census of Western Australian Plants (Western Australian Herbarium 1998–). Resolving distinct taxa with the *A. aneura* species complex is difficult (Miller *et al.* 2002), and variable entities were reduced to morphotypes which approximated the varieties described by Pedley (2001). The conservation listing of taxa presented are those recognised under the Western Australian Department of Conservation (DEC) conservation codes, and were based on the most recently available publication (Atkins 2008) and herbarium records (Western Australian Herbarium 1998–).

RESULTS

Flora

From collections within or adjacent to the 50 quadrats, a total of 235 taxa (species, subspecies, varieties and forms) and three putative hybrids were recorded from the ironstone and greenstone hills, ridges and adjacent outwash and colluvial plains within the Gullewa survey region (Appendix 1). Fifteen of these 235 taxa are naturalised species, although *Portulaca oleracea* s.l. has been considered native to the region by Hussey *et al.* (1997). All weed species are either annual herbs or annual grasses. Taxa came from 47 families, the most common being the Asteraceae (28 native and three introduced taxa), Chenopodiaceae (29 taxa and one hybrid), Mimosaceae (23 taxa and one putative hybrid), Poaceae (16 native and four introduced taxa), Amaranthaceae (12), Myrtaceae (10 taxa), Proteaceae (9 taxa), Caesalpineaceae (seven taxa and one hybrid), Myoporaceae (eight taxa), Goodeniaceae (seven taxa), Malvaceae (seven taxa) and Lamiaceae (five taxa). The most speciose genera were *Acacia* (23 taxa and one hybrid), *Maireana* (10 taxa and one hybrid), *Ptilotus* (12 taxa), *Eremophila* (eight taxa), *Senna* (seven and one hybrid) and *Sida* (six) (Appendix 1). This pattern is typical of floras from the Yalgoo and Murchison regions (Beard 1976a, 1976b, Pringle 1998, Markey and Dillon, 2008a, 2008b, Meissner & Caruso 2008a, 2008b, 2008c).

Priority taxa

Five taxa listed as being of conservation significance (Atkins 2008) were collected during the course of this survey, and almost all of these were new records for the survey area. None of these species are considered as endemic to the region (an endemic being restricted to within a 100km radius). *Acacia speckii* (Priority 3) and *Acacia subsessilis* (Priority 3) were already known to occur within the Gullewa area, although this survey located new populations. One new population of *A. speckii* was located, and the Gullewa populations are at the southern limit of a distribution that extends into the Murchison and Gascoyne bioregions. Three new populations of *A. subsessilis* were located on the Buddadoo Range and Mugga Mugga Hill. Most occurrences of *A. subsessilis* are centred in the Gullewa-Yalgoo area, but the range extends futher into the Yalgoo bioregion to just within the western margin of the Murchison bioregion. *A. subsessilis* is considered here as a near endemic, with a distribution mostly restricted to within a radius of 100km with the exception of a few outlying populations.

A new population of *Calytrix uncinata* (Priority 3) was located at Murdaburia Hill, thereby extending the known range of this species by 45km westwards. *C. uncinata* has a relatively wide distribution over the Yalgoo and Murchison bioregions. *Persoonia pentasticha* (Priority 3) is recorded for the Gullewa region for the first time, occurring as isolated shrubs scattered widely over the lateritic pediments of Mugga Mugga Hill, 73km east of the nearest known population. This species has a distribution centred on the boundary of the Yalgoo, Avon Wheatbelt and Geraldton Sandplains bioregions. The greatest range extension of a priority taxon was that of *Dodonaea amplisemina* (Priority 3), which was a range extension c. 100km north-west from nearest previously known location. This was a significant find, as the two new populations encountered on the Buddadoo Range are large and cover substantial areas of the hillsides.

Range extensions / New records

In addition to the previously mentioned taxa, the ranges of two species were extended by c. 100–300km, and were new records for the Yalgoo IBRA bioregion The collection of *Zygophyllum lobulatum* at Gullewa is within the known range, but is a new record for the Yalgoo bioregion and c. 110km south-east of the nearest known population. As with *Sclerolaena microcarpa* (another poorly collected species found in this survey), there are few collections ($\leq$ 10) of *Z. lobulatum* in the Western Australian Herbarium. This may indicate infrequent collection rather than actual scarcity or a restricted range.

The largest range extension found by this survey was that of *Alectryon oleifolius*, which has two subspecies which are allopatric with a disjunction over the mid west region. *A. oleifolius* subsp. *oleifolius* is centred in the north-west of the state while *A. oleifolius* subsp. *canescens* is largely restricted to the south-east. The nearest collection for *A. oleifolius* subsp. *oleifolius* is 300km north-west of Gullewa, which is a range extension for the subspecies. Two collections, which have not been resolved to subspecific level, have been recorded at two other locations within the Murchison-Yalgoo region, the nearest collection being c. 110km east of Gullewa. Although tending to subsp. *oleifolius*, these collections have characters intermediate of both subspecies.

Floristic Communities

Classification Analysis

Ten closely allied pairs of taxa were amalgamated for the floristic analyses, where there was some difficulty in differentiating between closely related taxa, in particular where there was the presence of intergrades (e.g. *Senna glutinosa* subsp. *chatelainiana* and *Senna glutinosa* subsp. *chatelainiana* x *charlesiana*) or when closely related varieties and were more informative when combined at a higher taxonomic level (e.g. the two subspecies of *Ptilotus gaudichaudii* and two varieties of *Crassula colorata*).

The original dataset of 50 quadrats had 218 taxa, with an average species richness of 35.1 $\pm$ 1.1 (s.e.) taxa per quadrat (range of 17 to 49 taxa per quadrat). The final data matrix of shared perennial taxa consisted of 104 taxa from 48 quadrats, which was 48% of the original taxa. Species richness averaged 24.6 $\pm$ 0.8 (s.e) shared perennial taxa per quadrat (range 13–37 taxa per quadrat). Floristic communities were resolved at the two and seven group level of the classification analysis (Fig. 2). The classification analysis simultaneously resolved the 104 species into nine Species groups, which are illustrated in a two-way table of sites and species occurrences (Appendix 2). The primary division in the classification segregated communities on both mafic landforms (basalt and gabbro) and low depressions (Community types 5 and 6) from those associated with BIF landforms and laterite breakaways (Community types 1–4). This division is also discernable on the sorted two-way table ordered by the site and species classification (Appendix 2), where the floristic composition of both mafic and low depression communities is mostly associated with an absence of Species groups A–C and good representation in Species groups F, G and I. The BIF and laterite communities are characteristically composed of taxa from Species groups A–C. This primary segregation of mafic and low depression sites from BIF and laterite sites is also evident on the site floristic ordination (Fig. 3).

These primary groups were further split at the six group level to form six Community types (Fig. 2). The larger grouping of sites on BIF and laterite were further split into floristic types which correspond closely with the separation of vegetation communities on lower slopes, pediments and colluvial plains/alluvial outwashes (Community types 3 and 4) from those on hill slopes and crests (Community type 1) and laterite pediments (Community type 2) (Fig. 2). The remaining two communities consisted of a mafic landform community (Community type 6) and a community of low depressions in shallow valley flats (Community type 5).

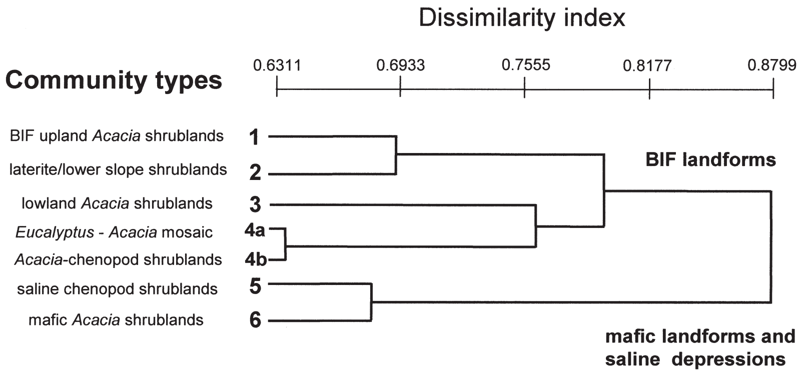

Figure 2. Summary dendrogram of floristic community types classified for the Gullewa survey area. Resolved from classification analysis and UPGMA clustering of a presence absence data matrix (Bray-Curtis measure of dissimilarity) of 104 perennial taxa from 48 quadrats. The dendrogram is resolved to the six group level, with two subtypes resolved within Community type 4.

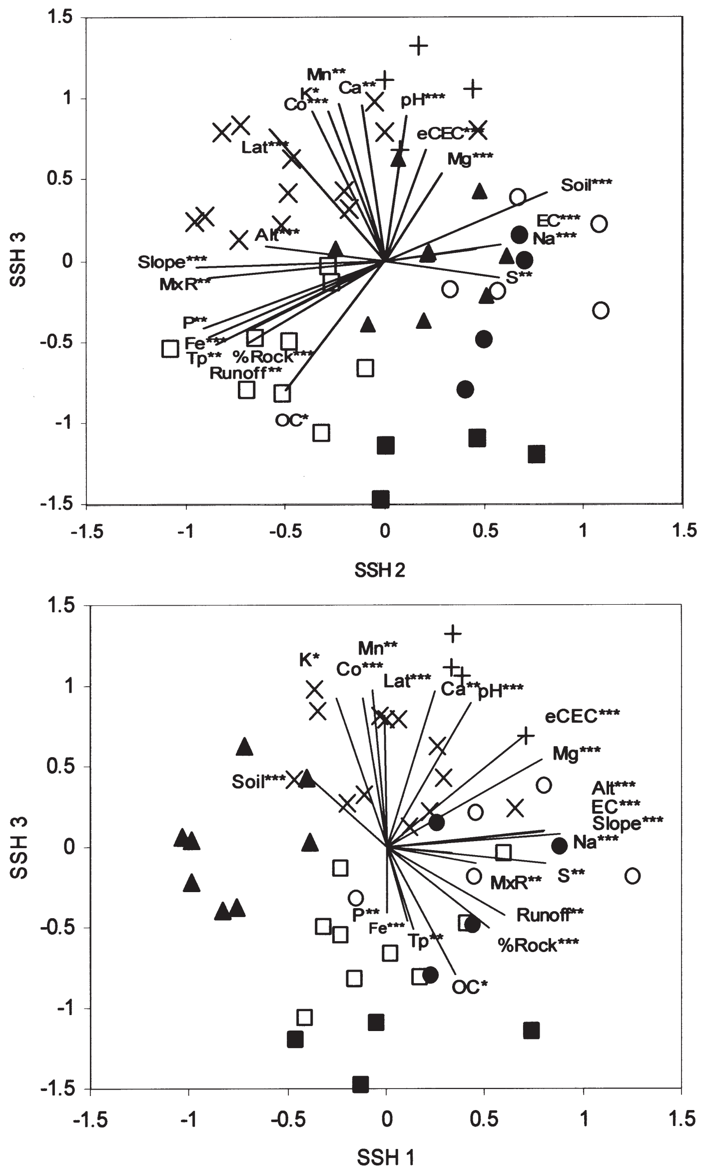

*Figure 3. 3D SSH MDS ordination of sites for the Gullewa survey area, based on dissimilarities in floristic composition from a presence/absence data matrix of 104 perennial taxa from 48 quadrats (stress = 0.18). Sites are coded by their respective floristic community types (1 □, 2 ■, 3 ▲, 4a ●, 4b ○, 5 +, 6 ×). Vectors of best fit linear correlations of site physical parameters and site ordination coordinates are superimposed on the ordination. Only significant vectors ($p < 0.05$) are displayed, as determined from Monte Carlo permutation tests. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.*

Community type 1: BIF upland *A. aneura* / *Acacia umbraculiformis* / *A. ramulosa* shrublands

Community type 1 consists of sites from gently – moderately inclined upper hill slopes and crests of massive BIF or heavily weathered haematite, BIF and / or laterite. This community can be described generally as sparse shrublands of *A. aneura*, *A. umbraculiformis* and *Acacia ramulosa* var. *ramulosa*, over various shrubs, including *Grevillea obliquistigma*, *Santalum spicatum*, *Thryptomene decussata*, *Prostanthera althoferi* subsp. *althoferi*, *Sida ectogama Philotheca brucei*, *Eremophila latrobei* subsp. *latrobei*, and *Ptilotus obovatus* (Appendix 2). Significant indicator species for this community type include *Dodonaea petiolaris*, *Acacia aneura* var. cf. *microcarpa*, *Cymbopogon ambiguus*, *Solanum ellipticum*, *Solanum lasiophyllum*, *Sida* sp. dark green fruits (S. van Leeuwen 2260), *Cheilanthes sieberi* subsp. *sieberi* and *Hakea recurva* subsp. *recurva* (Table 2). Other notable taxa include those that occupy rock fissures, such as the perennial herb, *Stylidium longibracteatum* and the myrtaceous shrub, *Micromyrtus sulphurea.*

There is good representation from Species group C, a group which characterises this community type and which contains taxa that are restricted to this community types, and group I, which is a group of taxa which occur across all community types. Conversely, there is poor representation from Species groups D and E. Some taxa from Species groups A, G, F and H distinguish this community type from Community type 2 (e.g. *Austrostipa nodosa*, *Cheilanthes sieberi* subsp *sieberi*) (Appendix 2). The total average number of taxa is 38.0 ± 1.2 (s.e.) per quadrat, which is marginally higher than most other community types (Table 3)

Community type 2: laterite breakaway / lower slope *Acacia* shrublands

Community type 2 was identified from four sites, all located on gently inclined laterite pediments, low hill slopes and breakaway escarpments around Murdaburia and Mugga Mugga Hills. Typically a tall open shrubland, the canopy stratum is dominated by a variety of acacias, notably *Acacia aulacophylla*, *A. aneura*, *A. ramulosa* var. *ramulosa* and *A. umbraculiformis,* over varied mid-stratum shrub layer which includes *Mirbelia bursarioides, Philotheca sericea, E. latrobei* subsp. *latrobei, Prostanthera patens* and the myrtaceous species, *Thryptomene decussata, Aluta aspera* subsp. *hesperia* and *Thryptomene costata.* Many of these taxa are significant indicator species for this community (Table 2). Other common species include *Eremophila forrestii* subsp. *forrestii*, *Philotheca brucei* subsp. *brucei*, *Solanum ellipticum* and *Monachather paradoxa* (Appendix 2).

Compared to Community type 1, Community type 2 has very little or no representation in Species groups A and D–G, and reduced representation across species in Species group C, H and I (Appendix 2). On the whole, while this community is affiliated floristically to Community type 1, it is species-depauperate and has the lowest species diversity among the six community types (27 ± 3.2 (s.e.) taxa per quadrat) (Table 3, Appendix 2).

Community type 3: lowland *Acacia ramulosa* / *Acacia grasbyi* shrublands

Community type 3 was assigned to nine sites located on substantial BIF ridges around Buddadoo and Murdaburia Hills and the northern section of Edamurta Range. These sites were flat to gently inclined stony plains at the base of the landforms or flat summit surfaces on BIF ridges. Community type 3 typically consisted of open tall shrublands of *A. ramulosa* var. *ramulosa* and *A. grasbyi* (an indicator species for this community), over open shrubland which includes of variety of shrubs, the most common including *E. forrestii* subsp. *forrestii*, *Ptilotus drummondii* var. *drummondii* and the significant indicator species *Senna glutinosa* subsp. *chatelainiana*, *Spartothamnella teucriiflora*, *Sida ectogama*, *Senna charlesiana*, *Solanum ellipticum* and *Ptilotus obovatus.* Chenopods are conspicuous in the lower shrub layers, including *Maireana convexa*, *Maireana triptera* and *Sclerolaena densiflora* (Table 2) (Appendix 2).

Species groups include near absence of taxa from Species groups B, C, D and G, and a distinctively high representation in Species group H which sets this community type apart from the other BIF and laterite associated community types. There is good representation from across Species group I (Appendix 2), and relatively high species richness (36.6 ± 2.7 (s.e.) taxa per quadrat).

Community type 4 was a heterogenous assemblage of nine quadrats located on gently inclined to undulating lower hill slopes, pediments, breakaways and stony plains surrounding Murdaburia and Mugga Mugga Hills.

The underlying geology is weathered BIF, haematite, laterite and associated metasedimentary rocks, and this lowland landscape grades from rocky breakaway escarpments and low outcrops of BIF to a mosaic of open York gum (*Eucalyptus loxophleba)* woodlands and *A. ramulosa* var. *ramulosa* / *A. burkittii* shrublands on the lowest points in this landscape. Consequently, Community type 4 was further divided into two subtypes (Fig. 2), corresponding with the separation of sites with more exposed rock outcrop and large rock boulders and fragments (type 4b), with those sites on a more subdued pavement of weathered BIF or deeper layers of colluvium and alluvial outwash (type 4a). There was also a greater influence on type 4b of associated metasediments (cherts, silts, shale) and some calcrete deposition. Both sites were observed to support a relatively rich suite of herbaceous and succulent annuals, such as *Helipterum craspedioides*, *Calotis multicaulis* and the introduced succulent herb, *Mesembryanthemum nodiflorum*.

Relative to other BIF communities, Community type 4 lacks taxa from Species group H, and has reduced numbers of taxa from Species group C (Appendix 2). Community types 4a and 4b are closely allied, and both have moderate species diversity among the various community types (averaging 35 and 37 taxa per quadrat respectively, Table 4). The main floristic differences are the presence of Species group D and more consistent representation in Species group F in Community type 4a (Appendix 2). Both Community subtypes share *P. obovatus* and *A. burkittii* as significant indicator species (Table 2).

Community type 4a: *Eucalyptus loxophleba* - *Acacia ramulosa* / *Acacia burkittii* woodland - shrubland mosaic

Community type 4a was represented by four sites on low weathered BIF pavements on pediments flanking the base of Mugga Mugga Hill. The typical community structure ranged from a mosaic of *E. loxophleba* subsp. *supralaevis*-*A. ramulosa* var. *ramulosa* woodland / shrublands to *A. burkittii*-*A. ramulosa* var. *ramulosa* tall open shrublands, often with *A. umbraculiformis*, over a very sparse stratum of various shrubs, including *Acacia exocarpoides* and *Enchylaena lanata*, over small tussocks of *Austrostipa nitida*, *A. elegantissima* and *M. paradoxa* (Appendix 2). In addition to those already listed for Community type 4, *A. exocarpoides* is a significant indicator species for Community type 4a (Table 2).

Community type 4b: *Acacia ramulosa* / *Acacia burkittii* / *Eremophila oldfieldii* chenopod shrublands

Community type 4b was sampled at both Mugga Mugga and Murdaburia Hills, and the species composition reflects the influence of the low outcrops of BIF, haematite and associated metasedimentary silts, shales and cherts. Sites were on lower slopes or flats downslope from BIF ridges or laterite breakaways, with evidence of calcrete deposition at some sites. The community typically consists of open tall shrublands of *A. ramulosa* var. *ramulosa*, *Acacia tetragonophylla* and *A. burkittii* with isolated trees of *Eremophila oldfieldii* subsp. *oldfieldii and Santalum spicatum*, over a sparse shrub stratum of *Senna* sp. Austin (A. Strid 20210), *Acacia andrewsii*, *Eremophila oppositifolia* subsp. *angustifolia, Dodonaea inaequifolia, P. obovatus, Scaevola spinescens* and *Eremophila pantonii.* Common components of the lower shrub and grass stratum include *Austrostipa scabra*, *Austrodanthonia caespitosa, A. elegantissima* and the chenopods, *Maireana thesioides, Sclerolaena diacantha, Maireana carnosa, E. lanata* and *S. densiflora.* Many of these taxa are indicator species (Table 2, Appendix 2).

Community type 5: Saline depression *Acacia eremaea* - chenopod shrublands

Community type 5 was sampled at four sites on the Edamurta and Buddodoo Ranges, and was a community associated with chenopod-rich low depressions in valley flats among BIF ridges,weathered haematite and lateritic beakaways. This was a distinctive community, which typically consisted of a sparse shrubland of *A. eremaea, Eremophila oldfieldii* subsp. *oldfieldii* and *Hakea preissii* over mid-lower strata shrub layers dominated by a rich variety of chenopods. Common and typical shrub species for this community include *Rhagodia eremaea*, *Rhagodia drummondii*, *S. spinescens*, *Solanum lasiophyllum*, *Maireana triptera*, *Atriplex codonocarpa*, *Maireana pyramidata*, *Maireana tomentosa* subsp. *tomentosa*, *Sclerolaena eriacantha, S. densiflora and Maireana georgei* (Table 2). *M. nodiflorum* was common to sites of this community, and was estimated to form a mid-dense (30–70%) cover at some sites. Many of these characteristic taxa for this community are grouped in Species groups E, F and I, which are the main Species groups associated with this Community type (Appendix 2). There is very little representation from the other Species groups. At an average of 33 ± 4.1 (s.e.) taxa per quadrat, sites are moderately species-rich (Table 3)

Community type 6: Mafic *Acacia umbraculiformis* shrublands

Community type 6 consisted of 13 sites which were all located on mafic substrates, primarily being gabbro or basalt on the Buddadoo and Edamurta Ranges and the hills east of Cagacaroon Hill. These sites covered a wide range of topographical positions, from hill crests to pediments, and were located over several ranges. Despite these differences, these sites were grouped within one relatively homogenous community type (Appendix 2).

This community can be described as *A. umbraculiformis* tall sparse shrublands, sometimes with *A. aneura* or *A. burkittii* in the canopy stratum, over a sparse - open shrubland of taxa such as *A. subsessilis, Pimelea forrestiana, P. obovatus* and *Sida calyxhymenia,* over the subshrubs *Solanum ellipticum*, *Abutilon oxycarpum* and *S. densiflora*, and the perennial grasses, *Cymbopogon ambiguus* and *Enneapogon caerulescens.* There are minor regional differences in species composition, most notably *D. amplisemina* and *T. costata* were only common in quadrats on the Buddadoo Range. Many of these taxa are significant indicator species (Table 2), and most taxa from Species group G (including *A. subsessilis, P. forrestiana* and *S. calyxhymenia*) are largely restricted to this community type. Nearly two thirds of taxa in Species group I are constantly present among sites within Community type 6. The absence of taxa distinguished this community type from the others, with little representation in Species groups A – E and H, and limited representation in Species group F (Appendix 2). Community type 6 is relatively species rich, having among the highest numbers of taxa per quadrat (37.2 + 1.7 (s.e.) (Table 3). Despite this diversity, these communities were structurally sparse, which may have been exacerbated by a history of heavy grazing.

Excluded sites

A pair of floristically similar quadrats were excluded from the analyses owing to their high floristic dissimilarity to the other 48 sites. Both sites consisted of sparse *Acacia effusifolia* and *A. ramulosa* var. *ramulosa* tall shrublands on low flats of laterite which extended southwards from Mugga Mugga and Murdaburia Hills. One site also had

Melaleuca leiocarpa as a co-dominant with the acacias over *Eremophila clarkei*, *Olearia humilis* and a sparse ground cover of *Chaemoxeros macrantha*. This site also had six singleton taxa, which was well above the average of 1.32 ± 0.26 (s.e.) but below the maximum of 8 singleton taxa per quadrat. The second site had *Grevillea obliquistigma* and *A. grasbyi* as co-dominants in the canopy, over a sparse mid-stratum shrub layer of *S. spinescens*, *Bursaria occidentalis* and *E. forrestii,* over a ground layer of *Ptilotus drummondii* var. *drummondii*. These two sites were relatively species poor, with 22 and 17 taxa per quadrat respectively, which is far less than the total average of 35.1 ± 1.1 (s.e.) taxa per quadrat for all sites (including singletons and annuals). It is possible that these sites sampled a distinctive vegetation community type which was first encountered in the south-west of the Gullewa study area and which does not occur elsewhere in the survey area.

SSH MDS Analysis

Semi-strong hybrid multidimensional scaling (SSH MDS) of the floristic association matrix was used to show relationships among sites in three dimensions. The stress value was 0.18, which is better than the desired maximum limit of 0.2 but still a less than a 'satisfactory' goodness of fit (Seber 1984). The seven floristic community types, derived from the classification analysis, are evident as relatively discrete clusters of sites in the three-dimensional ordination of sites (Fig. 3). There is minimal overlap among clusters of sites in ordination space, which supports the groupings obtained from the classification analysis.

Environmental Correlates

Topsoils from the Gullewa survey were generally shallow (2.18 ± 0.1 soil depth class, which equates to 5–20cm), leaf litter cover was scarce (average = 16.0 % ± 1.5 (s.e.)), and the bare ground covered 85.8 % ± 1.1 (s.e.) of the quadrat area. Soils were stony, with a surface mantle of rock fragments covering > 50% on average (cover class = 4.7 ± 0.1 (s.e.)), ranging from 10% to > 90%. Soil colour and texture was generally red to red-brown clay loam- sandy clay loams and clay sands, with a uniform profile and with a surface crust over loose soil. Soils were moderately acidic on average (pH = 5.4 ± 0.1 (s.e.)), and ranged from strongly acidic (pH 4.2) to the more neutral-slightly alkaline (pH 7.3) (for values measured in $CaCl^2$, *cf.* Slattery *et al.* 1999).

Two elements (B, Mo) were removed from the dataset as these elements were undetected in over half of the samples (Table 4). Most soil elements were inter-correlated (Ca, Cd, Co, Cu, K, Mn, Mg, Na, Ni and Zn), and positively correlated with soil pH and eCEC. Another inter-correlated group consisted of P, S, N and organic C, and was positively correlated with eCEC but independent of pH (Table 4). Among site physical variables, runoff, outcrop, maximum rock size, topographic position and slope were all inter-correlated, and this group was positively correlated with Fe and negatively correlated with soil depth. Both N and organic C were positively correlated with topographic position and rock outcrop cover (Table 4). Otherwise, there were few correlations between the suite of minerals, eCEC and pH and the suite of topographical variables (Table 4).

Differences in site soil parameter levels were evident among the seven floristic community types and subtypes, significant differences were found among these community types from nonparametric analysis of variance (Table 3). On average, the concentrations of a suite of soil elements (Ni, Ca, Cd, Co, Cu, Mg, Mn and Na) were lowest among Community types 1 and 2, and correspondingly high among Community types 4b and 5. Highest values were found in Community type 6, particularly Ni, Co, Cd, Mg and Mn (Table 3). Soils from these latter community types were also the least acidic, these values approaching weakly acidic pH values relatively higher levels of eCEC (Table 3). Levels of many of the trace elements (particularly Ni, Co, Cd, Mg and Mn) were particularly elevated in Community type 6 (Table 3), which is a community associated with metamorphosed gabbro-and basalt substrates. However, the average Ca:Mg ratios for all communities were below 6.0 (Table 3).

Community types closely associated with banded iron formation and laterites tended to have acidic soils with comparatively low levels of trace minerals (Community types 1–4). Soils from in Community types 1 and 2 were strongly acidic (c. pH 4.5) and relatively deficient in basic cations (Table 3). Community type 1, which characterised upland BIF landforms, was associated with soils with relatively high concentrations of Fe, P, S, organic C and N (Table 3). On the lower slopes and colluvial flats flanking BIF landforms, where Community type 3 was located, topsoil concentrations of Fe, P, N and organic C were lower while trace elements concentrations were elevated (Table 3). Community type 2, which occurs on lateritic pediments and lower BIF slopes, had soils with levels of trace minerals and P comparable to those from Community type 3, but with moderate levels of Fe. Levels of organic C and nitrogen were highest within Community type 1 and lowest in Community types 6 and 3. It is noted that these soils from Community type 1 were restricted to pockets among rocks and fissures, together with accumulations of leaf litter, organic material and loams.

Although not significant in multiple comparison tests, soil electrical conductivity (EC) and Na concentrations were highest on average within Community types 4b and 5, albeit highly variable in the former community. This indicated a tendancy for saline soils in these communities, while the remaining other communities had soils with a relatively low EC (Table 3). Community type 5 was typically located within low depressions among valleys and between ridges on the Buddadoo and Edamurta Ranges, receiving colluvium and alluvium from upland sites and developing what appeared to be calcareous soils. Community type 4b was also located low in the landscape, with both some degree of calcrete formation and receiving material from surrounding lateritic breakways, BIF ridges and mafic hills.

The majority of site physical parameters show significant differences among the floristic community types, most notably the inter-correlated parameters; slope, topographic position, altitude and runoff (Table 3). Community types 1 and 6 are clearly associated with steep sites at high elevations on upper slopes and hill crests. The largest loose rock sizes were found in both these community types (averaging at 60–200 cm). However, Community type 1 had a significantly greater cover of massive bedrock outcrop (50–90%), whilst outcropping bedrock cover within Community type 6 was comparable to the that found in the lateritic pediment Community types 2, 4a and 4b (generally ranging from 2–10%) (Table 4). Community types 3 and 5 had nearly no exposed bedrock, and together with Community type 4a were associated with sites at the lowest altitudes, lowest topographic positions within the landscape and with low runoff and gently inclined to flat gradients (Table 3). Corresponding with a decline in surface rock fragment size with distance from exposed and delaminating bedrock, rock fragments were smallest (20–60cm) within these latter communities. Regardless of fragment size, all sites associated with ironstone or greenstone landforms have an abundant mantle of surface rocks on an otherwise mostly bare surface (> 80% bare), hence there are no significant differences among community types in rock fragment or ground cover values. Leaf litter cover estimates were not significantly different among sites, but tended to be highest in the lowland BIF Communities types 3, 4 and 5 (Table 3).

Principal components correlation on the site ordination shows that the floristic groups are associated with three main soil chemical gradients and a topographic gradient (Fig. 3). These general trends in the ordination reiterate findings from the univariate analyses. One major gradient is associated with the two sets of collinear (and inter-correlated) variables; one consisting of Ca, Mn, Co and K, whilst pH, eCEC and Mg form another collinear trio (Fig. 3, Table 4). Community types 1 and 2 are associated with the low end of this soil nutrient gradient, especially Community type 1 (Fig. 3), hence soils are tending to be acidic, of low eCEC and relatively deficient in trace elements. Community types 3 and 4 occupy the middle range along this gradient, with Community type 4 aligning with the high end of the collinear vectors of pH, eCEC and Mg. As gauged from their centroids, subtypes 4a and 4b are marginally separated along this gradient, but there is some overlap when individual sites are considered. Community types 5 and 6 are both at the high extreme of the main trace element gradient, indicating relatively high levels of trace metals, a weakly acidic pH and comparatively higher eCEC. Orthogonal to the main soil element gradient is another minor gradient of three collinear parameters EC, S, and Na, which constitutes a salinity and S gradient. Community types 4 (especially 4b) and 5 are associated with higher values along this salinity gradient.

The second major gradient consists of the inter-correlated variables, organic C, P, Fe, topographic position, rock outcrop cover, runoff and soil depth (Fig. 3). This gradient is most closely associated with the segregation of upland and lowland community types. Community type 1 is at the extreme high end of this gradient, where the community is associated with steep rocky outcrops and scree slopes at higher altitudes, and where the skeletal-shallow soils are associated with relatively high levels of P, Fe and organic C (Fig. 3). Community type 2, being on lateritic breakaways on pediments, shares some soil, physical and floristic similarities to Community type 1, although this community is located at lower altitudes on less steep and outcropping terrain. Community types 4 and 5 are associated with the lower extremes of this major topographic and soil nutrient gradient. This occurs on the lower slopes and plains of deeper colluvium and alluvium where the slope and runoff are correspondingly at their lowest values. Community type 3 was also at the mid-lower extremes of this soil nutrient gradient, and consisted of sites both on stony plains and on flat summit surfaces high on BIF ridges. These sites had deeper soils and an abundance of colluvial debris which had either accumulated between near vertical BIF strata on the summits, or at the base of BIF hills. Community type 6 is associated at the higher end of this topographic gradient, where sites are located at relatively higher altitudes and topographic positions, with steeper, rocky slopes with shallow soils, although these sites are associated with low organic C levels, and are not associated with exceedingly high levels of Fe and P.

There is some suggestion of geographical segregation among the community types, which is a function of regional differences in geomorphology within the survey area. Part of this is due to a predominance of basalt and gabbro ranges in the north-east of the survey area. The lateritic pediments and breakaways that harbour Community type 4 and 2 are more commonly encountered in the south-western part of the area (Fig. 3, Table 3).

DISCUSSION

Flora

This survey reports a total 235 taxa and three hybrids for the Gullewa survey area, which is a rich flora of similar magnitude to ranges in the northern Eastern Goldfields, where counts from similar, quadrat-based surveys on BIF ranges vary from 238 to 345 taxa Gibson 2004b; Gibson & Lyons 2001a, 2001b; Gibson *et al.* 1997). It is also similar to counts from other surveys in the Yalgoo IBRA region, where 238 taxa were reported for the Koolanooka and Perenjori Hills (c. 55–70km south) (Meissner & Caruso 2008c) and 243 taxa for the Mount Gibson Hills (Meissner & Caruso 2006b). However, a more intensive survey recorded 414 taxa on the central Tallering Land System (c. 80km southeast), and 335 taxa were found around Mt Karara to Windaning Hill alone (c. 55km southeast, Markey & Dillon, 2008a). The flora list for Gullewa would be expected to increase if additional hills within the survey area are subject to detailed survey. These species counts are roughly comparable, as they do not take into account variations in season, survey area size and landform geology. When mafic landforms are excluded, 205 species were recorded from within the Gullewa survey area, which is at the lower end of the range of species estimates.

This survey was conducted during spring, which followed good summer rainfall but the driest winter period for Barnong Station in over a century of rainfall records (Australian Bureau of Meteorology 1908–). This had promoted the abundant growth of annual grasses, but herbaceous annuals and geophytes were relatively infrequent and probably under-represented in this survey. The species richness of annuals in this survey ranged between eight and 13 annual taxa per quadrat among the community types (Table 3). In comparison, averages of between 19 and 30 annual taxa per quadrat were recorded in the central Tallering Land System, which was conducted during a spring season (2005) where good winter rains had produced an abundance of herbaceous annuals (Markey & Dillon 2008a). Within the Asteraceae alone, numbers of taxa were less than half of those recorded from the previous year (31 versus 73 taxa). However, the Gullewa and central Tallering sites are comparable in perennial species richness, with an average of 24.6 and 23.4 shared perennial taxa per quadrat for each respective survey area. While it would be ideal to continue survey of permanent quadrats over seasons to sample inter-annual variation in diversity of annual taxa, this is beyond the scope of this study; and the scale of the Yilgarn Craton BIF-greenstone regional survey precludes revisiting individual ranges over subsequent seasons. Therefore, the use of perennial-only datasets is a means to control for inter-annual variation in annual abundances.

A further three priority taxa are known from the Gullewa area which were not located during this survey. Two of these are unlikely to occur on greenstone landforms within the survey area, as *Grevillea globosa* (Priority 3) occupies sandy habitats, and *Enekbatus dualis* (Priority 1) has not been recorded from either ironstone or greenstone hills. The diminutive herbaceous annual, *Chthonocephalus muellerianus* (Priority 2), could possibly occur around ironstone landforms, but has only been recorded from sandplain habitats within the general Gullewa area. It is unlikely to be found during years of low winter rainfall.

No regionally endemic taxa were identified within the study area and none are known from herbarium records, although *A. subsessilis* has been considered to be a 'near endemic'. This is far less than the nine regional endemics and near endemics which were identified by the central Tallering land system survey (Markey & Dillon 2008a). Relatively fewer taxa of conservation significance and no putative new taxa were recorded in the Gullewa survey area. In comparison, 12 taxa of conservation significance and several new taxa were also identified in the central Tallering land system, most of which were found in the southern portion of the survey area (Markey & Dillon 2008a). Similarly, eight priority taxa and five new taxa were located at the Koolanooka and Perenjori Hills (Meissner & Caruso 2008c) and eight taxa of conservation significance and one new species were recorded from the Mount Gibson Range. Using just the criterion of counts of rare and poorly known taxa, these adjacent ranges have relatively higher conservation values than the Gullewa landforms.

Floristic comparisons

The Gullewa survey area occurs within the Yalgoo IBRA bioregion, which is noted for being a transitional region between the species-rich South West and arid Eremaean biogeographical regions (Beard 1976a, 1990; Hopper & Gioia 2004; Thackway & Cresswell 1995). This is associated with a turnover in floristic composition and change in species richness between the two floristic regions Beard (1976a, 1990). The intermediate character of the Gullewa survey flora was evident in this survey, with representation from typically south-west genera (e.g.: *Persoonia*, *Pimelea*) and a predominance of genera more characteristic of the arid Midwest (e.g. *Acacia*, *Maireana*, *Sida, Eremophila, Senna*). On a smaller spatial scale, the recent Yilgarn BIF surveys within the Yalgoo and adjacent Avon bioregions have found the adjacent ranges share most of their species-rich genera (e.g. *Acacia, Eremophila, Senna, Sida* and *Ptilotus*) and dominant species (e.g. *A. assimilis*, *A. quadrimarginea*, *P. brucei*) (Markey & Dillon 2008a; Meissner & Caruso 2008b 2008c). However, many other dominant and characteristic taxa of the central Tallering Land System, Mount Gibson and Koolanooka-Perenjori Hills are absent or restricted within the Gullewa survey area. When the closest range (the central Tallering Land System) to Gullewa is compared, it is evident that there are some common and distinctive taxa which are absent from Gullewa, notably *Polianthion collinum*, *Calycopeplus pauciflorus*, *Leucopogon* sp. Clyde Hill (M.A. Burgman 1207), *Hibbertia arcuata, Xanthosa bungei, Drummondita fulva*, *Micromyrtus* trudgenii, *Melaleuca nematophylla* and *Persoonia manotricha* (Markey & Dillon 2008a). Other commonly encountered taxa in the central Tallering Land System appear to be restricted to the southern part of the Gullewa survey area, notably *Hemigenia benthamii*, *A. effusifolia*, *Mirbelia bursarioides, Cheiranthera filifolia* var. *simplicifolia, Grevillea obliquistigma* subsp. *obliquistigma, Chamaexeros macrantha*, *Allocasuarina acutivalvis*, *Persoonia hexagona*, *Persoonia pentasticha* and *Melaleuca leiocarpa.* Of particular note is the restriction of expanse of *Eucalyptus* woodlands to the southwest of the Gullewa survey area, whilst they are far more common on the lowlands of the central Tallering region and widespread over the slopes of the Koolanooka Hills (Markey & Dillon 2008a, Meissner & Caruso 2008b). This is consistent with the wider transition from *Eucalyptus* to *Acacia* woodlands which occurs within the Yalgoo bioregion (Beard 1976a), and further surveys have not located such woodlands north and east of Gullewa (author's unpublished data).

This high β-diversity among adjacent ranges becomes most apparent when comparing the proportion of perennial taxa shared between ranges that have similar species richness. The central Tallering Land System has

42.6% taxa in common with the Gullewa survey area. This declines to 27.0% perennial taxa in common with the Mount Gibson and the Koolanooka and Perenjori Hills share even less taxa (12.6%) with the Gullewa area (data from Markey & Dillon 2008a; Meissner & Caruso 2008b, 2008c). This remarkable species turnover occurs among ranges that are less than 100km apart.

Differences in floristic composition (high ß-diversity) among ranges in the Gullewa, central Tallering, Koolanooka and Mount Gibson survey areas can be attributed to several factors. The most prominent correlate is climate, with a gradient of increasing aridity in an easterly direction (Beard 1976a, 1976b; Hopper & Gioia (2004); Markey & Dillon 2008a). Differences in geology, topography and edaphic factors probably also account for floristic differences between the Gullewa survey area and adjacent BIF ranges, and these are evident at a smaller spatial scale than climate. BIF landforms are more prominent (40–160m above surrounding plains) and extensive in the adjoining central Tallering Land System (Markey & Dillon 2008a), and nearby Perenjori-Koolanooka Hills and around Mount Gibson (Meissner & Caruso 2008b, 2008c). Conversely, the Gullewa survey region is dominated by lateritic pediments and extensive, tall (100–150m) ranges of gabbro and basalt, while the BIF ridges are low in elevation (25–35m), have a more limited outcropping of massive ironstone and constitute only a small proportion of the hilly terrain. This limited habitat heterogeneity may play a significant role in limiting the species richness and number of endemic taxa relative to BIF ranges adjacent to the Gullewa region.

Finally, the evolutionary history of individual ranges has also been suggested to account for high species turnover among ranges and range-specific floristic communities (Gibson 1998a, 1998b). Climatic instability in late Tertiary and Quaternary and a stable landscape of old, nutrient poor soils has been invoked to account, in part, for the high level of speciation and high β-diversity of floras within the transitional rainfall zone of the South West Province (Hopper 2008, 1979; Hopper & Goia 2004). This hypothesis has been extended to address floristic patterns among rock outcrops in the adjacent pastoral regions (Hopper *et al.* 1997; Gibson 2004a). Ironstone ranges may have acted as refugia during these unstable climatic periods, consequently acquiring their unique floristic composition (Byrne 2008).

Vegetation Communities:

This current study described seven community types and subtypes for the Gullewa survey area. There is some general correspondence of these communities to some of the communities ('habitats') described for the Gabanintha, Tallering, Wiluna and Watson land systems by Pringle (1998). Community type 6 would be broadly equivalent to the greenstone hill acacia shrubland on hill slopes of the Gabanintha Land System. On the Tallering, Watson and Wiluna Land Systems, Community type 1 corresponds to stony ironstone mulga shrubland, and Community types 3, 4 and 5 could be equated to stony *Acacia/Eremophila* shrubland, lateritic hardpan plain mulga shrubland and stony plain bluebush mixed shrubland respectively. However, these 'habitats' of Pringle (1998) are defined by a relatively few dominant species, and do not take into account the progressive turnover of species over the wider Yalgoo and Murchison regions (Beard 1976a; Gibson *et al.* 2007; Markey & Dillon 2008a, 2008b; Meissner & Caruso 2008b, 2008c). Therefore, it is unlikely that some or all of the floristic communities described for Gullewa area will be widespread over the mapped extent of the land systems of Payne *et al.* (1998).

Communities described for the Gullewa survey area can be directly compared to those described for the adjacent central Tallering Land System, Mount Gibson and the Koolanooka Hills (Markey and Dillon 2008a; Meissner & Caruso 2008b, 2008c). Those communities described for the Koolanooka Hills have little in common with the Gullewa ironstone communities, and there are also fundamental floristic differences with the communities described for Mount Gibson. However, closer comparisons can be made with the ironstone communities described for the central Tallering Land System. There are broad similarities between the lower slope and stony colluvial and outwash plain communities of Gullewa and the central Tallering land system. However, there are distinctive community types that are not shared. The two rocky upland communities of the central Tallering (Community types 2 and 4a), are not represented in the Gullewa survey area. Conversely, the characteristic Gullewa communities of mafic hills and saline depressions are not described for the central Tallering land system (Markey & Dillon 2008a). Such differences in communities among sites are not unexpected when these ranges have less than 50% of taxa in common.

Environmental correlates

The association between floristic community composition with both underlying geology and a catenary sequence of interrelated soil, and geomorphological variables has been well documented among BIF and greenstone communities within the Eastern Goldfields, Midwest regions and Pilbara (Gibson 2004a, 2004b; Gibson & Lyons 1998a, 1998b, 2001a, 2001b; Markey & Dillon, 2008a, 2008b; Meissner & Caruso, 2008a, 2008b, 2008c; Payne *et al.* 1998; van Etten & Fox 2004). The Gullewa floristic communities were no exception, although this study does not determine which environmental variables are specifically driving responses in the floristic community.

The association of distinct floristic communities with mafic and BIF substrates has been documented in the wider Goldfields and Midwest regions (Mabbutt *et al.* 1961; Payne *et al.* 1998) and within individual greenstone ranges of varied geology (Cole 1973; Gibson 2004a; Markey & Dillon, 2008b). Floristic communities within the Gullewa region were grouped primarily on geology, where mafic and saline communities were segregated from BIF and laterite communities. In particular, a distinctive mafic community (Community type 6) was found on rocky hill slopes of metamorphosed basalt, dolerite and gabbro, where surface soils were found to be weakly acidic and relatively rich in metals. Soil chemical composition will reflect parent bedrock composition, particularly when it has developed *in situ*, and mafic rocks typically produce soils rich in Ni, Cr, Co, Mn, Fe and Mg, but low in N, Ca and P (Cole 1973; Cornelius *et al.* 2007; Britt *et al.* 2001; Gray & Murphy 2002). Clays produced from mafic rock also generally have a higher eCEC and reduced acidity as a consequence of the buffering capacity of exchangeable cations (Gray & Murphy 2002).

For the most part, Community type 6 was characterised by species that are restricted to mafic substrates in the Gullewa region and are usually recorded from mafic substrates throughout their range (Western Australian Herbarium 1998–). This includes the significant indicator species *P. forrestiana*, *D. amplisemina*, *A. subsessilis* and *S. calyxhymeniana.* However, these species are not mafic specialists as they have been recorded occasionally from BIF habitats. There may also be mafic ecotypes of the widespread species *E. forrestii* and *Eremophila platycalyx* in the Gullewa survey area, since both species were observed during this survey to exhibit vastly different growth morphologies on BIF and greenstone substrates. Ecotypes of widespread species have been documented for ultramafics in New Zealand (Lee *et al.* 1983), and physiological responses to metalliferous soils have been documented in some Western Australian species on ultramafics (Cole 1973), but plant tolerances and possible responses to the relatively less extreme mafic substrates in Western Australia have rarely been studied. A few studies from the Yilgarn greenstones have found that foliar metal concentrations can reflect soil composition (Britt *et al.* 2001), but other aspects such as rooting depth and soil element availability will determine element uptake and their physiological effects on plants (Cole 1973).

Within the BIF and lateritic communities of Gullewa, there was a clear catenary sequence of floristic communities that corresponded to an edapho-topographic gradient, and the greatest floristic differences were at the gradient extremes of upland versus lowland sites. Soil development is influenced by topographic position (Cole 1973; Hennig 1998b; Gray & Murphy 2002), and soils of the Gullewa upland communities (Community types 1 and 2) were skeletal, strongly acidic (c. pH 4.5), with low concentrations of exchangeable cations and reduced trace mineral concentrations, all of which are likely to be a consequence of both prolonged weathering and leaching of soils and bedrock (Ben-Shahar 1990; Cole 1973; Cornelius *et al.* 2007; Tiller 1962). Both underlying composition and prolonged weathering may also account for elevated levels of iron, the insoluble oxides of which remain in weathered rocks and laterites (Anand 2001; Brand & Butt 2001; Britt *et al.* 2001; Cornelius *et al.* 2007; Foulds 1993; Tiller 1962). Relatively high levels of phosphate have been recorded from other soils from BIF outcrops in the Yilgarn (Gibson & Lyons 2001b; Foulds 1993), which are notably higher than for other soils in southwest Australia (Foulds 1993). Both deficiencies in basic cations and relatively elevated levels of sulfur may lead to more acidic soils given the reduced capacity for soil buffering and the production of sulfates (Gray & Murphy 2002; Slattery *et al.* 1999). What little volumes of surface soils were available were found to be high in nitrogen and carbon, presumably because they were being enriched with a high proportion of organic material, particular from nitrogen-fixing *Acacia* species (Eldridge & Wong 2005; Foulds 1993),

Soils of communities on the lower slopes, stony plains or outwashes of BIF landforms were relatively deep, weakly acidic and enriched in soil elements. These trace elements are ultimately derived from weathered landforms of both BIF and mafic bedrock (Britt *et al.* 2001; Gray & Murphy 2002), and other studies describe similar patterns of the enrichment of colluvial and alluviual deposits with mineral leachates, clay and salts (Hennig 1998b; Gibson & Lyons 1998a 1998b, 2001b). While these soils were found to be weakly acidic, other studies have reported far more basic soils (pH > 8.0) in outwash locations which have been derived from the weathering of mafic rocks and deposits of calcrete (Gibson & Lyons 1998, 2001b). Relatively saline soils were also recorded in two lower slope communities (Community types 4b and 5), which supported an abundance of chenopods and succulents. Salts deposits are presumably derived from leachate from rocks and deposited by groundwater, and possibly are being released from clays in weathered breakaways (Britt *et al.* 2001; Gibson & Lyons 2001a). There is the possibility that the facultative halophyte and salt accumulating species, *Mesembryanthemum nodiflorum* may also contribute to surface soil salinity (Kloot 1983). Levels of sodium and EC values in these two communities are comparable to those found in flats adjacent to salt lakes on the Bremer Range (Gibson & Lyons 1998a).

It is inferred that other edaphic factors not assessed by this survey are also likely to influence floristic community composition. Among these is a soil moisture gradient, where upland sites with skeletal soils are more freely draining and have reduced overall soil water retention while lowlands sites receive runoff and overlie groundwater sources (Jacobi *et al.* 2007; Johnson 1998; Hopper *et al.* 1997; Specht *et al.* 2006). What is evident from this and other studies are that the physical and chemical attributes of these isolated landforms provide a diverse array of habitats within a relatively small area, which differ from the surrounding plains.

Conservation

Within the Gullewa survey area, exotic plants and animals, pastoralism and mining are some of the obvious threatening processes to the communities on outcropping mafic volcanics and BIF. All survey sites were found to be relatively weed-free in terms of cover and diversity, and all 15 introduced species were annuals. The most commonly encountered naturalised species was the grass, *Pentaschistis airoides* (30 of 50 plots), followed by the parasitic vine, *Cuscuta epithymum*, and the succulent herbs, *Cleretum papulosum* subsp. *papulosum* and *M. nodiflorum*. Only *M. nodiflorum* was found to be moderately abundant (in terms of cover), and this was at a few sites within the lowland, saline communities (types 4b and 5). In some grassland situations, *Mesembryanthemum* species are particularly invasive following disturbance as these salt-accumulators increase local soil salinity and suppresses re-establishment of other, less salt-tolerant species (Kloot 1983), but such a role has not been explored in the Yilgarn region. However, long term grazing by sheep and goats was observed to be having a noticeable effect on the structure of the vegetation around the hills and ranges. This was noted for all elevations, and particularly for mafic ridges and lower slope sites. This apparently poor vegetation condition has been compounded by the cumulative effects of a prolonged drought. Since quadrats were established in only the best available vegetation, it is difficult to comment from this current study on the interaction of grazing, weeds and other forms of disturbance, and if exotics are displacing native species. However, Western Australian granite outcrop communities have been noted to be vulnerable to invasion by annual exotics (Hopper *et al.* 1997), and both Meissner & Caruso (2008c) and Gibson & Lyons (2001b) noted that the most severely invaded sites on BIF landforms were those that had been impacted by tracks, grazing, infrastructure and mining. While recent research on pastoral leases in the Yalgoo district has focussed on stock management (Pringle & Tinley 2001), the impact of weeds, feral goats and drought on vegetation structure and recruitment could be addressed by future studies. Long-term goat control will be a significant conservation issue in this region, and will require a coordinated regional approach.

The impacts of past decades of mining and mineral exploration are clearly evident throughout the Gullewa study area, particularly around Mugga Mugga and Cagacaroon Hills. There are many old excavations, exploration drillings and over 10 inactive mines. There is little indication that any effort has been made to rehabilitate most of these areas, although the more recent mines may be under consideration for reopening (Department of Industry and Resources 2007). Mineral exploration has recommenced in the area, with interests in iron ore, silver, copper, gold and other base metals (Cornelius *et al.* 2001; Flint *et al.* 2000; Department of Industry and Resources 2007). Mining and exploration tenements effectively cover the entire extent of BIF and mafic landforms within the Gullewa survey area.

There are no areas within the Gullewa survey region which currently occur within conservation reserves, the closest being the Barnong Nature Reserve which covers woodlands and shrublands on sandy flats west of Gullewa. Barnong station has been recently acquired by Western Australian Department of Conservation for eventual incorporation in the conservation estate, but its current tenure status is unallocated crown land. There are very few reserves within the Yalgoo IBRA bioregion, and no ironstone or greenstone ranges in this wider area are protected. South-east of the Gullewa survey area, the Warriedar, Lochada and Karara pastoral leases have been purchased with the intention for future inclusion in the conservation estate. However, mining and exploration activities are already underway or proposed for the BIF ranges within this currently unallocated crown land (Department of Industry and Resources 2007; Markey & Dillon 2008a). Given the resurgence in mining and exploration activity within the Gullewa survey area, it is recommend that proposals are both carefully assessed and that industry adopts best practise measures to minimise impacts on the conservation-listed taxa, geographically restricted communities and on the general landscape.

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APPENDIX 1

Flora List for the Gullewa survey area. Nomenclature follows Packowska and Chapman (2000) and records of the Western Australian Herbarium (PERTH). Phrase (informal) names are are followed by a type or reference collection number, introduced weeds are indicated by an asterisk.

Adiantaceae
- *Cheilanthes adiantoides*
- *Cheilanthes brownii*
- *Cheilanthes lasiophylla*
- *Cheilanthes sieberi* subsp. *sieberi*

Aizoaceae
- *Cleretum papulosum* subsp. *papulosum**
- *Gunniopsis quadrifida*
- *Mesembryanthemum nodiflorum**

Amaranthaceae
- *Ptilotus aervoides*
- *Ptilotus divaricatus* var. *divaricatus*
- *Ptilotus drummondii* var. *drummondii*
- *Ptilotus exaltatus*
- *Ptilotus gaudichaudii* var. *gaudichaudii*
- *Ptilotus gaudichaudii* var. *parviflorus*
- *Ptilotus helipteroides*
- *Ptilotus holosericeus*
- *Ptilotus macrocephalus*
- *Ptilotus obovatus*
- *Ptilotus polystachyus* var. *polystachyus*
- *Ptilotus spathulatus* forma *spathulatus*

Anthericaceae
- *Thysanotus manglesianus*
- *Thysanotus pyramidalis*

Apiaceae
- *Daucus glochidiatus*
- *Trachymene ornata*

Asclepiadaceae
- *Cynanchum floribundum*
- *Marsdenia australis*
- *Marsdenia graniticola*
- *Rhyncharrhena linearis*

Asteraceae
- *Brachyscome cheilocarpa*
- *Brachyscome ciliocarpa*
- *Calocephalus multiflorus*
- *Calotis hispidula*
- *Calotis multicaulis*
- *Cephalipterum drummondii*
- *Chthonocephalus pseudevax*
- *Dielitzia tysonii*
- *Gnephosis arachnoidea*
- *Helipterum craspedioides*
- *Hypochaeris glabra**
- *Isoetopsis graminifolia*
- *Lemooria burkittii*
- *Millotia myosotidifolia*
- *Olearia humilis*
- *Olearia pimeleoides*
- *Olearia stuartii*
- *Podolepis canescens*
- *Podolepis capillaris*
- *Podolepis kendallii*
- *Podolepis lessonii*
- *Podotheca gnaphalioides*
- *Rhodanthe battii*
- *Rhodanthe chlorocephala* subsp. *splendida*
- *Rhodanthe maryonii*
- *Schoenia cassiniana*
- *Schoenia filifolia*
- *Sonchus oleraceus**
- *Urospermum picroides**
- *Vittadinia humerata*
- *Waitzia acuminata* var. *acuminata*

Boraginaceae
- *Halgania cyanea*
- *Trichodesma zeylanicum*

Boryaceae
- *Borya sphaerocephala*

Brassicaceae
- *Sisymbrium erysimoides**

Caesalpiniaceae
- *Senna artemisioides* subsp. *filifolia*
- *Senna charlesiana*
- *Senna glutinosa* subsp. *chatelainiana* x *charlesiana*
- *Senna glutinosa* subsp. *chatelainiana*
- *Senna pleurocarpa* var. *angustifolia*
- *Senna* sp. Austin (A. Strid 20210)
- *Senna* sp. Meekatharra (E. Bailey 1-26)

Caryophyllaceae
- *Petrorhagia dubia**
- *Spergula pentandra**

Casuarinaceae
- *Allocasuarina acutivalvis* subsp. *prinsepiana*

Chenopodiaceae
- *Atriplex bunburyana*
- *Atriplex codonocarpa*
- *Atriplex semilunaris*
- *Chenopodium curvispicatum*
- *Chenopodium melanocarpum* forma *melanocarpum*
- *Dysphania glomulifera* subsp. *eremaea*
- *Enchylaena lanata*
- *Enchylaena tomentosa* var. *tomentosa*
- *Eriochiton sclerolaenoides*
- *Maireana carnosa*
- *Maireana convexa*
- *Maireana georgei*
- *Maireana planifolia*
- *Maireana planifolia* x *villosa*
- *Maireana pyramidata*
- *Maireana thesioides*
- *Maireana tomentosa* subsp. *tomentosa*
- *Maireana trichoptera*
- *Maireana triptera*
- *Rhagodia drummondii*
- *Rhagodia eremaea*
- *Salsola tragus*
- *Sclerolaena densiflora*
- *Sclerolaena diacantha*
- *Sclerolaena eriacantha*

Sclerolaena fusiformis
Sclerolaena gardneri
Sclerolaena microcarpa

Crassulaceae
Crassula colorata var. *acuminata*
Crassula colorata var. *colorata*

Cupressaceae
Callitris collumellaris

Cuscutaceae
*Cuscuta epithymum**

Dasypogonaceae
Chamaexeros macranthera

Droseraceae
Drosera macrantha

Euphorbiaceae
Euphorbia boophthona
Euphorbia drummondii subsp. *drummondii*
Euphorbia tannensis subsp. *eremophila*
Phyllanthus erwinii

Geraniaceae
Erodium cygnorum

Goodeniaceae
Goodenia berardiana
Goodenia havilandii
Goodenia mimuloides
Goodenia occidentalis
Scaevola spinescens
Scaevola tomentosa
Velleia cycnopotamica

Haloragaceae
Haloragis trigonocarpa

Lamiaceae
Hemigenia cf. sp Yuna (A.C. Burns 95)
Hemigenia benthamii
Prostanthera althoferi subsp. *althoferi*
Prostanthera patens
Spartothamnella teucriiflora

Lobeliaceae
Lobelia heterophylla

Malvaceae
Abutilon cryptopetalum
Abutilon oxycarpum subsp. *prostratum*
Sida calyxhymenia
Sida ectogama
Sida sp. dark green fruits (S. van Leeuwen 2260)
Sida sp. Golden calyces glabrous (H.N. Foote 32)

Mimosaceae
Acacia andrewsii
Acacia aneura var. cf. *aneura*
Acacia aneura var. cf. *microcarpa*
Acacia aneura var. cf. *tenuis*
Acacia aneura var. cf. *argentia*
Acacia aneura var nov. (PERTH 07557671)
Acacia aneura var nov. (PERTH 07557698)
Acacia aneura x *craspedocarpa*
Acacia anthochaera
Acacia aulacophylla
Acacia burkittii
Acacia effusifolia
Acacia colletioides
Acacia eremaea
Acacia erinacea
Acacia exocarpoides
Acacia grasbyi
Acacia incognita
Acacia microcalyx
Acacia ramulosa var. *ramulosa*
Acacia sclerosperma subsp. *sclerosperma*
Acacia umbraculiformis
Acacia speckii
Acacia subsessilis
Acacia tetragonophylla

Myoporaceae
Eremophila clarkei
Eremophila forrestii subsp. *forrestii*
Eremophila granitica
Eremophila latrobei subsp. *latrobei*
Eremophila oldfieldii subsp. *oldfieldii*
Eremophila oppositifolia subsp. *angustifolia*
Eremophila pantonii
Eremophila platycalyx subsp. *platycalyx*

Myrtaceae
Aluta aspera subsp. *hesperia*
Calytrix strigosa
Calytrix uncinata
Eucalyptus loxophleba subsp. *supralaevis*
Melaleuca atroviridis
Melaleuca eleuterostachya
Melaleuca leiocarpa
Micromyrtus sulphurea
Thryptomene costata
Thryptomene decussata

Papilionaceae
Glycine canescens
Mirbelia bursarioides
Swainsona oliveri

Phormiaceae
Dianella revoluta

Pittosporaceae
Bursaria occidentalis
Cheiranthera filifolia var. *simplicifolia*
Pittosporum angustifolium

Plantaginaceae
Plantago aff. *hispida*

Poaceae
Aristida contorta
Austrodanthonia caespitosa
Austrostipa elegantissima
Austrostipa nitida
Austrostipa nodosa
Austrostipa scabra
*Bromus madritensis**
*Bromus rubens**
Cymbopogon ambiguus
Elymus scaber
Enneapogon caerulescens

Eragrostis dielsii
Eragrostis pergracilis
Eriachne pulchella subsp. *dominii*
Eriachne pulchella subsp. *pulchella*
*Lamarckia aurea**
Monachather paradoxus
Paspalidium basicladum
*Pentaschistis airoides**
Tripogon loliiformis

Polygalaceae
Comesperma integerrimum

Polygonaceae
*Acetosa vesicaria**

Portulacaceae
Calandrinia eremaea
Calandrinia granulifera
Calandrinia ptychosperma
*Portulaca oleracea**

Proteaceae
Grevillea extorris
Grevillea deflexa
Grevillea obliquistigma subsp. *obliquistigma*
Hakea lorea subsp. *lorea*
Hakea preissii
Hakea recurva subsp. *arida*
Hakea recurva subsp. *recurva*
Persoonia hexagona
Persoonia pentasticha

Rhamnaceae
Cryptandra imbricata

Rutaceae
Philotheca brucei subsp. *brucei*
Philotheca sericea

Santalaceae
Exocarpos aphyllus
Santalum spicatum

Sapindaceae
Alectryon oleifolius subsp. *oleifolius*
Dodonaea inaequifolia
Dodonaea petiolaris
Dodonaea amplisemina

Solanaceae
Nicotiana cavicola
Nicotiana cf. *rotundifolia*
Solanum ellipticum
Solanum lasiophyllum
Solanum nummularium

Stackhousiaceae
Stackhousia muricata

Stylidiaceae
Stylidium longibracteatum

Thymelaeaceae
Pimelea forrestiana
Pimelea microcephala subsp. *microcephala*

Zygophyllaceae
Zygophyllum eremaeum
Zygophyllum lobulatum
Zygophyllum simile

APPENDIX 2

Sorted two-way table from classification analysis of 104 taxa from 49 quadrats from the Gullewa survey area. Sites appear as columns, and species as rows. Species occurrence in a community type indicated by a black square.

	Community type						
	type 1	type 2	type 3	type 4a	type 4b	type 5	type 6
Species Group A							
Cheilanthes brownii	■						■
Marsdenia australis	■		■	■			■
Maireana planifolia x villosa			■				
Comesperma integerrimum			■	■	■		
Phyllanthus erwinii	■		■				
Acacia aneura var cf. *aneura*	■		■				
Sclerolaena microcarpa			■			■	
Species Group B							
Prostanthera patens		■					
Thysanotus manglesianus	■	■					
Eremophila clarkei	■	■			■		
Austrostipa scabra	■		■		■	■	
Allocasuarina acutivalvis subsp. *prinsepiana*		■		■			
Grevillea obliquistigma subsp. *obliquistigma*	■	■		■			
Acacia exocarpoides		■		■			
Acacia aneura x craspedocarpa			■				■
Dianella revoluta	■		■				
Acacia aneura var. cf. *tenuis*		■	■				■
Species Group C							
Aluta aspera subsp. *hesperia*		■					
Stylidium longibracteatum	■						
Philotheca sericea	■	■					
Sida chrysocalyx	■	■	■		■		
Prostanthera althoferi subsp. *althoferi*	■	■					
Thryptomene decussata	■	■					
Philotheca brucei subsp. *brucei*	■	■	■				
Thryptomene costata	■	■			■		■
Acacia aulacophylla	■	■		■	■		
Mirbelia bursarioides	■	■	■	■	■		
Eremophila latrobei subsp. *latrobei*	■	■	■	■	■		
Hakea recurva subsp. *recurva*	■	■	■		■		■
Santalum spicatum	■				■		
Cheilanthes adiantoides	■	■		■	■		■
Micromyrtus sulphurea	■						
Persoonia hexagona	■						
Acacia aneura var. cf. *microcarpa*	■		■				
Dodonaea petiolaris	■						■
Species Group D							
Eremophila pantonii					■		
Acacia andrewsii					■		
Eremophila oppositifolia subsp. *angustifolia*					■	■	
Dodonaea inaequifolia		■			■		
Exocarpos aphyllus	■				■		
Species Group E							
Senna sp. Meekatharra (E. Bailey 1-26)						■	■
Eremophila granitica			■		■	■	
Atriplex bunburyana						■	■
Ptilotus exaltatus			■		■	■	■
Hakea preissii					■	■	
Ptilotus divaricatus var. *divaricatus*					■	■	
Acacia eremaea			■			■	
Sclerolaena eriacantha						■	■
Rhagodia drummondii	■		■	■	■	■	■
Maireana pyramidata			■		■	■	■
Species Group F							
Senna sp. Austin (A. Strid 20210)			■		■	■	
Eremophila oldfieldii subsp. *oldfieldii*			■		■	■	■
Scaevola spinescens	■	■	■	■	■	■	■
Solanum nummularium	■		■	■	■	■	■
Acacia burkittii	■		■	■	■	■	■
Euphorbia drummondii		■	■	■	■	■	■
Austrodanthonia caespitosa				■	■		■
Atriplex codonocarpa			■			■	■
Atriplex semilunaris			■	■	■	■	■
Maireana georgei	■		■	■	■	■	■
Maireana tomentosa subsp. *tomentosa*	■		■	■		■	■
Sclerolaena diacantha	■			■	■	■	■
Senna charlesiana	■		■	■		■	■
Maireana carnosa		■	■	■	■	■	■
Species Group G							
Hemigenia cf. sp Yuna							■
Scaevola tomentosa							■
Eremophila platycalyx subsp. *platycalyx*							■
Salsola tragus			■			■	■
Austrostipa nodosa	■			■			■
Senna glutinosa subsp. *chatelainiana*	■		■			■	■
Dodonaea amplisemina							■
Acacia subsessilis							■
Sida calyxhymenia							■
Pimelea forrestiana							■
Maireana trichoptera	■				■		■
Species Group H							
Spartothamnella teucriiflora	■		■				
Rhyncharrhena linearis	■	■	■	■	■		
Hakea recurva subsp. *arida*	■	■	■				■
Cheilanthes sieberi subsp. *sieberi*	■		■				■
Sida ectogama	■		■				■
Ptilotus drummondii var. *drummondii*	■	■	■				■
Maireana planifolia	■	■	■	■	■	■	■
Maireana convexa			■			■	■
Acacia grasbyi	■	■	■		■		■
Maireana thesioides	■		■		■	■	■
Species Group I							
Rhagodia eremaea	■		■			■	■
Abutilon oxycarpum	■		■	■	■	■	■
Enneapogon caerulescens	■		■	■	■	■	■
Maireana triptera	■		■		■	■	■
Austrostipa nitida	■	■	■	■	■	■	■
Enchylaena lanata	■	■	■	■	■	■	■
Ptilotus obovatus	■	■	■	■	■	■	■
Sclerolaena densiflora	■		■	■	■	■	■
Solanum lasiophyllum	■		■		■	■	■
Solanum ellipticum	■	■	■	■	■	■	■
Cymbopogon ambiguus	■		■				■
Acacia umbraculiformis	■	■		■	■		■
Monachather paradoxus	■	■	■	■	■		
Acacia ramulosa var. *ramulosa*	■	■	■	■	■	■	■
Eremophila forrestii	■	■	■	■	■		■
Sida atrovirens	■	■	■	■	■	■	■
Acacia tetragonophylla	■	■	■	■	■	■	■
Abutilon cryptopetalum	■		■	■	■	■	■
Austrostipa elegantissima	■	■	■	■	■	■	■

Table 1

Summary table listing site physical and soil attributes and methodology used for data collection. Asterisks indicate environmental attributes using coding category definitions adapted from McDonald *et al.* (1998).

Environmental attributes	**Method**
Bare ground cover	Visual estimate (%) total soil and litter cover
litter cover	Visual estimates (%) litter-only cover
Slope	Clinometer angle
Soil depth (soil) *	Coded at three point scale of visual estimate of depth: 0–2 cm (1); 2–50 cm (2); >50 cm (3)
Runoff *	Coded at five point scale of visual estimate of runoff: no runoff (0); very slow (1); slow (2); moderately rapid (3); rapid (4); very rapid (5)
Aspect	Compass bearing
Topographic position (Tp) *	Coded as five point semi-quantitative scale: outwash / plain (1); lower slope (2); mid slope (3), upper slope or low, isolated ridge (4), crest (5).
Surface rock fragment (Frag Rock) *	Coded as five point semi-quantitative scale: 0 % cover (0); < 2 % cover (1); 2–10%, (2); 10–20% (3); 20–50% (4); 50–90% (5); > 90% (6).
exposed bedrock cover class (Rock) *	Coded as five point semi-quantitative scale: 0 % cover (0); < 2 % cover (1); 2–10%, (2); 10–20% (3); 20–50% (4); 50–90% (5); > 90% (6).
Maximum rock fragment size (MxR)*	Coded as semi-quantitative, seven point scale: 2–6 mm (1); 6–20 mm (2); 20–60 mm (3); 60–200 mm (4); 200–600 mm (5); 600 mm–2m (6); > 2 m (7).
Soil elemental composition	16 elements: Al, B, Ca, Cd, Co, Cu , Fe , K, Mg, Mn, Mo, Na, Ni, P, S and Zn Inductively coupled plasma atomic emission spectrometry (ICP AES), using the Mehlich No. 3 soil test procedure (Mehlich 1984; Walton & Allen 2004).
Soil pH	0.01M CaCl2 solution (Method S3; Rayment & Higginson 1992).
effective cation exchange capacity (eCEC)	Calculated as sum total the charge equivalents of Na, Ca, K and Mg , derived from concentrations determined by ICP AES (Rayment & Higginson 1992, Soil and Plant Council 1999),.
Electrical conductivity (EC)	Conductivity meter on a 1:5 solution of soil extract:deionised water at 25 ºC (Method S2; Rayment & Higginson 1992).
Soil organic carbon	Metson's colorimetric modification of the Walkley and Black wet oxidation method S09 (method 6A1, Rayment & Higginson 1992).
Total soil nitrogen	Modified kjeldahl digest (method S10). Colorimetry using nitroprusside dichloro-S-triazine modification of the Berthelot indophenol reaction (Rayment & Higginson 1992).
Soil texture	Soil bolus manipulation (McDonald *et al*. 1998)

Table 2

Significant indicator taxa of the eight group classification of floristic communities identified within the Gullewa survey area. Indicator values (%) are shown only for taxa which were significant at $p < 0.05$ (from Monte Carlo permutation test, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$). The highest indicator values per taxon are indicated by shading.

	Community type						
	1	2	3	4a	4b	5	6
*Cymbopogon ambiguus****	45	0	5	3	0	0	17
*Solanum ellipticum****	20	11	16	5	3	5	20
*Solanum lasiophyllum****	24	0	14	0	9	24	17
*Dodonaea petiolaris***	49	0	0	0	0	0	1
Sida sp. dark green fruits *	23	13	7	13	1	1	14
Acacia aneura cf var. *macrocarpa**	46	0	2	0	0	0	0
Cheilanthes sieberi subsp. *Sieberi**	34	0	24	0	0	0	0
Hakea recurva subsp. *recurva**	28	12	5	0	7	0	1
*Mirbelia bursarioides***	10	50	1	3	2	0	0
*Philotheca sericea***	10	52	0	0	0	0	0
*Thryptomene decussata***	24	43	0	0	0	0	0
Aluta aspera subsp. *hesperia**	0	50	0	0	0	0	0
*Thryptomene costata**	7	37	0	0	3	0	4
Eremophila latrobei subsp. *latrobei**	23	38	2	2	6	0	0
*Prostanthera patens**	0	50	0	0	0	0	0
*Maireana convexa****	0	0	65	0	0	5	0
*Acacia grasbyi***	1	14	44	0	2	0	0
*Ptilotus obovatus***	13	1	17	17	17	10	17
*Spartothamnella teucriiflora***	2	0	46	0	0	0	0
*Sida ectogama**	22	0	32	0	0	0	2
Senna charlesiana*	2	0	29	12	0	12	0
*Acacia exocarpoides****	0	5	0	80	0	0	0
*Acacia burkittii**	4	0	2	33	33	2	2
Senna sp. Austin (A. Strid 20210)***	0	0	1	0	73	5	0
*Acacia andrewsii***	0	0	0	0	60	0	0
Eremophila oppositifolia subsp *angustifolia***	0	0	0	0	42	7	0
*Austrodanthonia caespitose***	0	0	0	16	42	0	3
*Dodonaea inaequifolia***	0	19	0	0	49	0	0
*Scaevola spinescens**	4	2	4	2	35	9	1
*Eremophila pantonii**	0	0	0	0	40	0	0
*Maireana triptera****	3	0	23	0	5	29	17
*Atriplex codonocarpa****	0	0	7	0	0	67	2
*Maireana pyramidata****	0	0	1	0	3	65	3
Maireana tomentosa subsp. *tomentosa****	2	0	2	3	0	45	13
*Sclerolaena eriacantha***	0	0	0	0	0	62	3
*Acacia eremaea***	0	0	1	0	0	65	0
*Hakea preissii***	0	0	0	0	4	59	0
Eremophila oldfieldii subsp. *oldfieldii***	0	0	1	0	31	48	1
*Sclerolaena densiflora***	7	0	18	6	8	22	19
*Maireana georgei***	1	0	2	3	7	44	4
*Ptilotus exaltatus***	0	0	1	0	4	49	1
*Atriplex bunburyana**	0	0	0	0	0	43	1
*Rhagodia drummondii**	1	0	1	4	3	38	0
Ptilotus divaricatus var. *divaricatus**	0	0	0	0	6	36	0
*Pimelea forrestiana****	0	0	0	0	0	0	62
*Abutilon oxycarpum****	2	0	4	2	1	20	36
*Enneapogon caerulescens****	10	0	6	2	1	18	31
*Sida calyxhymenia****	0	0	0	0	0	0	54
*Acacia subsessilis**	0	0	0	0	0	0	38
Dodonaea amplisemina *	0	0	0	0	0	0	38
Total number of quadrats	9	4	9	4	5	4	13

Table 3

Summary statistics (average ± s.e.) of environmental variables for Community types of the Gullewa survey area. Differences between Community types for parameter averages (in bold) were determined using Kruskal – Wallis nonparametric analysis of variance (^{NS} indicates not significant, * indicates $p < 0.05$, ** indicates $p < 0.01$, *** indicates $p < 0.001$), with Dunn's posthoc test results indicated by letters (LSD $p < 0.05$). Parameter codes are explained in Table 1. Units for parameters; eCEC = cmol(±)/kg, minerals = mg/kg. Abbreviations: Rock Frag = surface rock fragment cover, Rock Max Size = maximum surface rock size category. Aspect values (radians) have been transformed into sine (EW) and cosine (NS) functions. Soil pH values are direct measures from $CaCl_2$ solution.

	Community type						
	type 1	**type 2**	**type 3**	**type 4a**	**type 4b**	**type 5**	**type 6**
Soil parameters							
EC**	**14.0 ± 4.3**	8.8 ± 4.1	**20.6 ± 5.3**	10.0 ± 2.0	**113.2 ± 70.1**	46.8 ± 10.8	**6.2 ± 1.1**
pH***	**4.57 ± 0.1**^{a}	4.48 ± 0.09	**5.13 ± 0.13**^{ab}	5.5 ± 0.34	**5.78 ± 0.41**^{bc}	6.35 ± 0.32	**5.98 ± 0.13**^{c}
OrgC**	**1.71 ± 0.37**^{b}	0.87 ± 0.07	**0.62 ± 0.05**^{a}	1.04 ± 0.10	**1.19 ± 0.24**^{ab}	0.75± 0.12	**0.66 ± 0.07**^{a}
N*	**0.14 ± 0.03**^{b}	0.07 ± 0.00	**0.07± 0.00**^{a}	0.10 ± 0.01	**0.10 ± 0.02**^{ab}	0.06 ± 0.00	**0.08 ± 0.01**^{ab}
Al^{NS}	**447.8 ± 30**	380 ± 55.2	**403.3 ± 18.3**	485.0 ± 49.7	**346.0 ± 59.7**	362.5 ± 22.9	**402.3 ± 13.1**
Ca**	**361.1 ± 57.9**^{a}	150.5 ± 29.0	**305.6 ± 46**^{a}	607.5 ± 156.8	**700.0 ± 240.3**^{ab}	460.0 ± 21.6	**913.8 ± 190.3**^{b}
Cd**	**0.01± 0.00**^{a}	0.01 ± 0.00	**0.01 ± 0.00**^{ab}	0.01 ± 0.01	**0.01 ± 0.00**^{ab}	0.01 ± 0.00	**0.02 ± 0.00**^{b}
Co***	**0.22 ± 0.10**^{a}	0.04 ± 0.00	**1.38± 0.38**^{ab}	1.68± 0.73	**1.37 ± 0.51**^{ab}	0.90 ± 0.28	**3.10± 0.32**^{b}
Cu**	**3.09 ± 2.36**^{a}	0.63 ± 0.07	**1.48 ± 0.17**^{ab}	2.48 ± 0.39	**1.68 ± 0.43**^{ab}	0.83 ± 0.15	**2.63 ± 0.31**^{b}
Fe***	**139.6 ± 49.2**^{b}	42.8 ± 3.6	**27.0 ± 1.7**^{a}	41.5 ± 5.9	**40.4 ± 2.4**^{ab}	31.3 ± 4.3	**48.2 ± 2.6**^{b}
K^{NS}	**227.8 ± 46.8**	110.5 ± 8.8	**277.8 ± 27.8**	275.0 ± 41.3	**226.0 ± 15.4**	272.5 ± 41.5	**261.5 ± 22.3**
Mg***	**91.3 ± 11**^{a}	52.3 ± 14.5	**110.2 ± 22.2**^{a}	124.5 ± 40.1	**512.0 ± 170.8**^{b}	262.5 ± 46.1	**252.3 ± 37.9**^{b}
Mn***	**26.7 ± 9.2**^{a}	11.8 ± 0.9	**73.0 ± 16.4**^{ab}	95.5 ± 34.8	**42.2 ± 6.0**^{ab}	46.5 ± 12.6	**107.3 ± 9.2**^{b}
Na*	**32.8 ± 11.2**^{a}	28.6 ± 20.1	**68.7 ± 20.1**^{ab}	39.0 ± 11.7	**680.8 ± 492.0**^{b}	257.0 ± 80.1	**34.5 ± 4.5**^{ab}
Ni**	**0.17 ± 0.02**^{a}	0.13 ± 0.03	**0.26 ± 0.02**^{ab}	0.38 ± 0.1	**0.92 ± 0.29**^{b}	0.25 ± 0.09	**0.58 ± 0.12**^{b}
P*	**67.0 ± 35.5**	9.3 ± 1.8	**10.0 ± 1.1**	10.3 ± 1.1	**9.0 ± 2.1**	14.3 ± 1.8	**10.4 ± 1.9**
S***	**17.0 ± 2.1**^{b}	16.0 ± 3.1	**18.8 ± 5.9**^{b}	10.0 ± 0.7	**76.4 ± 47.8**^{ab}	25.0 ± 6.1	**6.0 ± 0.7**^{a}
Zn^{NS}	**2.96 ± 0.49**	1.58 ± 0.24	**2.9 ± 0.26**	2.83 ± 0.27	**3.44 ± 0.63**	3.30 ± 0.64	**2.88 ± 0.18**
eCEC**	**3.28 ± 0.48**	1.59± 0.36	**3.44 ± 0.52**	4.93 ± 1.19	**11.24 ± 3.69**	6.27 ± 0.77	**7.46± 1.10**
Ca:Mg	**4.0 ± 5.3**	3.1 ± 0.4	**3.0 ± 0.2**	5.1 ± 0.6	**1.8 ± 0.4**	2.0 ± 0.5	**4.0 ± 0.8**
Site Physical Parameters							
Aspect (NS)^{NS}	**-0.35 ± 0.20**	-0.09± 0.24	**0.43 ± 0.20**	-0.30 ± 0.64	**0.01± 0.34**	0.26 ± 0.39	**-0.02 ± 0.15**
Aspect (EW)^{NS}	**-0.03 ± 0.27**	0.48 ± 0.44	**0.10± 0.35**	0.30 ± 0.06	**-0.56± 0.23**	-0.33 ± 0.36	**0.03 ± 0.25**
Slope***	**7.8 ± 2.1**^{b}	4.0 ± 1.5	**1.3 ± 0.5**^{a}	2.8 ± 1.5	**3.4 ± 0.5**^{ab}	2.3 ± 0.5	**9.0 ± 1.4**^{b}
Topography**	**4.8 ± 0.1**^{b}	3.8 ± 0.9	**2.1 ± 0.5**^{a}	1.5 ± 0.3	**3.0 ± 0.6**^{ab}	1.6 ± 0.1	**3.3 ± 0.3**^{b}
Rock Frag^{NS}	**4.7 ± 0.3**	5.5 ± 0.3	**4.6 ± 0.3**	3.8 ± 0.6	**5.0 ± 0.0**	5.0 ± 0.0	**4.8 ± 0.2**
Rock Max Size**	**5.2 ± 0.3**^{b}	4.5 ± 0.3	**3.7 ± 0.3**^{a}	3.8 ± 0.6	**4.6 ± 0.2**^{ab}	4.3 ± 0.3	**4.9 ± 0.2**^{b}
outcrop cover***	**4.1 ± 0.3**^{b}	2.5 ± 0.5	**0.2 ± 0.1**^{a}	2.0 ± 1.2	**1.6 ± 0.8**^{ab}	0.5 ± 0.3	**2.1 ± 0.4**^{ab}
Runoff***	**2.9 ± 0.1**^{b}	2.8 ± 0.3	**1.6 ± 0.3**^{a}	2.0 ± 0.4	**3.0 ± 0.0**^{ab}	1.5 ± 0.3	**3.0 ± 0.1**^{b}
soil depth***	**1.3 ± 0.1**^{a}	2.0 ± 0	**2.8 ± 0.1**^{b}	2.5 ± 0.5	**2.5 ± 0.3**^{b}	2.1 ± 0.1	**2.1 ± 0.1**^{b}
% litter cover^{NS}	**12.8 ± 1.9**	13.8 ± 3.8	**20.0 ± 3.3**	27.5 ± 8.5	**11.0 ± 2.9**	23.8 ± 9.4	**11.2 ± 2**
%bare ground^{NS}	**87.2 ± 1.5**	87.5 ± 1.4	**84.4 ± 2.3**	90.8 ± 3.9	**88.6 ± 4.1**	81.3 ± 3.1	**84.2 ± 3.3**
Latitude*	**-28.681 ± 0.034**^{ab}	-28.782 ± 0.028	**-28.685 ± 0.034**^{ab}	-28.704 ± 0.004	**-28.773 ± 0.019**^{a}	-28.63 ± 0.053	**-28.653 ± 0.02**^{b}
Longitude*	**116.45 ± 0.01**^{ab}	116.382 ± 0.041	**116.441 ± 0.006**^{ab}	116.25 ± 0.005	**116.398 ± 0.035**^{a}	116.466 ± 0.012	**116.454 ± 0.018**^{b}
Altitude***	**326.6 ± 7.3**^{b}	313.8 ± 9.4	**294.9 ± 4.9**^{a}	343.2 ± 5.2	**315.0 ± 8.6**^{ab}	315.0 ± 6.9	**345.9 ± 8.8**^{b}
Number of species / quadrat							
Annuals only [1]	9.8 ± 1.1	8 ± 1.9	9.8 ± 1.3	13.3 ± 3.0	11 ± 1.9	5.3 ± 1.7	11.8 ± 1
Perennials only [1]	28.2 ± 1.7	19.0 ± 1.7	26.8 ± 1.6	21.8 ± 3.1	25.6 ± 1.6	27.8 ± 2.5	25.4 ± 1.4
All taxa [1]	38 ± 1.2	27 ± 3.2	36.6 ± 2.7	35 ± 4.7	36.6 ± 2.7	33 ± 4.1	37.2 ± 1.7
No. quadrats	9	4	9	4	5	4	13

[1] including singleton taxa

Table 4

Matrix of Spearman rank correlation coefficients for environmental variables collated from 48 quadrats established on the Gullewa survey area. Only correlations significant at $p < 0.01$ are shown. Full details of environmental parameter codes are given in the methods section and Table 1.

	EC	pH	OrgC	N	Al	Ca	Cd	Co	Cu	Fe	K	Mg	Mn	Na	Ni	P	S	Zn	eCEC	NS	EW	Slope	Tp	%RF	MxR	Outcrop	Runoff	Soil	%litter	%bare	Alt	Lat
Soil Chemical Parameters																																
EC																																
pH	.																															
OrgC	.	.																														
N	.	.	0.884																													
Al	.	.	.	.																												
Ca	.	0.702	.	.	.																											
Cd	.	0.507	.	.	.	0.543																										
Co	.	0.692	-0.420	.	.	0.667	0.530																									
Cu	.	0.488	.	.	.	0.609	0.481	0.759																								
Fe	.	.	0.507	0.539	.	.	.	.	.																							
K	0.430	0.492	.	.	.	0.459	.	0.516	0.460	.																						
Mg	.	0.825	.	.	.	0.775	0.401	0.587	0.425	.	0.393																					
Mn	.	0.641	-0.407	.	.	0.561	0.584	0.898	0.785	.	0.609	0.486																				
Na	0.744	0.607	.	.	-0.453	.	.	.	.	.	0.475	0.645	.																			
Ni	.	0.457	.	.	.	0.476	.	0.650	0.536	.	0.333	0.606	0.579	.																		
P	.	.	0.544	0.523	.	.	.	-0.394	.	.	.	.	.	.	.																	
S	0.698	.	0.430	.	.	.	.	-0.643	-0.506	.	.	.	-0.565	.	-0.353	0.431																
Zn	.	.	.	.	.	0.462	.	.	.	.	0.456	0.408	.	0.424	.	.	.															
eCEC	.	0.835	.	.	.	0.883	0.413	0.612	0.509	.	0.506	0.938	0.504	0.585	0.525	.	.	0.460														
Physical Parameters																																
Site																																
NS	.	.	-0.438	-0.466	.	.	.	.	.	-0.399	.	.	.	.	.	.	.	.	.													
EW	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.												
Slope	-0.371	.	.	.	.	.	.	.	.	0.626	.	.	.	.	.	.	.	.	.	.	.											
Tp	.	.	0.439	0.453	.	.	.	.	.	0.628	-0.367	.	.	.	.	.	.	.	.	.	.	0.458										
%RF	.	.	.	.	-0.630	.	.	.	.	.	-0.412	.	.	.	.	.	.	-0.412	.	.	.	.	.									
MxR	.	.	.	.	.	.	.	.	.	0.592	.	.	.	.	.	.	.	.	.	.	.	0.653	0.628	.								
Outcrop	.	.	0.539	0.534	.	.	.	-0.399	.	0.766	.	.	-0.387	.	.	.	.	.	.	.	.	0.516	0.697	.	0.692							
Runoff	-0.418	.	.	.	.	.	.	.	.	0.632	.	.	.	.	.	.	.	.	.	.	.	0.815	0.565	.	0.623	0.557						
Soil	.	.	.	.	.	.	.	0.424	0.376	-0.580	.	.	0.381	.	.	.	.	.	.	0.394	.	-0.440	-0.530	.	-0.414	-0.752	-0.452					
%litter	.	.	.	.	.	.	.	.	.	-0.378	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.				
%bare	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	-0.420	.	.	.	.	.	.	.	.	.	.	.	.	-0.449			
Alt	.	.	.	.	.	0.385	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0.461	.	.	.	.	0.457	.	.	.		
Lat	.	.	-0.379	.	.	.	.	.	.	.	.	.	0.410	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0.470	
Long	.	.	-0.400	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0.529