IN THIS ISSUE

FRONT COVER: DEC marine scientist records the cover of benthic reef communities at Ningaloo Marine Park using underwater video. (Photograph by Suzanne Long (DEC)).

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The spread of the cat, *Felis catus*, in Australia: re-examination of the current conceptual model with additional information

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ABSTRACT

This paper is an update of Abbott, I (2002) Origin and spread of the cat, *Felis catus*, on mainland Australia, with a discussion of the magnitude of its early impact on native fauna. *Wildlife Research* **29**, 51–74. An additional 33 journals of expeditions of exploration or excursions beyond settled areas before 1895 were located, and as expected from the current conceptual model, none of these recorded cats. These accounts of travel through country as yet unsettled or sparsely settled by Europeans necessitate only one small modification (relating to north-east Queensland) to the conceptual model presented previously. In addition, nearly 150 new records of cats were located in other parts of Australia, and all are consistent with the chronology of spread hypothesized in the previous paper. For Tasmania, following their introduction in 1804, cats were first recorded there as feral in the 1840s. Incidental records were found indicating that in parts of Australia the spread of the cat was assisted by their release in regions experiencing their first outbreaks of rabbits, by flood-linked irruptions of the long-haired rat (*Rattus villosissimus)*, and by their release to control rodents destroying sugar cane plantations in northern Queensland. Feral cats of large size were first detected in various regions of Australia some 10–30 years after local settlement.

Keywords: exotic, mammal, predator, releases, spread, chronology

INTRODUCTION

From several hundred sources Abbott (2002) compiled information about the presence of the cat on mainland Australia and its apparent absence from newly explored country in the period up to 1883. The main outcome of that study was a conceptual model of the colonization of mainland Australia, presented as a series of eight maps (Fig. 3 of Abbott 2002), showing that there had been multiple introductions by Europeans as they settled the various regions of Australia. It was posited that cats first became feral around Sydney by 1820, around Perth and in south-east Australia by 1840, in north-west Australia by 1870, and over 90% of the continent by 1890.

Further research on historical changes in distribution and abundance of conspicuous bird and mammal species in Australia (Abbott 2008) has uncovered many additional records of cats, both domestic and feral, in Australia (including Tasmania). This, together with access to previously overlooked journeys of exploration or visits to country as yet unsettled by Europeans, provides an opportunity to examine the validity and robustness of the provisional conclusions presented by Abbott (2002).

Given the great increase in the database assembled, this paper also takes the opportunity to investigate when 'large' feral cats were first reported. This topic is of interest as domestic cats in the process of becoming feral are expected to have gradually increased in body size each generation because of the operation of natural selection as feral cats encountered large populations of medium-sized marsupials around farms and villages.

Four key questions are investigated in this paper:

1. Is absence of records of feral cats from newly assessed accounts of unsettled or sparsely settled country inconsistent with the previously proposed model of spread?
2. Are any of the new records of feral cats inconsistent with the previously proposed conceptual model of spread?
3. How adequately does the spread of the cat in Tasmania align with the model previously proposed for mainland Australia?
4. When were feral cats of noticeably large size first encountered?

METHODS

A large number of primary and secondary documents, not previously accessed, were reviewed for information on the presence of cats, either in domestic situations, or feral. The context of documents that included no references to cats was carefully appraised. If the document included references to conspicuous native species such as dingoes, kangaroos, quolls, bustards and emu, then I presumed

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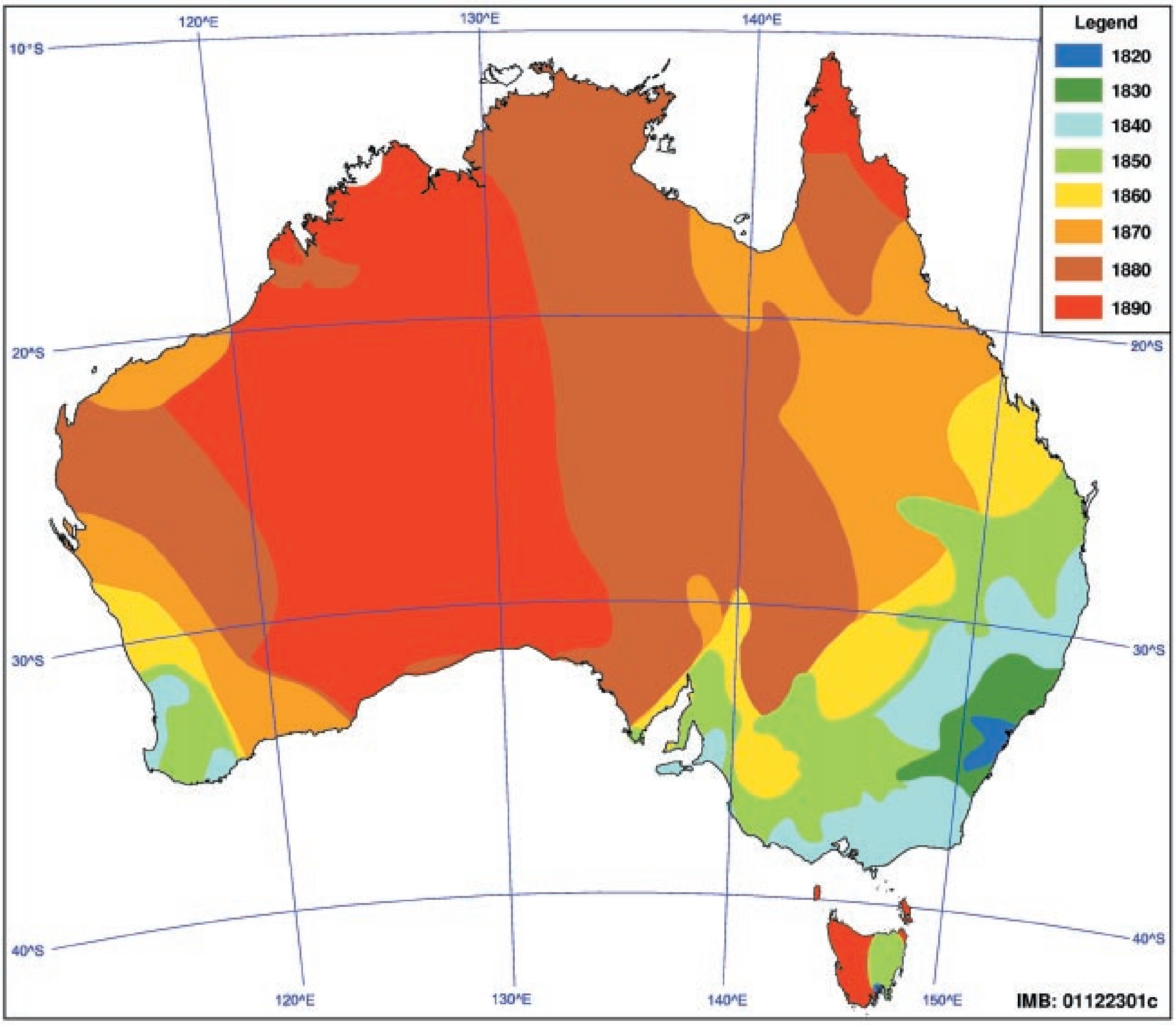

Figure 1. Conceptual model of the colonization of Australia by the cat, consolidated and updated from Abbott (2002: 63). Cats are present before, or by, the year shown.

that the observational ability and interest of the recorder was high. The absence of a record of a cat was therefore likely to be of significance. In contrast, the absence of records of cats by observers who failed to note much of the natural history of the district travelled through was regarded as equivocal. I took the view that absence of a record of a cat in such cases did not necessarily imply non-detection. Limited space precludes the listing of the many documents in this category.

RESULTS

Absence of records of feral cats

Several of the new accounts are by other members of expeditions of exploration led by Sturt, Leichhardt, and Burke and Wills (Table 1), none of whom recorded cats. These accounts provide a check on some of the accounts used by Abbott (2002). One of these accounts is particularly significant, being the diary of the astute naturalist and collector John Gilbert, who recorded no cats.

The accounts of travel through unsettled or sparsely settled country (Table 1) indicate the need for only one modification to the conceptual model presented in Fig. 3 of Abbott (2002). It appears that the dense rainforests of north-eastern Queensland had no feral cats present in the 1880s. This minor adjustment has been made to Fig. 1.

New records of feral cats

The c. 100 additional records of cats located (Table 2) allow many of the blank spaces depicted on Fig. 2 of Abbott (2002) to be detailed (Fig. 2). Records of cats in domestic situations (house, farm) have been distinguished from records of feral cats (remote from settled areas). The former are only suggestive of the possibility of cats becoming feral, whereas the latter actually demonstrate independence of cats from humans. None of the additional records are inconsistent with those previously discovered.

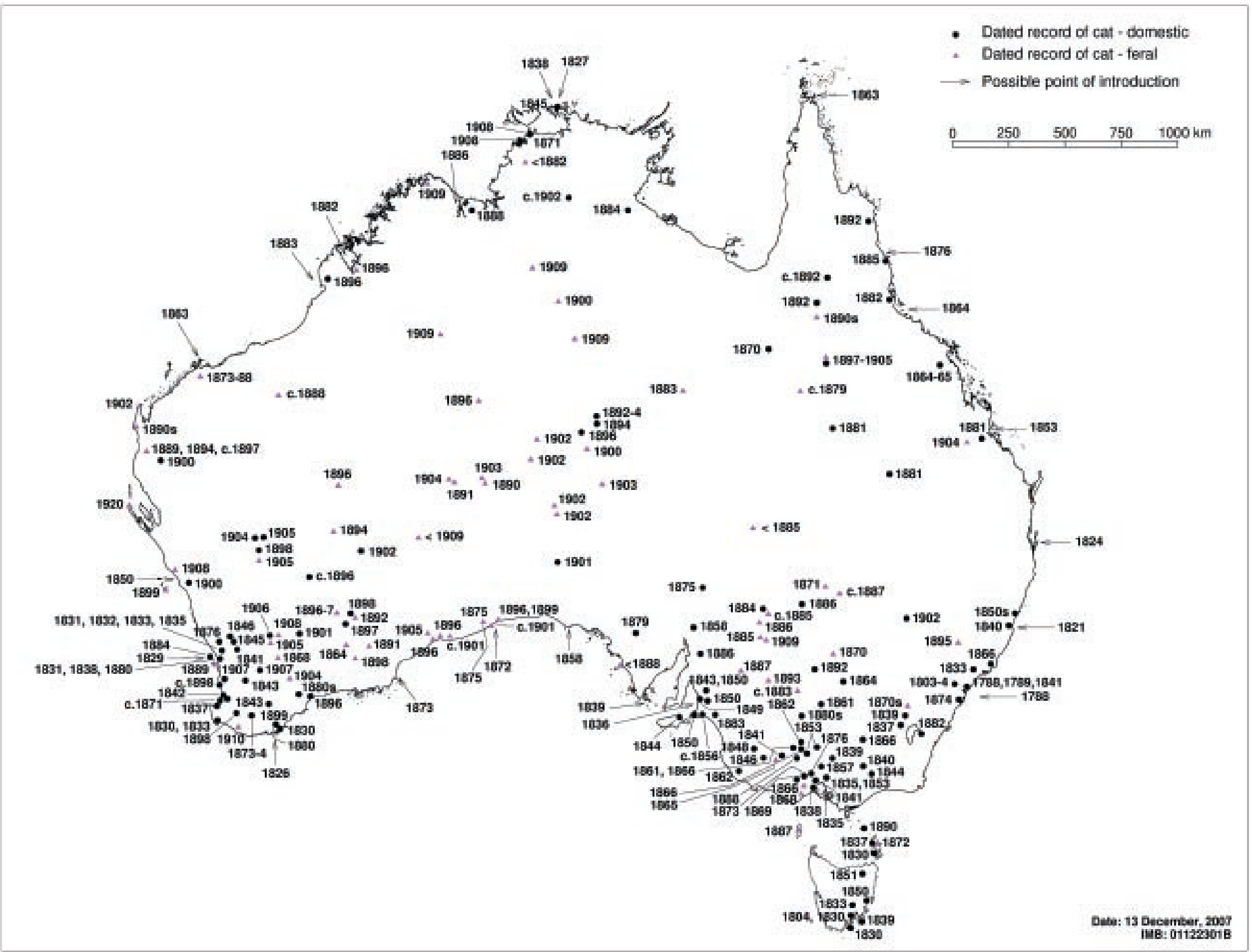

Figure 2. Records of domestic and feral cats in Australia during the period 1788–1910, consolidated and updated from Abbott (2002: 58). Note: A few late additions to Table 2 are not included on this map.

Spread in Tasmania

Domestic cats were introduced to Tasmania in 1804, the year after European settlement commenced at Hobart (Nicholls 1977, Hamilton-Arnold 1994). By the early 1820s, cats (along with other domestic and farm animals) were said to thrive abundantly (Evans 1822: 55). Early explorers in north-west Tasmania, such as C Hardwicke in 1823 and H Hellyer and J Fossey in 1827, and naturalists such as J Backhouse in 1832 and R Lawrence in 1833, did not record feral cats (Backhouse 1843; Bischoff 1832; Burns and Skemp 1961; Crawford *et al.* 1962; Ellis 1987; Meston 1958). GA Robinson, who traversed unexplored or little-explored parts of the island on six journeys during the period 1830–4, did not record feral cats. Because these journals (Plomley 1966) offer detail on many species of native animals, the absence of records of cats is suggestive of the absence in the early 1830s of feral populations remote from settled areas of Tasmania.

Rabbits were imported to Tasmania in the late 1820s and by 1831 were reported in the 'thousands' (Plomley 1987: 646), presumably in settled districts. By the 1840s, cats in Tasmania had become feral 'in some parts of the Colony' (Breton 1846: 132) and 'in many locations' (R Gunn in West 1852: 328). In the 1840s and 1850s, cats were first recorded depredating native animals such as snakes, birds and mammals (Gunn 1846, 1852; Cotton 1851; West 1852; Ellis 1979). Feral cats became well established in parts of Tasmania (*The Australasian* 14.6.1884: 780).

Earliest records of large feral cats

Most records simply state that a feral cat is large, without providing dimensions or weights. Early records of large feral cats were found in north-western New South Wales in 1870 (Randell 1978: 227), near Roebourne WA sometime between 1873 and 1888 (Anon. 1888), at Minilya River WA in 1889 (Brockman 1987: 142), at the eastern goldfields, WA in 1892 (Sligo 1995: 81), in south-west WA in 1904–7 (G. Shortridge in *The West Australian* 18.6.1907: 7), and near Broken Hill in 1909 (Macgillivray 1910: 89).

DISCUSSION

The model of spatial spread of the feral cat does not of course present any information on density. However, it appears from the numerous travels undertaken by GA Robinson in Victoria in the 1840s that feral cats were very uncommon, as he recorded none in contrast to his many records of other conspicuous fauna (Clark 2000a–e). In fact, the first documented record of a feral cat in Victoria is from the 1850s. This reinforces the concept proposed by Abbott (2002) that the process of domestic cats establishing feral populations was slow and patchy.

Similarly, the first records of feral cats in other regions of Australia are: 1860s (south-west WA), 1870s (New South Wales, Queensland), 1870s–80s (north-western WA), 1880s (South Australia, Northern Territory), and 1890s (south-eastern WA). These data are suggestive of a minimum of 10 to 20 years after domestic cats were introduced to a region as companion animals to settlers (as pets, ratters or mousers). It appears that feral cats established earlier in WA than in eastern Australia, other than Victoria and Tasmania, even though New South Wales was settled earlier than WA.

Other early observers noted many conspicuous species of birds and mammals, without recording encounters with feral cats. For example, James Backhouse in 1836 did not record cats in recently settled parts of New South Wales (Backhouse 1843). William Morton did not record cats in western and north-central Victoria during the period 1842–7, in southern NSW in 1848 and 1860, or in east-central Queensland in 1859 (Randell 1978). William Telfer Jr did not record cats in Tamworth NSW district in the 1850s, some 10 years after European settlement (Milliss 1980). The mounted policeman and officer in charge of native police, WH Willshire, wrote a short novel evidently based on his own experiences in the bush of southern Northern Territory during the period c. 1876–90 (Willshire 1895). Although alluding to numerous species of native fauna, Willshire did not refer to cats, either feral or domestic.

There are several instances where feral cats are known to be present, or can reasonably be presumed to be present, in a district (Abbott 2002), but no actual record was made by an observant traveller. Because such a traveller noted the occurrence of bird species and other mammal species, the absence of any record of feral cats probably indicates very low density of feral cats. Examples include: Normanton, Qld to Powell Creek Telegraph Station, NT, 1883 (Monteath 2004); Eucla WA, 1888 (Luck 1988); between Oodnadatta SA and Coolgardie WA, 1895 (Hübbe 1897); WA eastern goldfields, 1892-c. 1900 (Gaston 1984); WA eastern goldfields, 1895–6 (Thompson 1993); Kalgoorlie-Mt Magnet WA (Price 1896); northern Great Victoria Desert WA, 1897 (Russel 1899); between Kalgoorlie, Eucla and 50 miles north of Eucla, 1901 (Muir 1901); between Cardunia Rocks (east of Kalgoorlie, WA) and the South Australian border, 1908 (Anon. 1908); Coongan River, WA, 1908 (Whitlock 1909); northern Kimberley, WA, 1911 (Conigrave, CP 1938); and Kimberley, WA, 1916 (Basedow 1918).

Whether early settlers kept a domestic cat seems to have been a matter of personal circumstances, perhaps simply reflecting the degree of ailurophilia or antipathy towards cats. Some contemporary paintings are suggestive that some boundary riders did not keep a cat (JS Prout 1843 in Milliss 1980: 124), whereas others indicate that some squatters did (artist not identified but scene painted before 1846, Flower 1968: 46; E. Snell 1849 in Griffiths 1988: 77). One well-travelled visitor (Demarr 1893) spent five years living on the frontier in the early 1840s, including Queanbeyan NSW (9 months), droving to Port Phillip (5 months), living at Delatite Vic (12 months), and travelling in and shepherding at New England and Darling Downs districts (8 months) and Moreton Bay (12 months). In his book, Demarr records much interesting but trivial information, including the presence of pet dogs and cockatoos, and not once mentions pet cats kept at shepherds' huts.

The paucity of early records of cats in rural New South Wales may reflect the high proportion of single men employed by pastoralists (Blainey 1980: 121). It seems highly likely that as settlers married and had children at least one cat would have become part of the household. Photographs, usually undated, and reminiscences reinforce the link between the presence of women or girls and pet cats (Cerutty 1977: 88–89; Isaacs 1990: 65, 87, 103, 240; Muir 2006: 206, 244). In addition, two early records of cats preying on rodents in dwellings (1833, Waterhouse 1984a; 1840s, Henderson 1851) amplify records cited by Abbott (2002: 58), and confirm the value of domestic cats in controlling rats and mice. Cats were also valued for protecting fruit trees from frugivorous birds (The Western Australian Almanack 1842).

I also found an intriguing record, evidently from New South Wales, of female Aborigines 'with puppy dogs, occasionally cats and kittens' being carried in bags (Mann 1885: 58). The context makes it clear that this is referring to Aborigines in contact with settlers and may date from the early 1840s.

One or more cats were kept on ships, probably as pets and to repress populations of rats. Several records of cats on ships (including shipwrecks), additional to those cited by Abbott (2002: 58), were discovered: 1802 (one, Campbell 1896: 780); 1803 (more than one, Flinders 1814 vol. 2: 208); 1831 (four, Plomley 1966: 341); 1832 (one, Chapman 1985: 565); 1836 ('very numerous', Stevenson 1930: 26–27); 1849 (one, Griffiths 1988: 33–34); 1861 (one, Henderson and Henderson 1988: 46); 1870 (one, Cambridge 1903: 42); 1879 (2 cats on board a ship about to depart from Port Walcott WA, Bush 1879); 1896 (several, Twain 1897: 4), and c. 1910 (more than one present, Skinner 1972: 81). The most significant is that of a pet on a pearling lugger off the Kimberley coast of north-western Australia in c. 1900 (Bligh 1938: 223). Although a later record, a cat was kept on a lugger at Dirk Hartog Island in 1920 to prevent seabirds roosting (Whitlock 1921a: 175). Luggers anchored in sheltered coves and inlets of offshore islands and sometimes were wrecked during cyclones, and one or both of these mechanisms may have been responsible for a population of feral cats present in 1912 on Hermite Island in the Montebello Group (Montague 1914: 630–1). (It is also possible that cats may have been introduced to control rats present on islands). Although disbelieved by White (1788, letter dated May 1770), there are a number of instances where domestic and feral cats have been observed swimming (Flinders 1985: 12; Dutton 1994: 32–33; Read 2003: 93). Thus it is possible for cats to establish from shipwrecks.

In June 1885, the Victorian Government proclaimed feral cats, as well as quolls and goannas, as natural enemies of the rabbit under the Rabbit Suppression Act of 1884. Their destruction in districts experiencing rabbit outbreaks was prohibited (*The Australasian* 13.6.1885: 1113). It was noted that rabbit trappers were in the habit of killing any feral cats that were captured in rabbit traps. Feral cats, along with quolls and goannas, were thought to merit protection in Victoria given their value in depredating rabbits (*The Australasian* 10.1.1885: 60, 7.2.1885: 251, 18.7.1885: 106, 15.8.1885: 298).

In parts of Western Australia, Victoria, South Australia, Queensland and New South Wales the spread of the cat was augmented by human intervention to control outbreaks of rabbits. The rationale seems to have been that domestic cats could be increased in numbers 'more readily and more rapidly than any other suitable animal at the disposal of man' (*The Australasian* 17.10.1885: 730). In Queensland '[p]eople turned domestic cats loose in the bush' (Cameron 1956: 1212). In 1886 the NSW Government sent 400 cats to Tongo station, on the Paroo River NSW, to help control rabbits (*The Australasian* 3.4.1886: 633; Rolls 1969: 117). Large numbers of domestic cats were transported and released elsewhere, with the hope that some measure of control of rabbits would be achieved (*Adelaide Observer* 6.10.1888: 32; Keith 1892: 18; Fry 1900: 258; *The Kalgoorlie Miner* 12.4.1897 [unpaginated]; CD McLauchlan in *The Kalgoorlie Miner* 28.9.1904: 2; Anon. 1907: 309; *The West Australian* 7.2.1925: 11, 21.2.1925: 11; *The Western Mail* 18.6.1936: 5; Rolls 1969: 117–8). Such activities probably commenced in the early 1870s in Tasmania, late 1870s in Victoria and South Australia, early 1880s in New South Wales, late 1880s in Queensland, and late 1890s in Western Australia, following the arrival of, and increase in, rabbits (Stodart and Parer 1988).

Sometimes repression of rabbit outbreaks with tame cats took place locally (Rolls 1969: 116–117). In about 1869 a settler near Cape Schanck, Victoria, released 'scores' of domestic cats into paddocks when rabbits first appeared (*The Australasian* 4.10.1884: 635). One farmer near Bacchus Marsh, Victoria had erected two houses for cats, which initially were confined and fed daily, and were later allowed to come and go as they pleased (*The Australasian* 13.6.1885: 1113). Crommelin (1886: 32) recommended that domestic cats should be released in threes and fours (one being a tomcat), and 'a small house should be built for them, not far from water, where they should be partially fed for three or four weeks'. One grazier at Burrungul, near Mount Gambier, SA 'turned out some cats and built a shed for them. They started to breed, and in nine months cleared the rabbits off a thousand acres' (J Livingstone in Anon. 1893: 40). In Queensland, however, it was stated that ingestion of rabbits filled the stomach of cats with balls of rabbit fur, which killed the cats (Cameron 1956: 1212).

It is also likely that occasional plagues of the long-haired rat *Rattus villosissimus* in western Queensland facilitated an increase in feral populations of cats (Corfield 1921: 81; *The West Australian* 26.12.1925: 5; Crombie 1944). Domestic cats surfeited on these rats near Cloncurry/Julia Creek Queensland in 1869–70, and although dingoes, snakes, hawks and owls increased, Palmer (1886) did not mention the presence of feral cats. This locality had been settled in 1864. The earliest documented plagues of long-haired rats were in 1861 (Bonyhady 1991; Jeffries and Kertesz 1993) and in 1864 (the latter during flooding of the Darling River, NSW, Bennett 1887). It is likely that rat plagues in the 1860s in western New South Wales and south-western Queensland and in the late 1880s in north-eastern South Australia (Plomley 1972) increased the density of feral cats. The spread and increase of rabbits in South Australia, Victoria, and New South Wales during the 1870s and 1880s (Royal Commission 1890; Rolls 1969) should also have increased the spread and density of feral cats.

Cats were also introduced into the canefields of northern Queensland in order to combat the destructive activities of rats, presumably *Rattus sordidus* (AJ Campbell in *The Australasian* 27.11.1886: 571).

In the Wimmera district of Victoria in 1884 there was a plague of the house mouse *Mus domesticus* in houses and over the land (*The Australasian* 26.7.1884: 153). Although domestic cats soon ceased to kill mice, the great density of mice in the bush may have aided the spread of feral cats.

As noted *inter alia* by Abbott (2002: 59–60), the earliest records of large feral cats are from the 1850s (Victoria) and 1883 (eastern part of the Northern Territory). The additional information found confirms the presence of large feral cats some 10–30 years after settlement. It is understandable that measurements of body size are lacking in the historical record. Nonetheless, the observers who noted 'large' cats presumably were familiar with the range of body sizes exhibited by domestic cats. Consequently, there is no reason to doubt that 'large' cats were indeed recognizably large relative to domestic cats. Larger size would confer an advantage in subduing medium-sized marsupials. Furthermore it is difficult to understand why feral cats should confine their prey items to small rodents.

Despite the discovery of additional records of feral cats, many gaps remain in Fig. 2. Ideally, it should be possible to replace the map of inferred spread (Fig. 1) with a map of isolines (at decadal intervals), showing the actual spread.

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Table 1

Exploration of, or travel in, mainland Australia without any record of feral cats, 1788–1910.

Year(s)	**Explorer/traveller**	**Region traversed**	**Reference**
Jul 1801	J Grant	Hunter River, NSW	Grant 1803
Oct–Dec 1802	J Tuckey	Port Phillip, Vic	Tuckey 1805
Oct 1803–Jan 1804	G Harris	Sullivan Bay, Port Phillip, Vic	Hamilton-Arnold 1984
May–Jun 1839	E Eyre	Broughton River to Mt Eyre and Baxter Range, SA	Waterhouse 1984a
May 1839	P Stewart	Cobourg Peninsula, NT	Cameron 1999
Jul–Dec 1839	A Buchanan	Sydney to Adelaide	Buchanan 1924
May–Jun 1841	T O'Halloran	Adelaide to Rufus River and Lake Victoria	O'Halloran 1904
Jul–Aug 1843	C Frome, J Henderson	Gawler to Lake Frome, SA	Auhl and Marfleet 1977
Aug 1844–Dec 1845	D Brock (member of expedition led by C Sturt)	Darling River, NSW to Grey Range, Qld	Brock 1975
Aug 1844–Dec 1845	C Sturt	Darling River, NSW to Grey Range, Qld	Waterhouse 1984b
Oct 1844–Apr 1845	J Murphy (member of expedition led by L Leichhardt)	Jimbour to Burdekin R, Qld	Sprod 2006
Oct 1844–Dec 1845	W Phillips (member of expedition led by L Leichhardt)	Jimbour, Qld to Port Essington, NT	Sprod 2006
Oct 1844–Jun 1845	J Gilbert (member of expedition led by L Leichhardt)	Jimbour to Nassau River, Qld	Gilbert 1845
Jul–Aug 1846	J Horrocks	Depot Creek to Pernatty Lagoon, SA	Anon. 1906
Dec 1846–Jul 1847	H Turnbull (member of expedition led by L Leichhardt)	Jimbour to Peak Range, Qld and return	Turnbull 1983
Oct 1860–June 1861	H Beckler and W Wright (members of Burke and Wills expedition)	Darling River to Torowoto Spring NSW, and Bulbo River Qld, and return	Jeffries and Kertesz 1993
Sep–Oct 1862	J Bonnin	Gawler Ranges, SA	Bonnin 1909
May–Aug 1866	E Hooley	Geraldton to Port Walcott, WA	Sharp 1985
Jan–Mar 1867	F Barnett	Julia Creek, Williams River, Cloncurry River, Dugald River, Qld	Gill 1987
1874–1875 (months unknown)	J Brockman	Murchison River to Fortescue River, WA	Broad and Bridge 2006
Apr–Sep 1876	W Hodgkinson	Cloncurry, Diamantina, Mulligan and Georgina Rivers, Qld; Coongie Lake, SA; Cairns Range, NT	Hodgkinson 1877
Feb–Apr 1841	W Brodribb	Port Albert and Lake Wellington districts, Vic	Brodribb 1885
Sep–Dec 1880	C Palmerston	Upper Daintree, McLeod and Mitchell Rivers, Qld	Savage 1989
1881, Mar–Oct 1886	W Froggatt	Herberton, Cairns, Kuranda, Mt Bellenden Ker, Port Douglas, Qld	Froggatt 1935
Apr–Aug 1882	C Palmerston	Between Mowbray Creek and Mulgrave River, Qld	Savage 1989
Nov–Dec 1882	C Palmerston	Between Innisfail and Herberton, Qld	Savage 1989
Dec 1844–Jan 1885	C Palmerston	Between Herberton and Barron Falls, Qld	Savage 1989
Apr–Sep 1885	H Johnston	Ord River, WA	Johnston 1885
Jul–Nov 1886	C Palmerston	Russell River, Qld	Savage 1989
Jan 1889	B Spencer, C French	Croajingolong, Vic	Spencer and French 1889
1891–1892 (months unknown)	A Gunn	Prince Regent River, WA	Willing and Kenneally 2002
May–Oct 1897	H Russel	Barrow, Cavenagh and Warburton Ranges, WA	Russel 1899
Jul 1899–Mar 1900	H Hill	Lake Wells, Warburton Range, Rawlinson Range, WA, Petermann Range, Musgrave Range, SA	Chambers and Bridge 2007

Table 2

Additional records of cats on mainland Australia and islands, 1788–1910.

Year	Locality	Notes	Reference
c. 1803–4	?Parramatta, NSW	A nightjar was 'supposed to have been killed by a cat'	Vigors and Horsfield 1827: 194
1830	Anderson Island, Bass Strait	Resident 'keeps...cats'	Plomley 1966: 270
1830	?Bruny Island, Tas	'The natives train up the English cat to catch opossums'	Plomley 1966: 170, 231
1830	Hobart, Tas	Domestic cat on verandah	Fenton 1901: 394
1833	Near Singleton, NSW	At Mr Bell's house 'rats and mice...chased by a huge tom cat, who was generally stationed in the loft and not infrequently notified his presence in a most indelicate and disagreeable manner'	Waterhouse 1984a: 42
1833	Near Hobart, Tas	'[?domestic] Cats are very fond of this plant, *Drosera peltata*...'	Anon. 1859: 30
1837–8	Flinders Island, Bass Strait	A pet monkey took two kittens from the Aboriginal settlement; 'a domesticated cat of my own' [clearly distinguished from a quoll]; quarrel over the death of a cat	Plomley 1987: 425, 501, 534
1837	Near Urialla, NSW	Two cats noted at the beginning of an overlanding journey, but they soon ran away	Kiddle 1961: 42
1838	Point Henry, Vic	Three cats landed	Kirkland 1845: 176
1839	Pt Puer, Port Arthur, Tas	An overseer's cat killed by a youngster	Rosenman 1987: 519
1839	Yass, NSW	Four cats or kittens, domestic situation	Russell 2002: 88
1840	Yesabba, NSW	Cats mentioned, domestic situation	Frost 1984: 90
1840	Melbourne, Vic	Cats taken there by ship from Sydney	Boldrewood 1884 (Sayers 1969: 2)
1841	Sydney, NSW	One cat lost, Elizabeth Street; £5 reward offered for its return	*The Sydney Herald* 21.8.1841: 3
1841	Trawalla, Vic	One kitten in cart, travelling to Melbourne	Kirkland 1845: 206
1842	Australind, WA	'Cats we hear are scarce at Australind; this reminds us of old times, when a kitten was worth 20s in this colony [in Perth]. The inhabitants of Australind may easily obtain a reasonable supply from this neighbourhood [Perth]. In the early days of the colony, we had an importation of cats from Van Diemen's Land [Tasmania], and the advantage turned out very profitable'	*The Perth Gazette* 4.6.1842
1842	?Perth district, WA	'a number of cats and kittens have...been found serviceable in orchards and vineyards', to control birds destructive to fruit	The Western Australian Almanack 1842: 30
1843	Adelaide, SA	A cat ate the heads of 2 bird specimens	Chisholm 1938: 226
1844	Adelaide region, SA	Since European settlement, Aborigines eat dead cats, which are baked in the ground	Cawthorne 1927: 64
1844	Kangaroo Island, SA	Cat ran out of a hut set on fire	Tolmer 1882 vol. 1: 319
1844	Tambo River, Vic	'Saw the largest cat Tongiomunja hut'	Clark 2000d: 89
1845	Portland, Vic and Mt Gambier, SA	A domestic cat transported in a bag from Portland to Mt Gambier because stores were being ravaged by native rats	*Border Watch* 8.8.1957
1848	Newlands station, Victoria	Domestic situation	Hamilton 1914: 40
< 1849	?travelling to Murrumbidgee River from Sydney, NSW	'a favourite emigrant cat was teaching her kittens to lap milk out of the best tin meat-dish'	Harris 1849 (1867: 44) [a novel based on colonial residence]
1849	Between Noarlunga and Willunga, SA	Sketch of inside of a farm house, with 2 cats depicted	Griffiths 1988: 77
Late 1840s	Macleay River, NSW	'Cats are plentiful, and a good mouser is invaluable. Indeed, when an establishment is left for any length of time without this useful animal, it becomes overrun with rats, who devour or destroy everything'	Henderson 1851 vol. 2: 45
1850	Kensington, SA	Cat on house roof	Griffiths 1988: 90
1850	Near Cape Jervis, SA	Pet cat	Yelland 1970: 59
?1851	Kangaroo Island, SA	Island overrun with animals, including the wild cat [on p. 36 of vol. 1 the native cat is described, so presumably wild cat refers to the feral cat]	Lancelott 1852 vol. 2: 252
1853	Melbourne, Vic	Dead cat floating in Yarra River	Daniel and Potts 1970: 17
1853	Bendigo, Vic	Domestic situation	Kelly 1859 vol. 1: 247
c. 1856	Hindmarsh Island, SA	Domestic situation	Conigrave, JF 1938: 68
?1857	McIvor [=Heathcote], Vic	'cats being positive curiosities' in Victoria	Kelly 1859 vol. 2: 15

Year	Locality	Notes	Reference
1860s	Perth, WA	Cats numerous in Perth. Boys caught them for a German, who paid 1 shilling per head	*The Western Mail* 25.11.1920: 42
1861	Zara station [near Wanganella, NSW]	Goanna entered a shepherd's hut and seized a domestic cat	*The Argus* 11.2.1861: 5
1861	Peg Leg, Tarrengower, Vic	Domestic cat and snake killed each other	*The Argus* 18.3.1861: 5
1862	Mt Gambier, SA	'Notice. All Dogs and Cats trespassing on the premises of the Telegraph in this township after this date will be destroyed'	*Border Watch* 13.6.1862
1862	Bendigo, Vic	Domestic cat poisoned by arsenic	*The Argus* 7.3.1862: 5
1864	Lachlan River and back-country, NSW [Mossgiel]	Cats introduced to control a plague of rats	Bennett 1886: 164; KHB in *The Queenslander* 26.7.1879: 107
1864	York to Depot Hills, Lake Cowan, Lake Lefroy, WA	'Even when we were out with Hunt we often came across their tracks [cats gone wild], and now [1902] they are to be found in scores all over the country'	Anon. [JW Cowan] in *The Kalgoorlie Miner* 30.12.1902: 6
1865	Langi Ghiran ranges near Ararat, Vic	Skye terrier and wild [feral] cat in a fight	*The Argus* 19.4.1865: 4
1866	Near Beechworth, Vic	Blind domestic cat	*The Argus* 8.6.1866: 5
1866	Castlemaine, Vic	Small kitten [domestic] caring for ducklings	*The Argus* 19.9.1866: 5
1866	Porcupine Flat, Tarrengower, Vic	Cat [domestic] shot raiding a pigeon roost	*The Argus* 19.9.1866: 5
1866	Near Avoca, Vic	Large domestic cat seized a child by the neck and thighs at some little distance from a dwelling	*The Argus* 9.10.1866: 5
1868	Barwon Park (near Winchelsea), Vic	Becoming a nuisance; > 100 lately destroyed because eating Ceylon partridges; breeding in rabbit burrows	*The Argus* 5.6.1868: 5
1868	Cuminin station, WA	'wild domestic cats were distributed all about'	BW Leake in *The Western Mail* 5.7.1951: 58
1869	Near Teesdale, Vic	A great number railed in packing cases from Ballarat	*The Argus* 3.4.1869: 5
1870s	Boro, NSW	Pure white domestic cat at inn	Atkinson 1980: 25
1870	North-west of Lake Cargelligo, NSW	'It is a very remarkable fact that the domestic cat is to be found everywhere throughout the dry back country. I have met with cat, some of enormous size, at least fifty miles from water'	Randell 1978: 227
1870s	Murrumbidgee River near Yass, NSW	'The domestic cat has become wild, and breeds in these fastnesses, a dangerous adjunct to our carnivora, which should be determinately destroyed'	Atkinson 1980: 32
Early 1870s	Cressbrook, Qld	Domestic situation	Banks 1931: 48, 74
1871	Between Warrego and Paroo Rivers, NSW	'We were further disturbed by wild cats (domestic cats gone wild) fighting with each other, or killing birds, near our camp'	Randell 1978: 242
c. 1871	Australind, WA	Grandmother always had a box of kittens in house	Jephson 1933: 60
< 1872	Victoria (no locality provided)	Kitten kept in bedroom 'with a view to keeping the mice at a distance'; also describes interaction with a pet sugar glider	'A Resident' 1872: 177
1872	Flinders Island, Bass Strait	Many 'domestic cat gone wild have been destroyed by dogs'	Murray-Smith 1987: 23
1872	Drayton, Qld	Cat taken on dray with family moving to Stanthorpe	Davis 1976: 19
1873	Mt Bolton district, Vic	Cat in hut	Evans 1975: 37
1873–4	Deeside, WA	Numerous references to domestic cats: 'Got plenty of cats don't know what to do with them, confound them'	Muir Diaries 28.10.1873, 20.1.1874, 30.1.1874, 2.2.1874
1873–88	North-west Australia [?Roebourne, WA]	'It is an impossibility to keep [domestic cats] long about a place, as they instinctively take to the bush, and become not only very wild, but with each succeding [sic] generation increase greatly in size, and I can assure you they are animals you have to be very careful in tackling. Once when I was out riding after kangaroo one of these monster cats suddenly jumped out of a tree right in front of my horse, and so fierce did he look that, I got out of his road as quickly as possible'	Anon. 1888: 118
1875	Wingana, near Mundrabilla, WA	Domestic cat with 5 black kittens. 'The cats are all black here. The natives brought in a wild kitten and it was black with a small white bit on its breast'	Muir 2005: 173
1875	Sliding Rock, east of Beltana, SA	Cat recorded as present in findings of an inquest relating to a fire in a store	State Records SA GRG1/27 #31 (F. Williams, pers. comm.)

Year	Locality	Notes	Reference
1876	?Upper Swan, WA	A large black cat, in an inn	Broad and Broad 1992: 188
1876	South Australia	'All the domestic animals, and most of the birds known in Europe, have been acclimatized here, and without a single exception they seem to do well'	FG Waterhouse in Harcus 1876: 281
c. 1876	?Ballan, Vic	Domestic cat catching mice	Cambridge 1903: 168
c. 1879	Winton, Qld	Cats surfeited from eating rats with bushy tails in plague. Rats followed by a plague of dead cats in the waterholes	Corfield 1921: 81
1879	Kyneton, Vic	Pet cat of a lady visited by a local physician	Anon. 1935
1879	Thurulgoona, Warrego River, Qld	Cats were introduced in about April 1879 to assist in the destruction of a plague of rats	Armstrong 1879–80: lxii
1879	Yartoo station, SA	A newly formed station with 'tame cats & kittens of the household rubbing, jumping & purring over and about us all night' [sleeping in a waggon]	Anon. 1998: 7
c. 1880s	Victoria	Government secured all domestic cats they could obtain and let them run in the bush, as rabbits began to assume serious proportions	*The West Australian* 7.2.1925: 11
?1880s	Dirk Hartog Island, WA	'No doubt cats were introduced with the sheep'; 'approaching the size of leopards'	Whitlock 1921b: 129; *The Sunday Times* 24.10.1920: 4
?1880s	Tyntyndyer station, near Swan Hill, Vic	References to pet cats	Cerutty 1977: 88–89
1880s	Moyarra, Vic	Cat brought by coach from Buninyong to control rats; one night it killed 30 rats	J. Rainbow in South Gippsland Development League 1920: 321–322
1880	Perth, WA	'Had great cat shooting match today after dinner, being overrun with the beasts, we had two cats and they appear to increase the population every month and were a nuisance so I murdered the whole lot, two cats and four kittens'	Hillman 1990: 439
1880	Kendenup, WA	'wild cats' tails' hung on sticks on an Aboriginal grave	North 1892: 151
1880–85	Queensland	Cats killed bush rats in western Queensland in 1880 and 1885 as they moved south. Cats wearied of killing kangaroo mice in plague in Queensland in 1884	*The West Australian* 26.12.1925: 5
1882	Wangamana, between Wanaaring and Bourke, NSW	A pet black tomcat, shepherds' camp	Burdett 1936: 26
1882	Near Queanbeyan, NSW	Two records of a cat being let out of her box at night and finally escaping into the scrub	Frost 1984: 215, 218
c. 1882	Mallee Cliffs, NSW	A domestic cat reported to bring in a rabbit every morning to a hotel	Crommelin 1886: 32
c. 1883	Balranald-Wentworth district, NSW	Five cats killed by poisoning a warren under an old house and 'a large red Cat came out of the Bilbee hole and dragged the dead Rabbit under, and the [rabbit] inspectors lost their supper'	Crommelin 1886: 30, 32
1883	southern NSW	'The [feral] domesticated cat is protected from destruction in the districts of Albury, the Hume, the Murrumbidgee, the Murray, Balranald, Bourke and Wentworth'	Noble 1997: 118
1883	Near Goolwa, SA	Cat got out of box, on journey to Meningie	Frost 1984: 227
1884	On the Lower Broughton [River], apparently SA	Cats used successfully to extirpate rabbits	Royal Commission 1890: 103
1884	Lower Broughton [River], apparently SA	'the cats were successful'	Keith 1892: 18
1884	Rottnest Island, WA	Wild cats numerous	Barker 1885: 159
1885–95	Wimmera district, Vic	Government policy to exterminate rabbits through the agency of cats	*The West Australian* 21.2.1925: 11
1885	Johnstone River district, Qld	Following a plague of 'bush rats' *[?Rattus sordidus]* in sugar cane plantations, planters were importing cats with a view to exterminating the rats. Some 25 cats had arrived from Townsville, followed by a consignment from New South Wales, 'for a plantation north'	AJ Campbell in *The Australasian* 27.11.1886: 571
1885	Netley, NSW	Rabbiters killed [feral] cats and other natural enemies of the rabbit	Royal Commission 1890: 61

Year	Locality	Notes	Reference
c. 1885	Tintinallogy, NSW	'Before [rabbit] trapping began we had large numbers of [feral] cats, but there were very few cats left when the trappers knocked off'; 'The natural enemies here are...tame cats, many of which have gone wild here; we turn out as many as possible; some come back, but not many; they do not come back if half grown when turned out'	Royal Commission 1890: 89, 108
1886	Menindie, NSW	Rabbiters: 'if they could get hold of a good sized [feral] tom-cat and kill it, it was a great feature to them'	Royal Commission 1890: 63
1886	Tarcowie, SA	Boiled a lark egg for sister's cat	Robinson 1977: 90
1887	King Island, Bass Strait	'Wild domestic cats...were very numerous'; 'we killed some perfect monsters'	Campbell 1888: 136; *The Australasian* 9.3.1889: 534
1887	Paringa, SA	Rabbit trappers killing the natural enemies of the rabbit, including 'wild cats'	Royal Commission 1890: 60
c. 1887	Kallara (between Wilcannia and Bourke), NSW	[Feral] cats noted as one of the natural enemies of rabbits	Royal Commission 1890: 94
< 1888	Flinders Island, SA	Cats extirpated rabbits	Royal Commission 1890: 103
1888	Maldon, Vic	A dead cat (domestic)	Evans 1975: 164
1888	Thargomindah, Qld	'Plague of [?feral] cats', 9 July; 'The proprietors of Thargomindah Station are paying half-a-crown a head for all domestic cats delivered there'	Knight 1895: 382; Noble 1997: 118
1888	Tintinallogy, NSW	'a disease had destroyed a great number of cats, and the bodies of eighteen were seen on the bank of the river...the cats, in a great measure, live on rabbits'	Royal Commission 1890: 200
c. 1888	?Nullagine district, WA	'Years ago, I was out prospecting in the North-West, where white people had never been before, and I saw cats and the tracks of cats many times. That is over twenty years ago'	W. Kingsmill in Western Australian Parliamentary Debates **43**: 1341, 28.8.1912
1889	Minilya station, WA	A 'large wild cat' killed	Brockman 1987: 142
1889	Rottnest Island, WA	'the large number of wild domestic cats roaming over the island at will'	AJ Campbell in *The Australasian* 3.5.1890: 888
Late 1880s	Kimberley region, WA (Fitzroy River, ?Myoorda station)	Domestic cat introduced soon after 1886	*The West Australian* 7.8.1926: 9
1890s	Bangate station via Angledool, NSW	Cats, farmhouse	Parker 1902: 113–114; Muir 1982: 74, 90, 124
1890	Pelsaert Island, Houtman Abrolhos, WA	'the domestic cats run wild accounted for many [rabbits] also, so much so, that since about 1897 I have neither seen nor heard of a rabbit present there – the cats literally wiped them out, as they could not escape'	FC Broadhurst in *The Western Mail* 24.10.1908: 10
1890	Deal Island, Bass Strait	'half wild domestic cats'	Le Soeuf 1891: 124
c. 1892	Curham (near Georgetown, Qld	'There were no fewer than six cats in the house'; three of these were shot by a drunken tenant	Bicknell 1895: 127–8
c. 1892	?Lake Alexandrina, SA	Tame cats left unmolested on a small island in order to control rabbits	*The Australasian* 27.2.1892: 391
1892	Georgetown, Qld	Cats on roof interfering with sleep	Ellis 1991: 69
1892	Wyalla, Qld	A cat brought in a small snake	Ellis 1991: 96
1892	c. 30 km east of Kalgoorlie, WA	'a large lean famished black cat' shot, at night	Sligo 1995: 81
1892	Mossgiel, NSW	'Some time ago Mr. Parsons tried the experiment of raising wild cats, and actually built a cat house on one part of the run, placed a man in charge, and purchased every domestic cat which was in the district, besides importing others. The experiment, however, did not succeed, a disease of some kind sweeping the cats away to another kingdom. Indeed cats have never proved an unqualified success, although they have been tried on most of the stations in the west. They do not thrive on rabbit, become exceedingly emaciated, and die in a short time. In the old days [?1880s] the rabbiters killed the cats'	Keith 1892: 18
1892	Upper Burnett River, Qld	'The best checks to the entry of serpents within the precincts of human habitations are cats'	Semon 1899: 181
1892	Broken Hill, NSW	[Domestic] cats satiated with rabbits	*The Australasian* 6.2.1892: 264

Year	Locality	Notes	Reference
1892	Balmoral, Vic	'a large number of domestic cats gone wild...caught in these abominable traps'	*The Australasian* 16.7.1892: 104
1892	Rendelsham, SA	'dogs killed a wild (tame) cat'	D. Stewart (b. 1834) (D. Peacock, pers. comm.)
1893	Sorell, Tas	Domestic cats introduced to destroy rabbits, but they rapidly disappeared once rabbit trappers were employed	*The Australasian* 25.2.1893: 342
1893	West of Polpitch Lake, NSW	Aborigines 'very fond of cats'	Cudmore 1894: 525
1894	Minilya station, WA	Wild cats killed pet magpie	Brockman 1987: 156
1894	Alice Springs, NT	The mounted trooper's cat brought a specimen of *Dasycercus cristicauda* into the house	Spencer 1895: 222
1895	Wingen, NSW	'domestic cats gone wild'	Abbott 1913: 11, 13, 16
1895	Snowy River, Vic	A 'domestic cat' disturbed capturing a landrail [not mapped, as it is unclear whether the cat is feral or domestic]	Le Soeuf 1896: 19
c. 1896	Near Mt Ida, WA	Kitten in house	Luck 1988: 89
1896	Yeeda station, WA	'hundreds of cats live on the river [Fitzroy River, Kimberley] and kill all the small game'	Tunney 1896
1896	'a lagoon south of' Fitzroy River, WA	The skeletons or skulls of 47 cats counted; these [feral] cats had probably died of thirst when the lagoon dried up	Keartland 1920: 100
1897	Roebourne, WA	Cat eating lizards [unclear if domestic or feral]	Anon. 1897
c. 1897	?Wandangee station, Minilya River, WA	Aboriginal caught two 'wild cats' and ate them	Gunning 1952: 180
1897–1905	Richmond district, Qld	References to domestic cats (one black), their avian prey, and to 'bush cats'	Berney 1905: 75; 1906: 47; 1907: 106, 108
c. 1898	Near Lake Preston, WA	Bronzewing pigeons killed by domestic cats gone wild: 'are now more numerous in the bush than is generally supposed'	T. Hayward in *The West Australian* 4.3.1898: 3
1898	Swan Hill, Vic	House cat killed seven welcome swallows during six weeks	Hall 1900
1898	South Gippsland, Vic	Domestic cats perished during February wildfires	TJ Cloverdale in South Gippsland Development League 1920: 353
1898	Golden Valley (Balingup), WA	15 cats present in farmhouse	Honniball 1968: 78
1898	South Lead, Kanowna, WA	Cat found fallen 18' down a shaft- famished	*The North Coolgardie Herald and Menzies Times* 16.7.1898: 2
1898	Mt Morgan, WA	Numerous tracks of cats which have gone wild and taken to the bush	*The West Australian* 16.8.1898: 3
1898	Mt Magnet, WA	Cat found fallen 30' down a well	*Magnet Miner and Lennonville Leader* 24.12.1898
1899	Eucla district, WA	Cats which were let loose to destroy rabbits have apparently succeeded	*The North Coolgardie Herald and Miners' Daily News* 20.10.1899: 2
1899	Pelsaert Island, Houtman Abrolhos, WA	Noddy terns have been made more sensitive by the depredations of wild cats, once introduced to subdue the rats. Cats are wild in the adjacent group [Easter Group]	Hall 1902: 201, 204
1900	Newmarracarra, WA	c. 60 cats: 'the nucleus of an army to confront the rabbits when they invade Newmarracarra'	Fry 1900: 258
1900	Minilya station, WA	Cat killed a snake in kitchen	Brockman 1987: 174
c. 1901	Eyre's Sand Patch and Eucla, WA	200 tabby cats released c. 6 years ago	HA John in Anon. 1907: 309
1901–4	Eucla, WA	'the consignment of a 100 or more cats brought on a ketch from Port Adelaide. Their mission was to keep down the growing rabbit population. These cats, I was told, were purchased for a shilling a head from small boys in the Port Adelaide district'	V Hopewell in Jeffery 1980: 89
1902	Vlamingh Head, WA	'Several wild cats (domestic variety) were seen about here'	Carter 1902: 83
1904	Day Dawn, WA	Three cats and one kitten, domestic situation	Tyler 2002: 254
1904	Western side of Rabbit proof fence (between Burracoppin and south coast), WA	'The domestic cat grown wild is very plentiful...where cats...are found in the traps, the boundary riders release them'	[Crawford] 1904: 487–8

Year	Locality	Notes	Reference
1904	Eucla west almost to Balladonia and Israelite Bay, WA	Some time ago Government purchased (at £1 per head) a large number of cats, which were distributed throughout the Eucla and Israelite Bay districts. These multiplied. Now that kangaroo hunting for skins is now almost unpayable, the hunters are eking out a livelihood by destroying the cats and exporting skins for sale	CD McLauchlan in *The Kalgoorlie Miner* 28.9.1904: 2
1905	Near Cocklebiddy Rockhole, WA	One tabby and 4 kittens. Dead rabbits found. 'cats are doing valuable work'	HA John in Anon. 1907: 309
1905	Webb Patch out-camp [Mt Magnet district], WA	Cat taken there and lived there until its death in 1927	*The Murchison Times* 2.7.1927(unpaginated)
1905	Near Baldina [?Burra district], SA	'a beautifully marked tortoiseshell cat, of exceptionally large growth...a large number...in the hills...It measures 2ft. 8in. from ear to tip of tail, and stands about 1ft. 2in. high, its weight being 10lb. Barring its marks it looks like a young tiger'	*The Kalgoorlie Miner* 1.4.1905: 4
1905	Nangeenan, WA	'The wild domestic cat...is...a perfect pest to the poultry-keeper, far worse indeed than the native cat'	*The Western Mail* 25.12.1905: 85
1906	Nangeenan, WA	Pet cat on farm	*The Western Mail* 20.1.1906: 9
1907	Near junction of Waroona Road and Bunbury-Mandurah Road, WA	Woman lived with 12 cats	Hasluck 1967: 9
1907	Rabbit proof fence south of Burracoppin, WA	'wild cats...very plentiful'	*The Western Mail* 25.5.1907: 5
1908	Rabbit proof fence north of Burracoppin, WA	Cats very numerous. Great many tracks seen. One cat found in a trap but Sub/Inspector Craig on his last trip liberated 45 on this portion of fence	Crawford 1908: 516
1909	Between Caloola Creek and Langawirra, NSW	'a wild black cat was put up from the undergrowth... These cats were met on all our rambles. They grow to a larger size than the ordinary domestic "Tom", and kill many birds'	Macgillivray 1910: 89

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Assessment, evaluation and a comparison of planned and unplanned walk trails in coastal south-western Australia

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ABSTRACT

Three walk trails, the 'Bibbulmun Track' in West Cape Howe National Park and The Bald Head and Peak Head trails, in Torndirrup National Park were compared and evaluated using a problem assessment method. Indicators used to categorise trail degradation in the problem-assessment-trail-census included trail depth, excessive width, root exposure and trail proliferation. Other environmental variables measured in the trail assessment were slope, soil type and trail-side vegetation. Maintenance features such as boardwalks, steps, water bars and signs were assigned a condition and effectiveness rating. The most prevalent degradation problems on the assessed trails were soil erosion, exposed roots and excessive width. Trail proliferation was problematic in sections of indistinct trail or where a view could be accessed. The Bald Head and Peak Head trails were highly degraded compared to the assessed section of the Bibbulmun Track, which has been subject to a higher level of planning and management intervention. An evaluation of past management actions in relation to present trail conditions for all three trails indicates that trail alignment following natural contours and the installation of maintenance features such as board-walks, water-bars and steps on sloped sections are crucial to sustainable trail management. The utility of a trail problem assessment method developed in mountainous areas of the US has worked well in the assessment of sandy coastal walking trails, with the monitoring of trail conditions recommended as part of a sustainable trail management program and made possible due to the data that has been generated during this trail assessment.

Keywords: Trail assessment, environmental characteristics, maintenance features, West Cape Howe and Torndirrup National Parks

INTRODUCTION

Walking trails are an important means of access into a wide range of environments, some more resistant to the impacts of recreation than others. Furthermore, increasing recreational pressure from walkers has meant that walk trails world wide have suffered accelerated degradation problems that diminish the natural, social and cultural values of an area and potentially make trail usage unsafe (Leung and Marion, 1996; Liddle, 1997; Newsome et al., 2002). Information on trail conditions is essential for the maintenance and sustainability of walking trails and should include descriptive variables, assessment of maintenance features and an analysis of temporal visitation data including user type and behaviour (Marion and Leung, 2004).

The majority of research into the recreation ecology of walking trails has traditionally focused on high use mountainous environments in Europe and the United States. Following on from this, a number of techniques for assessing walking trails have been developed by researchers in the US as a way of evaluating trail conditions and degradation problems (e.g. Bratton et al., 1977; Cole, 1983; Leung and Marion, 1999). The suitability of trail assessment techniques developed for mountainous environments, however, has not been tested in sandy coastal environments. In addition to this, the popularity and increasing use of fragile coastal environments in many parts of the world has meant that these areas have often required rehabilitation and careful planning at a local level due to degraded conditions (Oma et al., 1992; Harvey and Caton, 2003).

Coastal locations in south-western Australia such as West Cape Howe and Torndirrup National Park (hereafter referred to as WCHNP and TNP) are areas of significant biological diversity and attract a large number of recreational visitors each year (CALM, 2004). Walking trails within the two parks occur in stabilised (fixed) sand dune environments and have been subject to different levels of use and management actions over the last three decades (CALM, 1992; CALM, 1995). Western Australia's icon walking trail, the 'Bibbulmun Track' (964km) traverses both WCHNP and TNP. Conceived in 1972 and completed in 1998, a considerable amount of time and effort has gone into its planning and implementation. Unplanned trails, on the other hand, have received reactive management actions in response to degradation problems. Despite this, no formal assessment of trail conditions that occur along the Bibbulmun Track and for other trails in sandy coastal locations has been

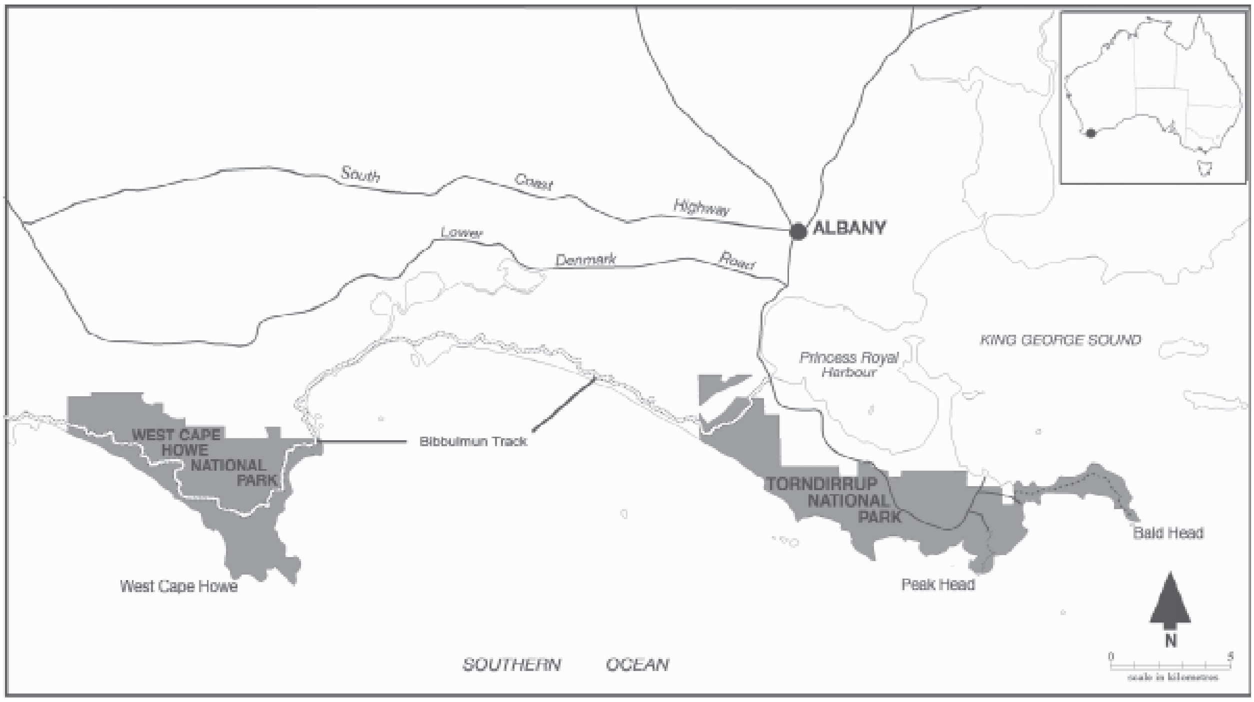

Figure 1. Study area, WCHNP and TNP on the South Coast of Western Australia

undertaken in Western Australia. Currently there are no baseline data that categorise trail conditions and there has been no assessment of the effectiveness of trail management actions in either WCHNP or TNP.

The objectives of this paper are therefore to:

- Assess, evaluate and compare a section of the planned Bibbulmun Track in the WCHNP with two unplanned but popular access trails, the Bald Head and Peak Head walk trails in TNP.
- Report on the suitability of current trail assessment techniques in sandy coastal environments in Australia.

Location of West Cape Howe and Torndirrup National Park

The study area focuses on two National Parks, WCHNP and TNP on the south coast of Western Australia (Figure 1). The two parks are located close to the regional centre of Albany and contain walking trails that meander through stabilised coastal sand dunes. WCHNP is located approximately 400km south east of Perth and 30 km south west of Albany (Figure 2). Western Australia's most southerly point, Torbay Head and West Cape Howe are contained within approximately 23 kilometres of rugged coastline on the park's southern border (CALM, 1995). The Bibbulmun Track traverses the park from east to west (Figure 1) and continues along the coast line terminating at Albany (Figure 2).

TNP is located approximately 400km south east of Perth and 10 km south of Albany. The area was set aside as a reserve in 1918 and elevated to National Park status in 1969 (Smith, 1991). Located on the Flinders Peninsula, Princess Royal Harbour is located to the north and the Southern Ocean forms the parks southern border. The Bibbulmun Track passes through the western corner of the park (Figure 1) with the Bald Head and Peak Head trails located at the eastern end of the park (Figures 3 and 4).

ENVIRONMENTAL CHARACTERISTICS

Climate

The study area is described as having a sub-Mediterranean climate with mild summers and cool wet winters. Air temperature is constantly moderated by the marine influence, ranging between a mean daily minimum and maximum air temperature of 10° and 20° C respectively. Annual mean rainfall is 1000mm with the majority of rainfall between May and August (Smith, 1991; CALM, 1995). Summer rainfall, however, is a common occurrence mostly as overnight drizzle in an easterly airstream but also as thunderstorms, the result of converging tropical cloud delivered to the region in a northerly airstream (Smith, 1991). The wind is a significant climatic factor that has the potential to erode exposed sandy soils and affect the behaviour of wild or prescribed fires in the parks (CALM, 1995). North westerly to southerly winds are commonly associated with cold fronts between May and August. Strong and gusty south easterly to northerly winds are experienced September to December, with persistent easterlies in January and February (Smith, 1991).

Geology and Soils

Both National Parks are underlain by a combination of pre-Cambrian granites, dolerite and banded gneisses that

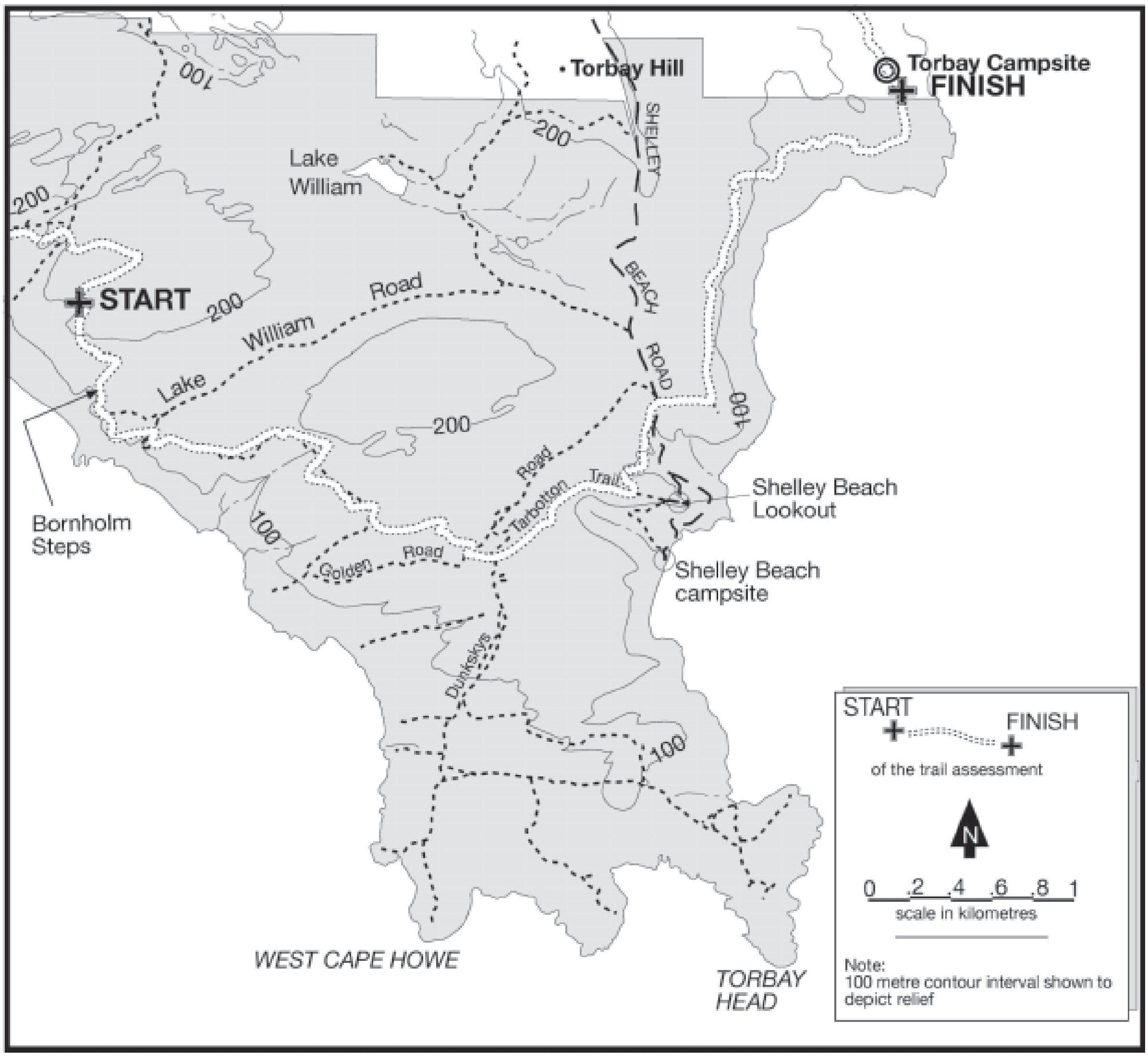

Figure 2. The assessed section of the Bibbulmun Track in WCHNP showing the Tarbotton Trail and historical vehicle trail network, trail length 11657.9 m

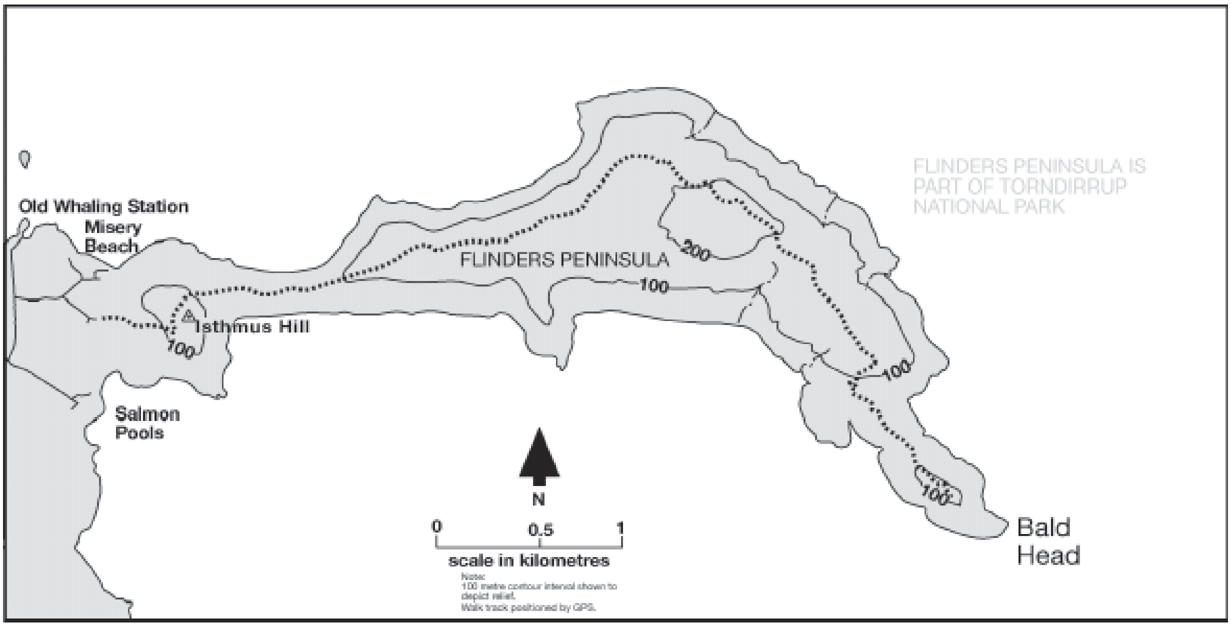

Figure 3. The Bald Head trail on the Flinders Peninsula in TNP, trail length 6552.8m

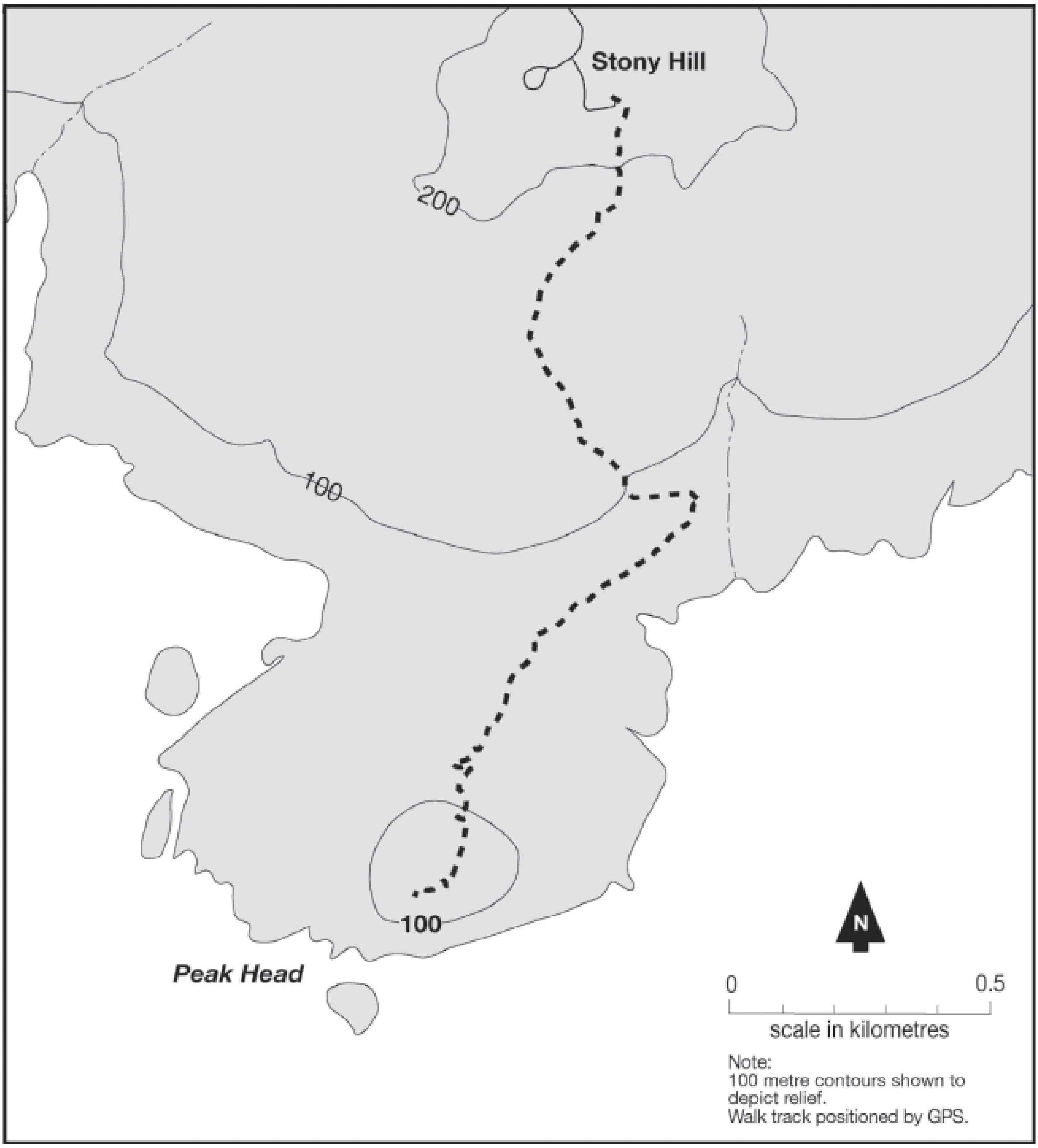

Figure 4. The Peak Head trail in TNP, trail length 2188.5m

form rock outcrops, coastal cliffs and monadnocks. Subjected to a long history of weathering, the physiography is expressed as variations in topography, soils and hydrology (Churchward et al., 1988). The weathering of basement rock has produced localised clay, gravel and a laterite profile more noticeable inland due to the dominance of a mantle of limestone sand along the coastline. Although there is some gravel or laterite development on the coastal strip occurring in association with exposed granite or gneiss monadnocks (CALM, 1995). The coastal mantle exhibits a largely continuous ridge of Tamala Limestone (karst) of Pleistocene age, overlain by younger sections of aeolian sands of Holocene age, now largely stabilised parabolic dunes. The surface soil in both parks is nutrient poor white to grey and yellow to brown fine to medium quartz sand with minor clay soils. Aeolian sands, distributed along the southern coastline, display a uniform grain size, lack cohesion and are generally poor in organic matter. (McArthur and Bettenay, 1960).

Coastal Dune Morphology

The granite and gneiss headlands that characterise the south coast are connected by shallow, curved sandy bays that have acted as the supply point for vast quantities of aeolian sand being moved inland during four major marine transgressions during the Pleistocene (Hodgkin and Hesp, 1998). Ancient parabolic dune fields have generally accreted in low-lying areas but wind blown sand has also covered granite peaks and Tamala Limestone along the coastline forming a belt some 2–3km in width (Churchward et al., 1988). The most recent marine transgression was during the Holocene, when sea levels reached about 1m higher than the present before receding approximately 4000 years ago. Coastal dunes are now mostly stabilised by vegetation but still vulnerable to erosion following disturbances such as fire, human activity and high winds associated with storm fronts (Beard, 1979).

Vegetation

Beard (1979) described the dominant plant communities that occur in the immediate study areas as being Low Forest, Shrubland and Rock Outcrop. Shrubland is further divided into two groups of heath found on the coastal strip in both parks (Table 1).

Recreational Use of Selected Walk Trails

TNP is the most visited park on the southern coastline. Visitation statistics for both WCHNP and TNP are displayed as percentage values and compared to the total numbers of visitors to 6 major National Parks in the Great Southern District which contains both WCHNP and TNP (Table 2).

Data on trail usage from electronic pedestrian counters placed at selected positions on the Bibbulmun Track, between Denmark and Albany between1996–2003 and at the beginning of the Bald Head and Peak Head trails between1996–1999 are indicated below (Figure 5).

TRAIL ASSESSMENT METHODOLOGY

General considerations

The total length of each assessed trail (see Figure 2 for the assessed section of the Bibbulmun Track) was established by pushing a measuring wheel from a designated start point to a designated finish point. Start points were also made easily identifiable and locatable with a photographic image and Global Positioning System (GPS) reading. Indicators measured during the trail assessment comprised environmental, degradation and maintenance features (Table 3). The assessed variables were measured concurrently and recorded directly onto a field proforma.

The trail-problem-assessment-method (Leung and Marion, 1999) was chosen because of the generated data's capacity to document the extent, location and frequency of the chosen indicators and would also prove useful to further identify problem sections of trail that could be assessed by point sampling techniques that measure changes in soil micro-topography (Randall, 2004). Environmental and degradation indicators as outlined in

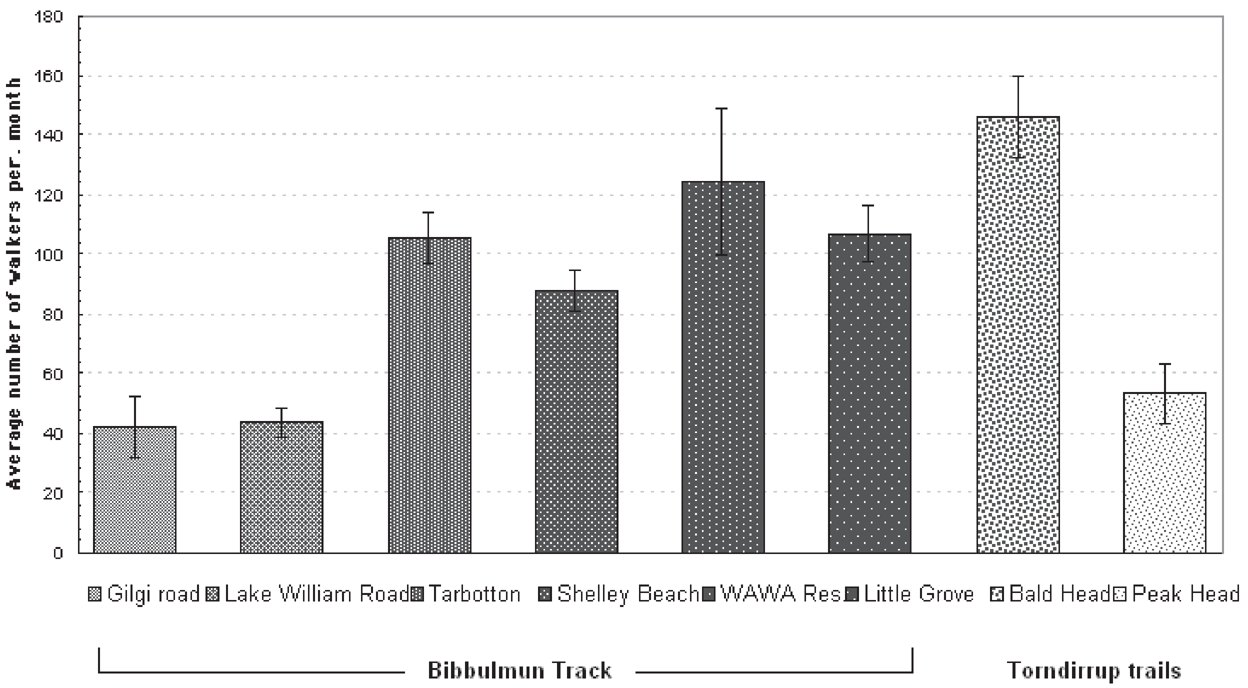

Figure 5. Average numbers of walkers per month on the Bibbulmun Track between Denmark and Albany, and the Bald Head and Peak Head trails in TNP

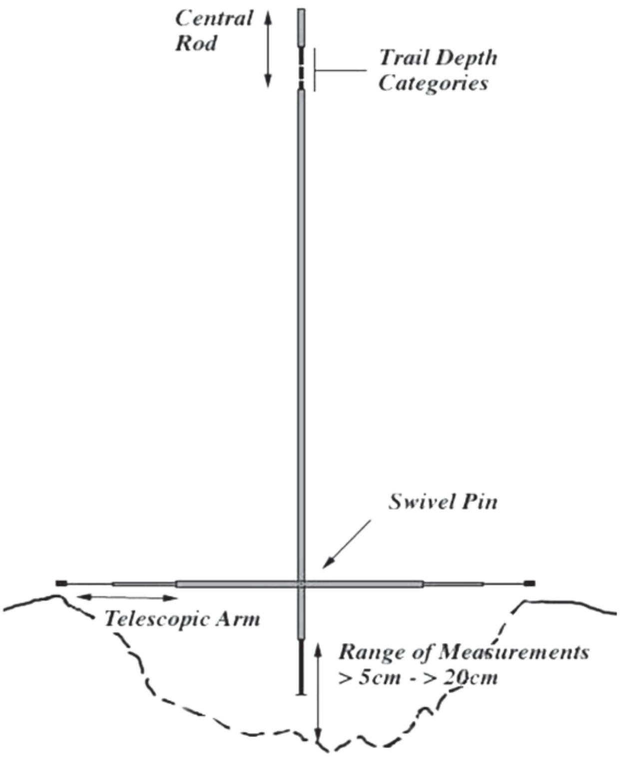

Figure 6. Trail depth and width measuring device, telescopic cross arms measure width, while central rod is calibrated to measure range of trail depth categories at a glance

Table 3 were recorded as the lineal extent of each segment occurring on the trail length. Exposed roots and trail proliferation were given a severity rating from 1–5 or low to high.

Trail erosion depth and excessive width

Trail erosion depth and width categories were standardised by measuring the minimum and maximum parameters during a preliminary field trip (Table 4). A trail-depth-measuring device was developed to facilitate measuring trail depth and width categories, which were recorded as the start and finish point of each linear section (Figure 6).

Maintenance features

Maintenance features are engineering or educational solutions (i.e. steps or signs) that help to counteract walk trail degradation or increase user comfort. Features are preferably made from locally available materials such as stone or wood but are also made from steel or geo-synthetic surfaces such as rubber. Maintenance features were divided into 2 categories defined by the system of measurement. Maintenance features that had a continuous occurrence described in metre length, such as a board-walk or wood chip surface were documented by recording the start and finish point. Single, non-continuous maintenance features such as water-bars or signs were recorded with a single data point, which was recorded at the centre of each feature. Maintenance features were also given a condition rating and an effectiveness rating (Table 5). The condition of a maintenance feature refers to the physical condition of the material used in construction e.g. wooden water bar in poor condition is suffering from dry rot or split along entire length. The effectiveness of a feature refers to the observational evidence that degradation is being counteracted e.g. a water bar is diverting the flow of water off a sloped trail tread. Observational evidence is confirmed by the presence of trail sediment adjacent to the water bar and lack of trail degradation below the water bar.

Results of trail assessment

Environmental attributes and indicators of erosion of the assessed section of the Bibbulmun Track and the Bald and Peak Head Trails are summarised in Table 6.

Indicators of trail degradation

The Bibbulmun track has 2.5% total erosion recorded along the assessed section of trail compared with 51% of Bald Head and 62% of Peak Head. Comparative results are similar for excessive width (2.3% on the Bibbulmun Track v 11% along Bald Head), trail proliferation (0.8% on the Bibbulmun Track v 6% along Bald Head) and root exposure (0.3% on the Bibbulmun Track v 29.7% along Peak Head). All indicators of trail degradation are low along the Bibbulmun Track as compared with the Bald and Peak Head trails (Figure 7; Table 6).

MAINTENANCE FEATURES

Assessed Section of the Bibbulmun Track (Total length 11.65 km)

Trail maintenance features were noticeably more numerous than the Bald or Peak Head trails. Continuous maintenance features included: 298.8m of board-walk (3 sections), 293.4m of soil retaining boards (45 sections), 150.9m of rubber belting (4 sections), 442.8m of stairs (28 sections) and 50.9m of wood chip surfacing (1 section). Non-continuous features included: 2 bridges, 2 boot cleaning stations, 6 excluding barriers, 6 seats, 18 single steps, 75 signs and 551 water bars (Table 7).

Continuous maintenance features described as being in excellent condition totalled 11.1%, while 49.8% of continuous maintenance features are described as having an excellent effectiveness. Overall the condition of continuous maintenance features is moderate to moderate-excellent and the comparative effectiveness is moderate-excellent to excellent. A total of 83.8% of non-continuous maintenance features are in moderate-excellent condition while only 59.5% of features have moderate-excellent effectiveness. A minor proportion (1.5%) of non-continuous maintenance features are placed between the moderate to poor condition categories, with 27.7% of non-continuous features located between the moderate to poor effectiveness categories.

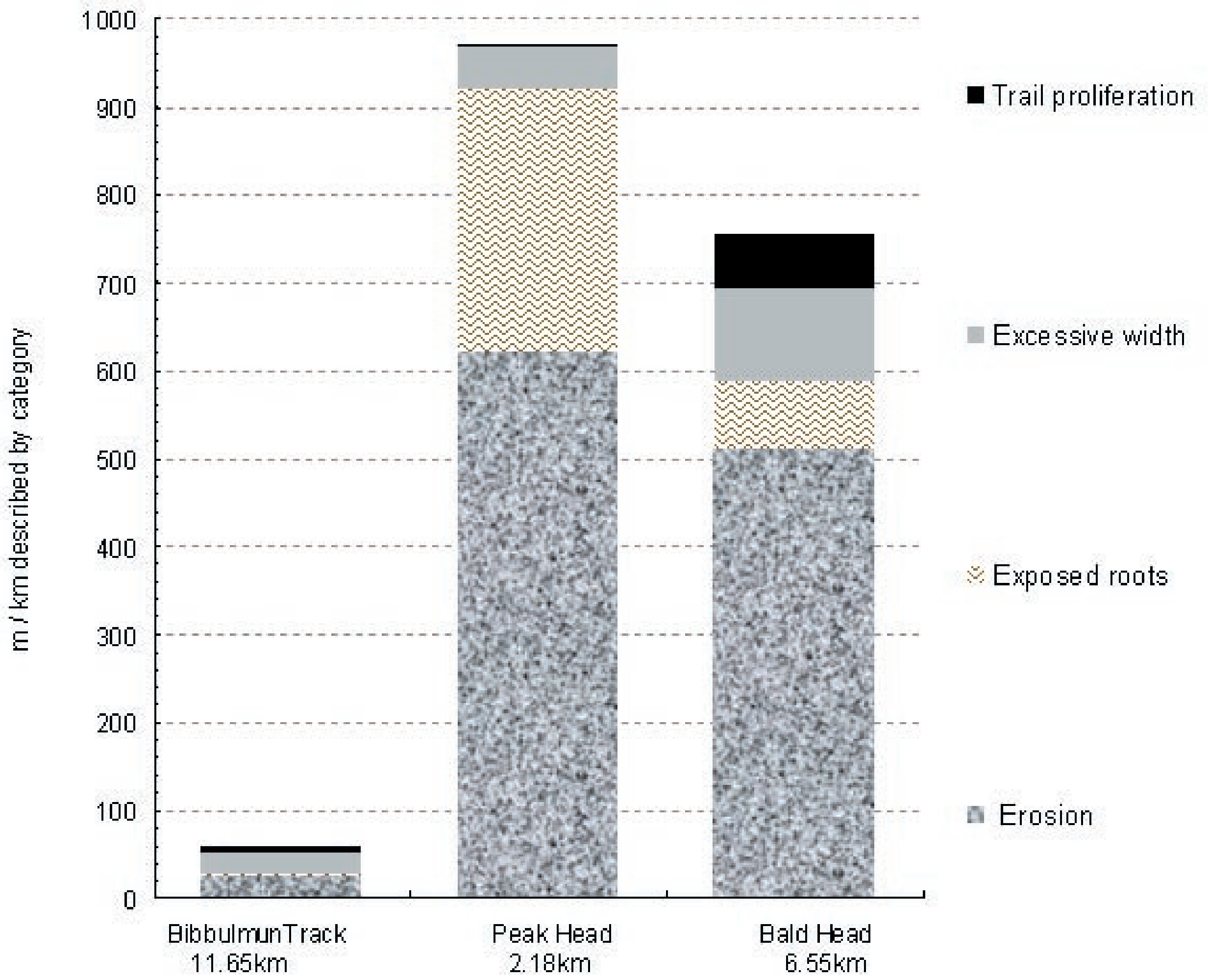

Figure 7. A comparison of degradation (m/km) between assessed trails in the study area

Bald Head trail (Total length 6.55 km)

Continuous maintenance features on the Bald Head trail were restricted to 7 sections of timber board-walk (552.2m), stairs (2.9m) and one fence (1.3m). Directional signs (75), and other non continuous maintenance features comprising 1 water bar. The majority of the 7 board-walks were in moderate to moderate-poor condition while still maintaining a 100% moderate-excellent effectiveness rating. The timber board–walk was 24.6% in moderate-poor condition, 66.9% in moderate condition and 8.6% in moderate-excellent condition. The effectiveness rating for the board-walk was 100% moderate-excellent, indicating that the features effectiveness was not reliant on its condition. The condition and effectiveness of directional signs on the trail were very similar. Of the 75 signs, 93.4% were in moderate to excellent condition with 53.9% classified as having a moderate-excellent effectiveness, but with only 10.5% attracting an excellent effectiveness rating (Table 8). Signs that were in need of re-painting were difficult to detect. Any moderate to moderate-poor effectiveness ratings were given to signs that were difficult to see from a distance and therefore potentially encouraged trail proliferation.

Peak Head trail (Total length 2.18 km)

Of the 89 water bars on the Peak Head trail, 48 were totally covered by displaced soil and 14 were between 70–90% covered by soil rendering them ineffective. All water bars were in moderate-excellent condition. However, the majority (48) were classified as being poor in effectiveness with 12 achieving moderate-excellent effectiveness (Table 9). Directional signs (24) were between the moderate to excellent classification in both condition and effectiveness with some general comments during assessment highlighting the need for repainting. A relatively minor number of steps (12) were all in moderate-excellent condition and of moderate to moderate-excellent effectiveness.

COMPARISON OF THE ASSESSED TRAILS

Overview

The trails selected for assessment in the study area have been subject to different use levels and management actions, while environmental conditions (soils, slope and climatic factors) that affect the rate of water and wind erosion, are very similar (see Table 6). Areas of exposed granite outcrop were not assessable in terms of erosion but contributed to the total length of the trail. The Bibbulmun Track in WCHNP is a carefully planned and implemented walk trail that has benefited from government and community funding, regular volunteer maintenance work and a higher level of management in relation to other walk trails. In contrast, the Bald Head and Peak Head trails have existed as unplanned access trails prior to the creation of the Bibbulmun Track in the study area. The closure of vehicle trails, partial upgrades and maintenance work in response to erosion problems on both the Bald Head and Peak Head trails in the mid 90's have improved the conditions of both trails. The levels of erosion evident along the Bald Head and Peak Head trails is a reflection of the unplanned nature of these trails and represents ongoing degradation that management has had to react to. In addition, park management is constrained by constantly shrinking land management budgets a situation seen in other protected areas worldwide (Leung and Monz, 2006).

Vegetation

The vegetation types occurring on all three assessed trails in the study area are very similar. Shrubland scrub-heath and heath communities are the dominant vegetation types on the assessed trails (see Table 1). The main differences being *Eucalyptus angulosa* as the dominant small tree/shrub on the Bald Head trail compared with *A. flexuosa* the dominant small tree/shrub on the Bibbulmun Track and Peak Head trail. Vegetation plays an important role in protecting exposed trail soil from the effects of raindrop splash erosion by dissipating the kinetic energy of falling raindrops (Brandt, 1989). Furthermore, in coastal areas the presence of high trail-side vegetation affords protection from the effects of deflation by providing a barrier that intercepts and accumulates wind blown sand particles (Harvey and Caton, 2003). Sections of high trail-side vegetation comprising *A. flexuosa*, E. *angulosa*, *Eucalyptus marginata, Acacia fraseriana* and *Melaleuca cuticularis* were present along the Bibbulmun Track in WCHNP and comprised 4.2% of the total trail length (Table 6). A further 30% of the Bibbulmun Track comprises myrtaceous heath (< 60cm in height) with occasional small trees of *E. marginata* and *A. fraseriana*. This shrubland scrub heath community exhibited a very dense organic rich under-trail root network which most likely contributes to trail resilience along the Bibbulmun Track (eg. Oma et al,. 1992).

On the Peak Head trail, shrubland scrub heath dominated by *A. flexuosa* comprises 28.6% of the total trail length. Trail erosion in excess of 10cm depth and root exposure was not evident in these sections (Table 6). In contrast, the Bald Head trail comprised 72.9% shrubland scrub heath with an almost continuous cover of *E. angulosa* and *A. flexuosa* (< 3m in height). These sections of trail, apparently sheltered from the effects of rain splash and wind erosion by the trailside trees, were badly eroded (see Table 6) and did not seem to benefit from the presence of high trailside vegetation.

Soils / substrate type

The assessed trails mostly traverse the fixed component of the coastal dune system comprising Tamala Limestone in association with unconsolidated nutrient poor medium to fine quartz sand, although 26% of the Bald Head Trail comprises exposed granite (Table 6). Exposed granite surfaces are not subject to measurable erosion but can influence the velocity of water running onto the adjoining trail, leading to root exposure, as was observed on the Bald Head trail (Table 6). Limestone karst features were noticeably vulnerable to compaction and deflation and occurred as exposed features on degraded sections of the Tarbotton trail (Bibbulmun Track) and the Bald Head trail.

Variable levels of organic matter were present in the surface soils. For example, 96% of the assessed portion of the Bibbulmun Track were classified Grey/Black soil indicating the presence of organic matter. The addition of organic matter and the development of soil horizons in coastal locations reflects stable surface conditions and is strongly influenced by vegetation type and the rate of water infiltration (Thompson, 1983; Jungerius and van der Meulen, 1988; Jungerius and Dekker, 1990). Organic matter also aids in reducing deflation by adding cohesion to sand particles (eg. Eldridge and Rosentreter, 1999) The role of organic matter, however, can be complex due to the development of water repellence from hydrophobic residues that coat sand grains at the soil surface (eg. Bridge and Ross, 1983; Thompson, 1983). Extreme dryness of surficial organic matter also contributes to water repellence (Jungerius and de Jong, 1989). This in turn reduces infiltration and where vegetation is sparse and ground is sloping increased run-off and erosion occurs as buoyant sand particles and organic matter are entrained in surface wash (Jungerius and van der Meulen, 1988). In contrast to the darker soils of the Bibbulmun Track, the Peak Head and Bald Head trails had a larger proportion of white sub-surface soil present on the trail tread and given the high levels of recorded degradation the colour reflects the creation of new surfaces as organic matter has been lost to lower-lying sections of the trail.

Slope and Degradation

Erosion categories have been combined to represent the total erosion from > 5cm. This is in order to simplify the comparison of trails and because each successive erosion category is also a contributor to the previous categories e.g. an erosion depth of 20cm also contributes to the lower categories 5–9cm and 10–19cm. Figure 7 compares the extent of degradation (m/km) of the assessed trails in the study area.

Trail proliferation is most noticeable on the Bald Head trail occuring on sections of indistinct trail that are poorly signed and occur in the area of exposed granite outcrops. On both the Bald Head and Peak Head trails excessive width is generally the result of sections of trail being located on a dissused vehicle trail.

A comparative analysis of total erosion within slope categories for the assessed trails shows a proportional increase in erosion with increasing slope on the Bald Head and Peak Head trails. The Bibbulmun Track, in contrast to the Bald Head and Peak Head trails, shows minimal erosion with a noticeable lack of erosion for slope values >18° (Figure 8).

The Bibbulmun Track does not exhibit the same increase in total erosion with increasing trail slope that the Bald Head and Peak Head trails show, despite being the longest assessed trail (11.65 km). This is most likely due to: the way in which the trail is aligned on natural contours avoiding steep slopes; the type of vegetation communities (low forest and myrtaceous heath); presence of organic matter in the trail soil and the presence of effective maintenance features such as water bars, retaining boards and steps. Effective maintenance features help to inhibit erosion by slowing the velocity of surface water on the trail tread and stabilising the poorly consolidated sand on sloped sections of trail.

Maintenance Features

A comparison of non-continuous maintenance features that occur on the three assessed trails in the study area reveals that the Bibbulmun Track has the highest proportion (85%) of water bars, steps, signs, seats, bridges, and boot cleaning stations. Figure 9 represents a comparison of selected non-continuous maintenance features (water bars and steps) present in each slope category on the assessed trails in the study area. The presence of effective water bars and steps in sections of trail with a slope value of between 6–17° and >18° is the most likely reason that erosion is not evident on these sloped sections on the Bibbulmun Track in WCHNP (see Figure 8). It also appears that the installation of water bars in sections of slope 18° > has been abandoned in preference of the construction of steps and stairs. This represents a good management decision, as steps level the soil surface reducing the velocity of surface water on the trail, even if the steps are only in moderate condition. Average tread of steps designed for steep slopes should be less than 1m to enhance this attribute (Parks and Wildlife Service Tasmania, 1994). Moreover, water bars can become covered in sediment and no longer operate effectively to slow any surface water flow, they require regular maintenance to clear away debris and are probably not as effective as steps, on steep slopes.

Of the three assessed trails, the Bibbulmun Track has the highest percentage (58%) of continuous maintenance

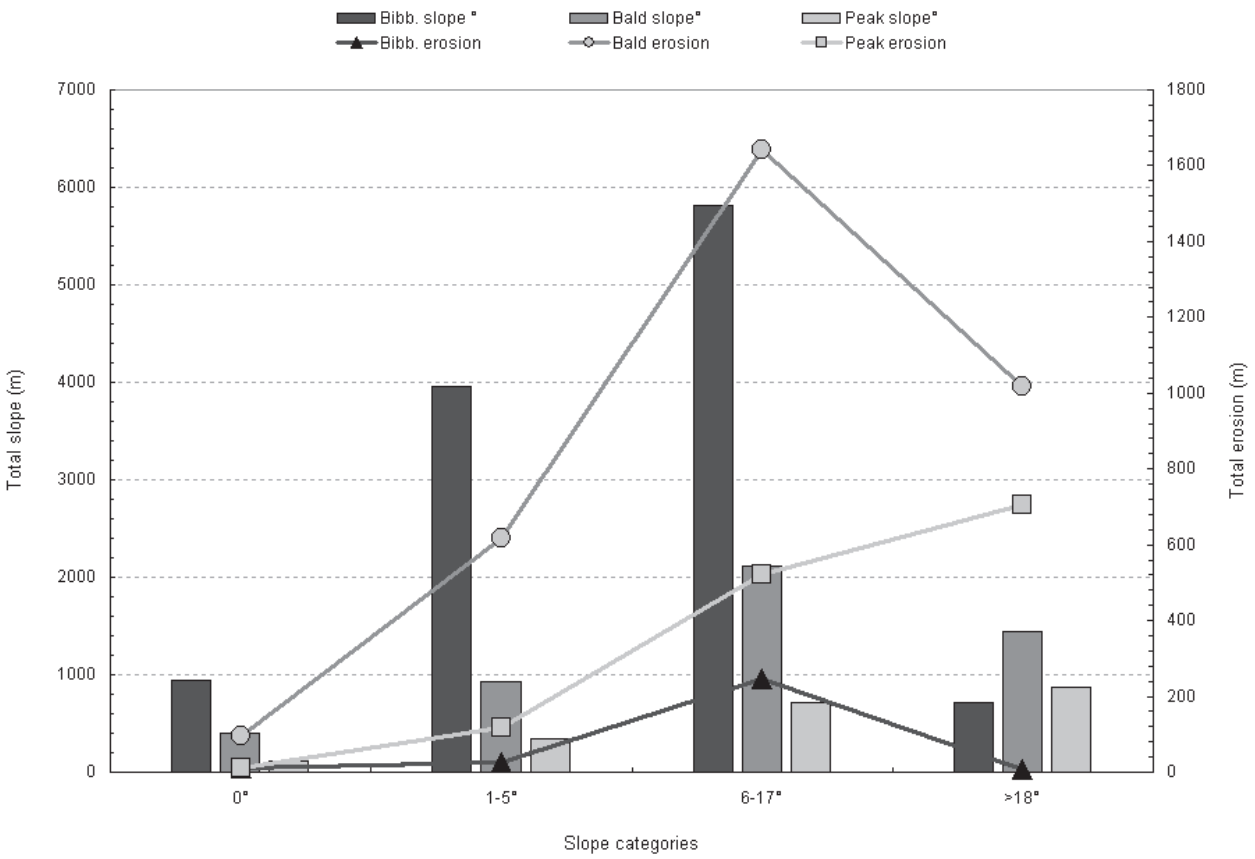

Figure 8. A comparison of slope categories and total erosion on the assessed trails in the study area

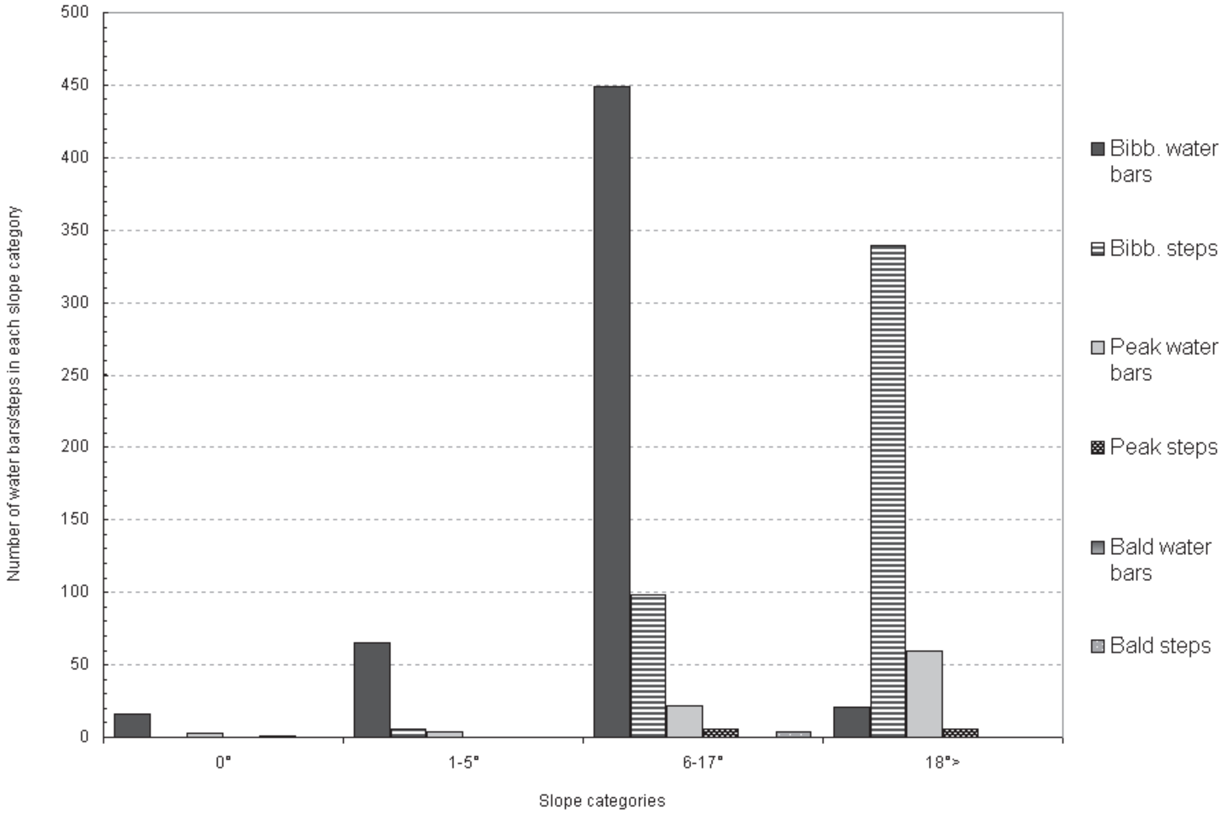

Figure 9. A comparison of the number of steps and water bars in each slope category on the assessed trails in the study area

features such as board-walks, zones of wood chip application, groups of steps (stairs), retaining boards and rubber belt surfacing. The remaining continuous maintenance features are the Bald Head board-walk (41%) and the Peak Head stairs (1%). The charring of sections of board-walk on the Tarbotton trail due to the damaging effects of wild fire (Figure 10) has not lowered the effectiveness rating which was moderate-excellent to excellent. The decline in the condition of these maintenance features is representative of their age (~ six yrs). Moreover, as long as the surface of the feature receives and disperses the weight of the walker, compaction and movement of the trail soil is averted. Because walkers are confined to a narrow board-walk, the trampling of trailside vegetation is averted.

Moderate–poorly effective maintenance features on the Bibbulmun Track such as water bars were mainly located on the Tarbotton trail. The shear number of water bars on the Bibbulmun Track (551) meant that some water bars had attracted a moderate-poor effectiveness rating because they had been undercut by deflation. The non-continuous maintenance features on the Bald Head trail were mainly directional signs on exposed granite and were sometimes difficult to detect from a distance, leading to disorientation that can ultimately lead to trail proliferation. Water bars on the Peak Head trail were mainly of poor

Figure 10. A charred board-walk with split cross tread and protruding nails, moderate-poor condition but moderate-excellent / excellent effectiveness rating for Bibbulmun Track in WCHNP

effectiveness and did not seem to be arresting erosion as well as the numerous exposed tree roots that were acting as surrogate water bars on severe sections of trail degradation. A water bar should be aligned on a 45–60° angle to the trail. Water bars that were positioned at 90° in relation to the trail and lacked the angle necessary for the diversion of surface water appeared to create a lip that surface water could fall over and erode the soil at the base of the water bar (Figure 11). In some cases it was difficult to establish whether or not the feature was meant to be a water bar or a step. Groups of steps on slopes > 10° with widely spaced treads were observed to be eroded at the stair base due to the effects of vertical water spillage over the step lip. The effectiveness rating of grouped steps on slopes > 10° was markedly increased if the tread space between each step was < 1m with 60cm treads being suggested as a standard for single lane walking trails in Tasmania (Parks and Wildlife Service Tasmania, 1994). Mende and Newsome (2006) in their assessment of walking trails in the Stirling Range National Park, south-western Australia, noted that the effectiveness of a maintenance feature was not necessarily dependant on its condition but related more to the proper placement of the feature and the number of such features along a given trail. This was also observed to be the case from the results of the assessment for the three assessed trails in this study.

SUSTAINABLE TRAIL MANAGEMENT ALONG THE COASTAL ZONE OF SOUTH-WEST WESTERN AUSTRALIA

Basis for a Monitoring Program

The collection of census data for the trails in the study area has provided a comprehensive profile of the present trail conditions for the Bald head and Peak Head Trails and for the assessed section of the Bibbulmun Track. By using the initial census as the baseline data to create a monitoring program, any subsequent census will be able to detect changes in trail conditions when compared to the baseline measurements. Census techniques, however, are not suitable for repeated measures of very long trails (>10km) such as extended sections of the Bibbulmun Track due to the constraints of time and money commonly faced by land management agencies. One option would be to undertake a preliminary observational assessment looking for a basic indicator of degradation such as trail erosion depth greater than 10cm e.g. Tarbotton trail (Figure 2). The start and finish of problem sections could be recorded by a GPS system to facilitate a more efficient and comprehensive census of the problem sections at a later date.

Trails such as the Bald Head and Peak Head trails are

Figure 11. Water bars (left) with a tread space > 1m showing water erosion at the base of each bar due to the on trail waterfall created during surface water flow. Grouped steps (right) on a steep slope with a tread space of < 1m, show no signs of water erosion or soil movement. Bibbulmun Track in WCHNP

relatively short and therefore census techniques can be applied to the whole trail at a rate of approximately 3km per day. Point sampling techniques were chosen for selected degraded sections on the Peak Head and Bald Head trails using Point Intercept Frame (PIN) measurements. This was done to collect a series of cross sectional trail profiles, repeated over time to establish changes in soil micro-topography on deeply incised sections of sloped trail that represent some of the most severe degradation on these two trails. A complete review of the PIN frame methods can be found in Phillips and Newsome, (2002) with the methods and results for this study in Randall (2004).

Suitability of Methods for Sandy Coastal Environments

The application of the trail problem assessment method (Leung and Marion, 1999) to sandy coastal environments therefore appears to work well. Leung and Marion (1999) suggest that changes can be made to the methods they developed to collect census data on trail conditions, such as including different types of indicators for different environments. Standards for indicators such as trail erosion depth and root exposure were chosen following preliminary field trips to establish the extent of these problems and therefore assign suitable categories that were representative of the host environment. Vegetation communities were largely specific to the sandy coastal environment. Soil type, although broadly uniform was categorised into two main groups, grey or white, aided by the inclusion of the general trail condition categories, firm or loose, which showed a strong relationship with the soil categories (i.e. grey-firm and white-loose) in preliminary strip graph interpretation analysis (Randall, 2004).

An analysis of the results has shown that the management and planning efforts responsible for the creation of the Bibbulmun Track in WCHNP have been very effective in designing a trail for a sandy coastal environment that will not easily degrade. The comparative analysis of the three assessed trails, made possible by the census data, has been a useful way of evaluating the suitability of the trail design techniques used on the Bibbulmun Track. Information produced as a result of census data can also help in anticipating the logistics of applying those techniques to the Bald Head and Peak Head trails for maintenance work or trail realignments.

The issue of increasing trail usage

The increasing popularity of outdoor recreation and hiking in natural areas points to increased usage of the Bibbulmun Track and other walk trails in the Great Southern District of Western Australia. In order to understand the relationships between usage and trail deterioration it is crucial to establish a database of visitation to trail networks. Electronic counters are probably the best way of recording data that is accurate, as end-of-trail log books can be notoriously unreliable. However, the location of a trail counter has an influence on the accuracy of the data gathered as a result. For example in the case of the Bald Head trail, the data logger that recorded trail usage between 1996–1999 (Figure 5), was positioned at the beginning section of the trail (car park end) and would not represent those walkers that did not complete the whole trail. A more reliable way of recording trail usage and exploring the relationships between use factors and degradation would be to position a trail counter on a known problem section. Temporal changes in erosion on and off the trail could then be recorded by point sampling techniques at the same location the counter is positioned and thus related to trail use with an increased level of confidence.

Limitations of the approach applied in this study

Leung and Marion (1999) suggest that when undertaking large scale trail surveys that involve multiple recorders, error arising from subjective decision making can be reduced by training staff with written and photographic descriptions and by constantly rotating multiple staff who record in teams. A series of photographs and written descriptions was included in this project and will aid in reducing this source of error should a future monitoring program evolve.

Some inaccuracies are possible if repeated as a monitoring program. This can be apparent when a subjective decision, made by the recorder as to the correct location of the start and finish points of degradation or environmental indicators and correctly allocating standardised variables such as percentage root exposure, the condition and effectiveness of maintenance features and the severity of trail proliferation. It is recommended that the original recorder repeats any subsequent survey, or that training of new staff is undertaken prior to the commencement of a subsequent survey program. Despite such limitations the approach has proved to be useful in validating the planning and management effort applied to the assessed section of Bibbulmun Track and in confirming that trail alignment following natural contours and the installation of maintenance features such as board-walks, water-bars and steps on sloped sections are crucial to sustainable trail management.

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Table 1

Vegetation communities of fixed dunes and granite monadnocks in the study area

	Vegetation Community	Characteristics
Low Forest		Stunted trees < 10m three different associations *Eucalyptus marginata, Allocasaurina fraseriana* and *Melaleuca cuticularis.* Other spp. include *Banksia* spp., *Dryandra* spp.
Shrubland	Scrub Heath	Occurs on inland coastal strip Dominant trees < 4m *Agonis flexuosa* and *Eucalyptus angulosa* in association with a Proteaceous upper layer of tall shrubs and a Myrtaceous lower layer. Other Spp. include *Adenanthos sericeus, Templetonia retusa* and *Hardenbergia comptoniana*
	Heath	Closed lower layer of dwarf shrubs < 60cm, Species diverse, often Myrtaceous dominant, independent or in association with scrub heath with scattered shrubs of *A. flexuosa* and *E. angulosa* occurring as stunted ecotypes. Other spp.include *Hakea prostrata, Scaveola crasifalia, Loxocarya cinerea* and *Adenanthos obovatus*
Rock Outcrop		Mosses, grasses and scattered shrubs *Anthocercis viscosae, Agonis marginata, Hakea elliptica* and *Dryandra formosa*

source: Beard (1979)

Table 2

Total visitors: Great Southern District 1993-2003 and percentage comparison, WCHNP and TNP

Great Southern District	TNP	WCHNP
4,338 606	1,749 199	297, 539
100%	40.3%	6.9%

source: CALM (2004)

Table 3

Indicators used to evaluate walk trails by the problem assessment method

Environmental	Degradation	Maintenance Features
Vegetation community Rock type Soil texture Slope°	Erosion depth Excessive trail width Exposed roots Trail proliferation	Bridge, board-walk, boot cleaner, excluding devices, fences, retaining boards, seats, water-bars, steps, signs, woodchip and rubber belt surfacing

Table 4

Categories used to measure trail erosion depth and excessive width

Category		Description
< 5cm	(N)	normal level of soil compaction between trail-side berms
5 - 9cm	(E1)	trail depth between 5cm and 9cm
10 – 19cm	(E2)	trail depth between 10cm and 19cm
20cm >	(E3)	trail depth 20cm or greater
60 –120cm	(W1)	trail width between 60 –120cm
> 120cm	(W2)	trail width greater than 120cm

Table 5

Maintenance features and ratings description used during trail assessment

Continuous	Non-continuous	Condition/effectiveness rating
board-walk, wood chips and rubber belt surfacing, retaining boards, fence, stairs (multiple steps)	bridge, seat, water- bars, step (single) boot cleaning station (removes fungal pathogens from footwear)	1 excellent 2 moderate to excellent 3 moderate 4 moderate to poor 5 poor

Table 6

Combined results of the assessed section of the Bibbulmun Track WCHNP and the Bald and Peak Head trails in TNP

Bibbulmun Track 11.65 km	Bald Head Trail 6.55 km			Peak Head Trail 2.18 km					
Trail impact indicator	**Occurrence (n)**	**Total (m)**	**% of trail**	**Occurrence (n)**	**Total (m)**	**% of trail**	**Occurrence (n)**	**Total (m)**	**% of trail**
Excessive width (total)		265	2.3		698	11		104	4.8
Category									
Width 60-120cm	2	36	0.3	9	223	3.4	2	14	0.6
Width > 120cm	2	229	2.0	15	475	7.2	4	90	4.1
Erosion depth (total)		292	2.5		3341.4	51.0		1359.9	62.1
Category									
5-9cm	18	227	1.9	92	1680.9	25.7	17	852.3	38.9
10-19cm	6	59	0.5	59	768	11.7	8	394	18
> 20cm	1	7	0.1	32	892	13.6	37	113	5.2
Exposed roots (total)		32	0.3		504	7.7		649	29.7
Category									
3-5%	0	0	0	5	67	1	0	0	0
6-10%	1	8	0.07	12	148	2.3	19	427	19.5
11-20%	2	13	0.11	9	81	1.2	9	163	7.4
> 20%	2	11	0.09	5	209	3.2	5	60	2.7
Trail proliferation (total)	21	100	0.8	39	396	6		11.9	1
Severity 1-5									
1 low	8	75	0.6	3	98	1.5	0	0	0
2	4	14	0.1	10	63	1	3	11.9	0.5
3	3	11	0.1	6	192	2.9	0	0	0
4	0	0	0	1	7	0.1	0	0	0
5 high	0	0	0	2	36	0.5	0	0	0
Slope º									
Category									
0 º		942.3	8.1		406.5	6.2		107.3	4.9
1-5 º		3959.1	34.0		929.6	14.2		343	15.7
6-17 º		5816.1	49.9		2118.1	32.3		720.1	32.9
18 º >		711.2	6.1		1436.2	21.9		873.8	39.9
Vegetation Community									
Low Forest		486.9	4.2		0	0		0	0
Shrubland Scrub Heath		8247.2	70.7		4779.1	72.9		625.1	28.6
Shrubland Heath (limestone)		2655.9	22.8		9.2	0.1		1304.2	59.6
Shrubland Heath (granite)		18.9	0.2		166.9	2.5		134.9	6.2
Rock Outcrop		249	2.1		1597.6	24.4		124.3	5.7
source: Beard (1979)									
Soil Type (standardised)									
White (sand)		0	0		1805.5	27.6		156.4	7.1
Grey / black (+ organic matter)		11196.3	96.1		2506.3	38.3		1805	82.5
Conditions (underfoot)									
Loose		26.3	0.2		1808.8	27.6		367.4	16.8
Firm		11170	95.8		2225.8	34		1602.9	73.2
Rocky		461.5	3.9		1968.8	34.2		218.2	10.5
Rock Type									
Granite		309.3	2.6		1691.7	25.9		219.4	10.1
Limestone		152.2	1.3		549.3	8.3		7.7	0.4

Table 7

Maintenance features present on the Bibbulmun Track in WCHNP

Category	Continuous =1236.8 m		Non-continuous n=661	
Condition	Total (m)	% of total length (m)	Total (n)	% of total
excellent	136.9	11.1	97	14.7
moderate-excellent	611.9	49.5	554	83.8
moderate	486.3	39.3	7	1.1
moderate-poor	1.7	0.1	1	0.2
poor	0	0	1	0.2
Effectivness				
excellent	615.5	49.8	85	12.7
moderate-excellent	513.3	41.5	393	59.5
moderate	75.6	6.1	72	10.9
moderate-poor	32.4	2.6	104	15.7
poor	0	0	6	1.1

Table 8

Maintenance features present on the Bald Head Track

Category	Continuous =556.4 m		Non-continuous n=76	
Condition	Total (m)	% of total length (m)	Total (n)	% of total (n)
excellent	0	0	8	10.5
moderate-excellent	50.2	9	42	55.3
moderate	369.3	66.4	22	28.9
moderate-poor	136.9	24.6	4	5.3
poor	0	0	0	0.0
Effectivness				
excellent	0	0	8	10.5
moderate-excellent	556.4	100	36	47.4
moderate	0	0	29	38.2
moderate-poor	0	0	3	3.9
poor	0	0	0	0.0

Table 9

Maintenance features present on the Peak Head Track

Category	Non-contiuous n= 124	
Condition	Total (n)	% of total (n)
excellent	4	3.2
moderate-excellent	111	89.5
moderate	10	8.1
moderate-poor	0	0
poor	0	0
Effectivness		
excellent	4	3.2
moderate-excellent	33	26.6
moderate	27	21.8
moderate-poor	13	10.5
poor	48	38.7

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Post-fire vegetation succession in *Taxandria linearifolia* swamps in the northern jarrah forest of Western Australia

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ABSTRACT

The structural and floristic changes occurring with time since fire in *Taxandria linearifolia* swamps were investigated using chronosequence analysis. Sixty-six swamps in the northern jarrah forest of south-western Australia were investigated and the effect of fire on them was quantified. Habitat units were mapped from aerial photographs that were imported into a geographic information system. Field surveys were then conducted at each site to ground-truth mapped habitat units. Habitat units were differentiated using factor analysis. The vegetation within the swamps remained relatively open for the first five years following a fire while being largely dominated by three or four species. Thereafter, vegetation density increased to a peak between 20 and 24 years (>90%) and species richness from 10 to 14 (mean = 5.7 ± 0.4). Long unburnt *Taxandria* swamp shrubland habitat returned to intermediate vegetation density levels, although becoming increasingly woody, as relatively few species dominated. Such a response to fire probably reflects adaptations to the frequent, low intensity fire regimes utilised by Aborigines prior to European colonisation.

Keywords: chronosequence, fire regimes, floristics, succession, swamp shrubland, vegetation structure

INTRODUCTION

The effect of fire on jarrah (*Eucalyptus marginata*) forest communities has been studied in detail (Bell 1995; Burrows et al. 2003; Grant & Loneragan 1999; Hatch 1959; Wallace 1966). Jarrah is recognised as one of the most fire resistant eucalypts and is highly adapted to a fire-prone environment (Burrows et al. 1987). Low intensity fires assist in opening seed capsules and in minimising seed competition (Wallace 1966). Seedlings develop lignotubers and then lie dormant for ten to 20 years until an opening in the canopy, possibly caused by fire, enables a single shoot to develop (Wallace 1966). Adult trees develop bark up to four centimetres thick (Wallace 1966). Jarrah also exhibits dormant budding, epicornic shooting and a surge in growth rate in the first five years following a fire (Wallace 1966).

The *Taxandria linearifolia* swamp shrublands of Western Australia's jarrah forest are distinct communities (Havel 1975; Mattiske & Havel 1998) that form on alluvial soils in the broad, gently-sloping, upper reaches of creek systems (Mulcahy 1967; Mulcahy et al. 1972) in the wetter, western side of the jarrah forest (DCE 1980). On the basis of the tolerance to fire in the surrounding vegetation communities, we could assume that *T. linearifolia* swamps within the jarrah forest would be similarly tolerant. *Taxandria linearifolia* dominates swamps within the jarrah forest but is burnt back by fire before resprouting again.

Despite the amount of research into the effects of fire on the jarrah forest communities (Burrows et al. 2003), very little is known about the post-fire succession in these swamp shrublands. Consequently, the aim of this study was to examine the effect of fire on the *T. linearifolia* swamps of the northern jarrah forest.

METHODS

The 66 *T. linearifolia* swamps surveyed were situated within the northern half of the jarrah forest bioregion (Thackway & Cresswell 1995) in the south-west of Australia (Fig. 1). Sites were selected based on the presence of *T. linearifolia* across a range of environmental conditions in the region. Once selected, aerial photographs, provided as high-resolution images by the Western Australian Department of Land Administration (DOLA), were geo-referenced to GPS surveyed points and mapped using the MapInfo Professional Version 5.5 computer package (MapInfo Corporation Inc. 1985–1999). Visual examination of mapped vegetation units enabled different age classes within the swamps to be identified.

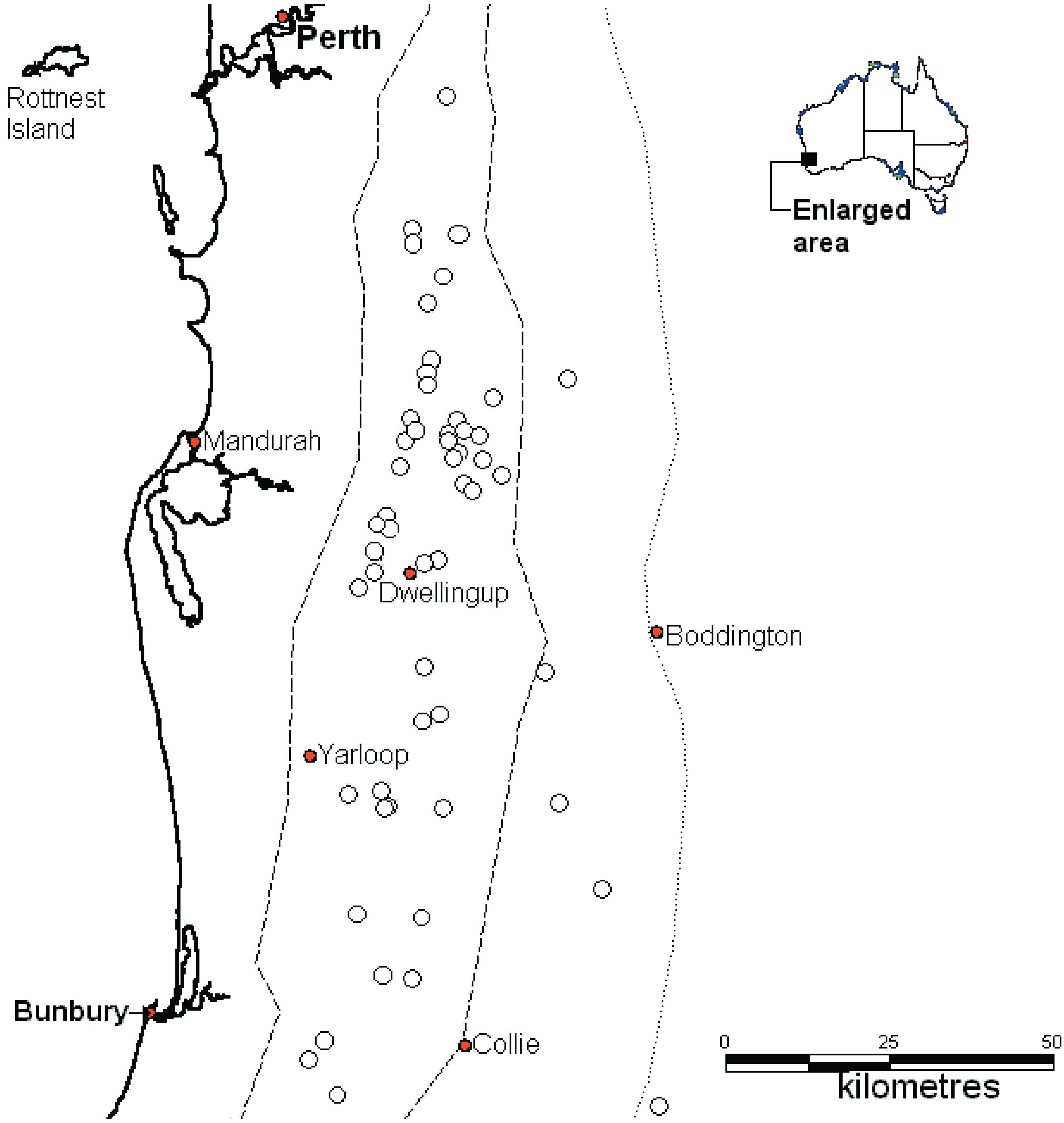

Figure 1. Map of the northern jarrah forest study region with the 66 study sites shown as open circles. The dashed line represents the 1,000 mm rainfall isohyet and the dotted line represents the 700 mm isohyet.

Vegetation units at each site were delineated, 'typed' and subsequently ground-truthed. Each 'typed' habitat unit was representatively sampled with between 5 and 40 quadrats which were determined by the frequency of each habitat units' occurrence (Fig. 2). Quadrats were located in the centre of each unit to minimise the influence of ecotonal features. The structure of each unit was determined by estimating the vegetation density at 0.1, 0.3, 0.5, 1.0, 1.5, 2.0, 3.0 and 5.0 m about ground level. Vegetation density was estimated using the Braun-Blanquet scale of stems covering a 1 m x 0.2 m coverboard held vertically (Braun-Blanquet 1932; Gauch 1986). Floristics at these sites were determined using a 2 m x 1 m quadrat for shrubs, sedges and grasses and a 10 m x 10 m quadrat for trees that was centred in the smaller quadrat. The percent cover of each species within and overhanging the quadrats was categorised according to the Braun-Blanquet scale. Species were identified according to Marchant et al. (1987a; 1987b) and nomenclature was based on the Western Australian Department of Environment and Conservation (DEC) FloraBase web site (http://www.naturebase.net/content/view/2452/1322/)

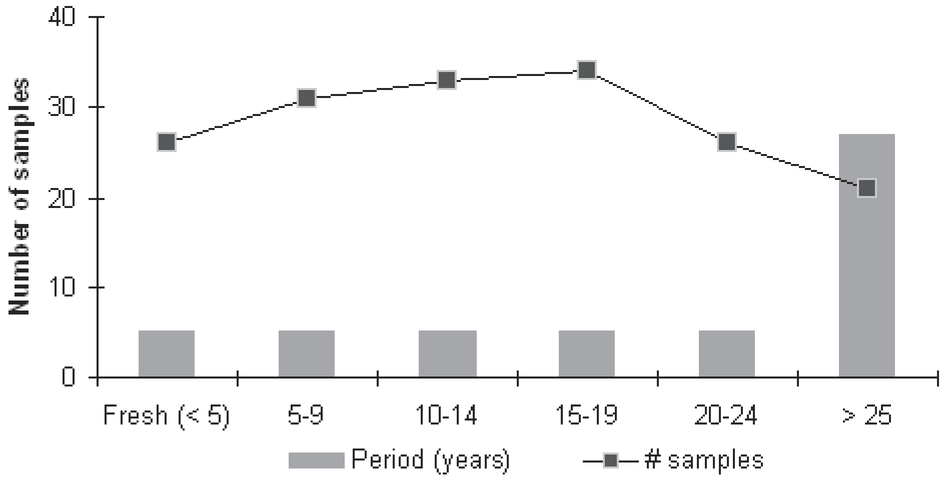

Figure 2. Number of samples and the period of years which they span for each age class within the Taxandria *swamp shrubland.*

Leaf litter depth was measured using a standard DEC litter depth gauge at three places within the 10 m x 10 m quadrat. We also recorded the number of stags (dead trees or shrubs); percent cover of bare earth and open water; the number of cut stumps and logs. The stags, cut stumps and logs were counted in 10 m x 10 m quadrats and the remainder were recorded in the smaller 2 m x 1 m quadrats. These habitat components are grouped hereafter as 'other habitat variables'.

The number of years since the last fire burnt each habitat unit (termed here as the age of the habitat unit) was estimated by counting growth rings on the *T. linearifolia* which has only one growth period per year (L. McCaw *pers comm.*[1]; Hayward 2002). A 240 mm straight pruning saw was used to cut the stems to provide a surface without the need for further preparation. These growth rings were validated by comparison with the known fire history of three sites (Hayward 2002). Growth rings at three sites were used for the comparison: the recently burnt Findlay Brook site (one growth ring in six months since a fire); the older Victor Road site (three to four rings in the three and a half years since a fire) and the Kesners site (ten to 12 rings in the 12 years since a fire). Where growth rings indicated more than one age present within a quadrat, the oldest age (largest ring count) was used.

Data analysis

Factor analysis was conducted on structural, floristic and other variables to differentiate *T. linearifolia* swamp age classes using the Statview Version 5.0 computer program (SAS Institute 1992–1998). Other habitat units within the swamps were differentiated using TWINSPAN (Hayward et al. 2005b), but are described here in more detail. Variables not conforming to the assumptions of normality and heterogeneity were normalised using square-root transformations (small counts) and arcsine transformations (percentages). Analysis of variance was used to determine the significance of differences between the factor scores of each habitat unit. Age classes that could not be differentiated in this manner were plotted on two dimensional factor plots to allow differentiation.

RESULTS

The flora of the *T. linearifolia* swamp shrublands studied in the northern jarrah forest comprised 57 plant species including one exotic weed species. The eight heights at which vegetation density was measured were reduced to four factors that explained 82.9% of the variation in the data (Table 1). The ten plant species used to differentiate the age classes of *T. linearifolia* swamps were reduced to five factors that explained 62% of the variation (Table 2). The six 'other habitat factors' were reduced to three factor scores that explained 52% of the variation in the data (Table 3).

Taxandria swamp shrubland habitat units were largely differentiated using individual factors with significant differentiation occurring on 13 out of 15 habitat type comparisons (Tables 4 and 5). Plotting of two factor scores from most structural and floristic factors allowed the separation of the two *Taxandria* age class comparisons that could not be statistically differentiated using individual factors. For example, structural factors two and three and floristics factors one and two differentiated between the 5 – 9 and 10 – 14 and the 20 – 24 and > 25 year old *Taxandria* swamp shrubland habitat units (Fig. 3 and Table 5).

High values in structural factor two relate to dense vegetation 2 – 3 m tall while high factor values in structural factor three relate to high density 1 – 2 m above ground level (Fig. 3 and Table 5). High factor values for floristics factor one relate to a high species cover of *Astartea fascicularis* while negative values relate to low cover of *Lepidosperma tetraquetrum* (Fig. 3). High factor score values for floristics factor two relate to high cover of *T. linearifolia* (Fig. 3).

The *Taxandria* swamp shrubland habitat units are

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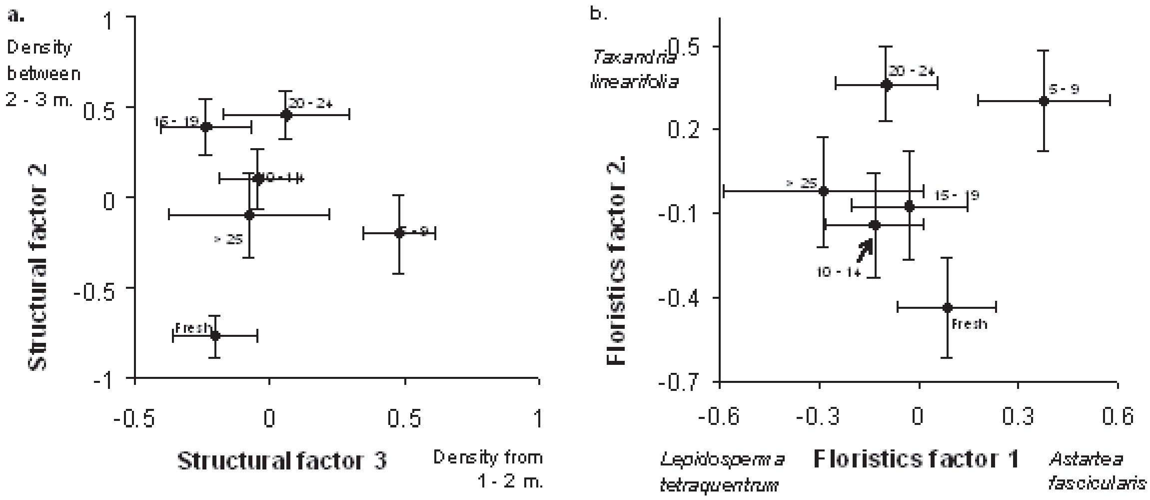

Figure 3. Factor score plots highlighting the differentiation between the 5–9 and the 10–14 year old and the 20–24 year old and long unburnt (>24 year old) Taxandria *swamp shrubland habitat units. a) Positive values of factor 2 relate to high vegetation density between 2–3 m above ground level while high values of factor 3 relate to high vegetation density between 1–2 m. b) Positive values of factor 1 relate to a high cover of* Astartea fascicularis *and negative values relate to a high cover of* Lepidosperma tetraquetrum. *High values of factor 2 relate to high cover of* Taxandria linearifolia.

generally similar in their species composition, all being dominated by *Taxandria linearifolia* with *Lepidosperma tetraquetrum* almost always dominating the ground layer. Other plant species present in these habitat units include *Hypocalymna cordifolium*, *Xyris lacera*, *Thomasia* species and the sedge *Gahnia decomposita*.

The early post-fire seral stage of the *Taxandria linearifolia* swamp was characterised by relatively low vegetation density (Figs 3 and 4) and dead stems (stags) of *T. linearifolia* (Fig. 5) that resprouted from lignotubers at the base of the plant. Very little leaf litter remained following the recent fire and the proportion of bare ground was high (Fig. 5). Species richness was very low. For the first four years following a fire *Lepidosperma tetraquetrum* and *Astartea fascicularlis* were among the few species that coexisted with *T. linearifolia*.

Between five and nine years following a fire the vegetation density at the ground layer increased (Fig. 4), as did species richness and litter depth (Fig. 5). The dead stags found in freshly burnt habitat were no longer present (Fig. 5). Between years 10 and 14 post-fire, species richness per quadrat reached a peak, leaf litter continued to develop and the amount of bare earth and number of stags declined (Fig. 5). Vegetation density at ground level reached an intermediate level, however vegetation density between 2 and 3 m increased substantially (Figs 3 and 4). By 15 to 19 years post-fire, species richness began to decline which continued until the long unburnt stage (Fig. 5). Vegetation density (Fig. 4) and leaf litter depth continued to increase (Fig. 5). Vegetation at ground level and between 2 – 3 m attained its highest density (Figs 3 and 4).

In long unburnt swamps (> 24 years since fire), vegetation density returned to a more intermediate level, akin to that between five and 14 years post-fire (Figs 3 and 4). Long unburnt swamps were almost completely dominated by a canopy of *Taxandria linearifolia,* which may reach up to 10 to 15 m, and *Lepidosperma tetraquetrum* in the ground layer. *Astartea fascicularis* is also occasionally present.

Also within the *Taxandria* swamp shrublands are habitat units dominated by bullich (*Eucalyptus megacarpa*) overstorey with the shrubs *T. linearifolia*, *Hypocalymna cordifolium*, *Thomasia* species and *Boronia molloyiae* interspersed with the sedge *Lepidosperma tetraquetrum.* This habitat unit has a high species richness (mean = 7.6 ± 0.7 s.e.).

Lepidosperma – Hypocalymna swamps are also found within *Taxandria* swamps and are low but densely vegetated (below 1.5 m) areas that lack the *T. linearifolia* dominated canopy. Instead *L. tetraquetrum* and *H. cordifolium* dominate these areas. Nonetheless, they are also relatively species rich with a mean number of species recorded per quadrat of 6.3 (± 0.7 s.e.).

Also within the *Taxandria* swamp are small pockets dominated by the swamp paperbark (*Melaleuca rhaphiophylla*). These areas exhibit relatively high floristic richness (m = 6.1 ± 0.5 s.e.) and the deep leaf litter implies they may require long periods without fire to develop.

Flooded gum (*Eucalyptus rudis*) woodland occurs in seasonally inundated areas when topography changes from the broad, flatter areas where the *Taxandria* swamps dominate to slightly steeper, narrower, more deeply-incised valleys along larger watercourses on the drier eastern side of the jarrah forest. To the more mesic western side of the jarrah forest, the steep-sided banks of larger rivers are dominated by *Grevillea diversifolia* and *Banksia littoralis.* The *Taxandria linearifolia* swamp shrublands in the northern jarrah forest are generally surrounded by open forest dominated by bullich and/or Western Australian blackbutt or yarri (*Eucalyptus patens*) on the lower slopes

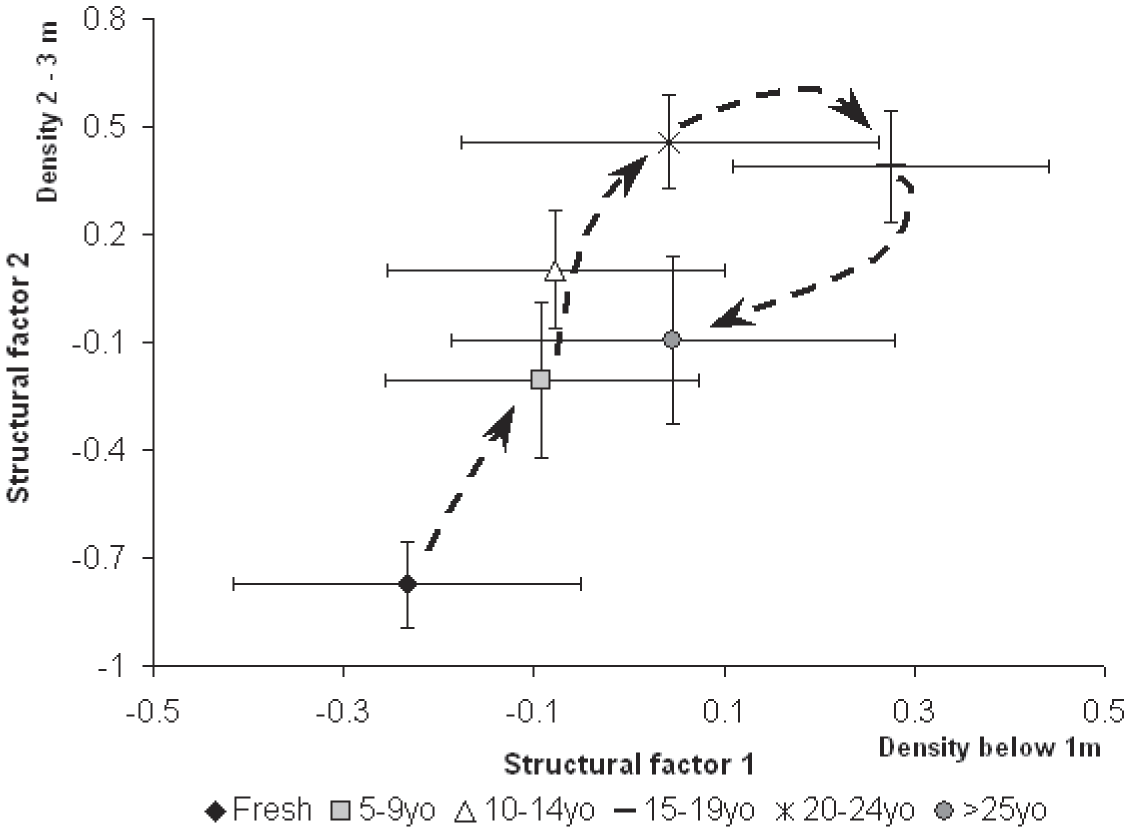

Figure 4. Relationship between structural factors one and two and the differentiation of Taxandria *swamp shrubland habitat units. The mean point is shown along with standard error bars. Positive values of factor one relate to dense vegetation below one m and high positive values of factor two relate to high density between two and three m. The arrows show the increase in vegetation density for both structural factors as time since fire increases until the 20–24 year age class, after which the vegetation structure returns to a more intermediate level.*

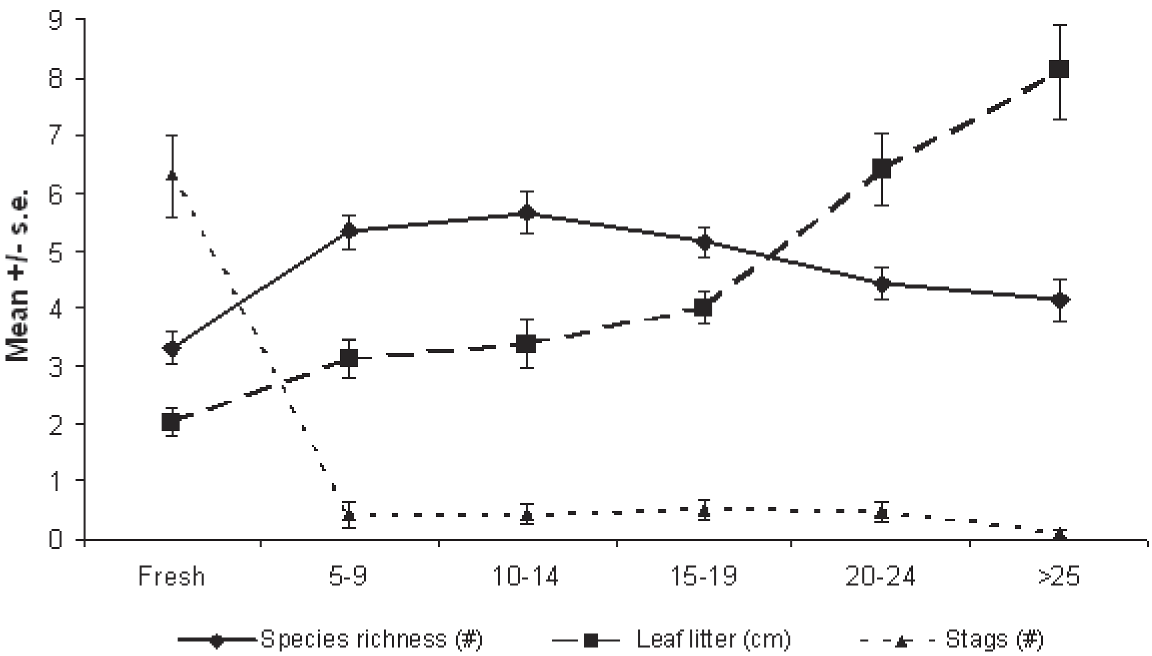

Figure 5. Relationship between mean (± s.e.) species richness per quadrat, leaf litter depth (cm) and the number of dead stems (stags) for each age class of the Taxandria *swamp shrubland habitat units.*

which give way to jarrah forest communities on the upper slopes and ridge tops.

Changes with age since fire within the Taxandria swamp shrubland

Increased time since fire results in a continuum of increased vegetation density below 1 m and between 2–3 m until 24 years when the structure opens out to a more intermediate level (Fig. 4). Initially the structural change reflected by increased density was detected at heights of 2–3 m but after 14 years the density below 1 m also increased.

DISCUSSION

The jarrah forest is susceptible to wildfire during the six hotter months of the year in normal conditions, however during drought it is considered possible for wildfires to occur throughout the year (Wallace 1966). Under Aboriginal fire regimes, much of the jarrah forest is thought to have burnt at low intensity every three to four years (but see Miller et al. 2007), except for wet areas such as swamps that escaped fire for longer periods (Burrows et al. 1995; Wallace 1966; Ward & Sneeuwjagt 1999). Jarrah is considered well adapted to fire (Wallace 1966) in conjunction with the surrounding flora (Gardner 1957). The *Taxandria* swamps also show characteristics that suggest they too have evolved to cope with such regimes.

The immediate impact of a fire on the vegetation within a swamp is major, but short-term and often unburnt patches result in a mosaic of age classes (Abbott 2000; Burrows & Friend 1998). Within a month, the *Taxandria linearifolia* resprouts and vegetation density increases. Plant species richness peaks between five and 19 years after a fire but is highest between ten and 14. There is a 3–5 year peak in species richness occurring after fires in the wider jarrah forest communities (Bell & Koch 1980), which is twice as frequent as that of the swamps, and is thereby illustrating evolution for a lower frequency of fire in the swamps. This pattern of species richness is not restricted to the jarrah forest and occurs in coastal woodland in eastern Australia where richness peaks around five years after a fire (Fox 1988). Floristically, as well as being species rich, the swamps less than 14 years after a fire appear more diverse (although not quantified) in that they have non-dominant plant species exhibiting higher percentage cover than older swamps which are dominated by one or two species.

Species richness in *Taxandria* swamps declines 14 years after a fire and this decline may begin to plane after 25 years. Again this pattern has been observed in other areas, however elsewhere there is an increase in species richness in long unburnt sites (Fox 1988). This reduction in species richness may reflect the long history of Aboriginal burning and lightning-caused fires in the jarrah forest.

Swamps over 25 years of age are characterised by a few, large *Taxandria* shrubs with a canopy at least 5 m high. The vegetation returns to a more intermediate density similar to 5–14 years post-fire. Species richness is also low with older swamps dominated by *T. linearifolia* and *Lepidosperma tetraquetrum* while any other species present generally occur at very low levels.

The trajectory of succession within the swamp based on structural density (Fig. 4) reflects similar trajectories occurring in other ecosystems (Fox 1988). Such trajectories have been applied to small mammal community succession in those same areas and these show similar behaviour where the community exhibits a circuit before returning to similar compositions at intermediary ages (Fox 1990). The mammal community inhabiting the *T. linearifolia* swamps probably behave in a similar fashion with variation in abundance caused by the succession of their habitat (Hayward et al. 2005b; Hayward et al. 2007). It may be such habitat requirements are a response to both predator-avoidance in the dense vegetation (Hayward et al. 2005a) and dietary requirements (Hayward 2005) but the frequent and low intensity fire regimes adopted by the Noongar Aboriginal people of south-west Western Australia (Abbott 2000; Burrows *et al.* 1995; Ward *et al.* 2001; Ward and Sneeuwjagt 1999) were probably conducive to maintaining a mosaic of successional stages.

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Table 1

Factor scores for the vegetation structural factors used to differentiate age classes within *Taxandria linearifolia* swamps and the variance they explained. Variables explained by each factor are illustrated in bold.

Variable	Factor 1	Factor 2	Factor 3	Factor 4
Density at 10 cm	**0.870**	0.080	-0.023	0.097
Density at 30 cm	**0.934**	0.025	0.175	0.043
Density at 50 cm	**0.772**	-0.035	0.475	-0.010
Density at 1 m	0.333	0.016	**0.856**	0.061
Density at 1.5 m	0.046	-0.095	**0.877**	-0.116
Density at 2 m	-0.024	0.445	0.427	**-0.557**
Density at 3 m	0.076	**0.938**	-0.110	0.017
Density at 5 m	0.090	0.068	0.037	**0.943**
Variance explained	37.5%	20.2%	14.9%	10.3%

Table 2

Factor scores for the floristic factors used to differentiate age classes within *Taxandria linearifolia* swamps and the variance they explained. Variables explained by each factor are illustrated in bold.

Variable	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Agonis linearifolia	0.010	**0.800**	0.068	0.010	-0.046
Aotus cordifolia	-0.053	-0.075	-0.095	**0.653**	-0.187
Astartea fascicularis	**0.877**	0.037	-0.009	-0.047	-0.011
Boronia molloyiae	0.209	-0.419	0.031	-0.102	**0.559**
Dampiera hederacea	0.307	0.290	**0.629**	-0.203	0.041
Hypocalymna cordifolium	-0.160	0.056	-0.133	-0.051	**0.720**
Lepidosperma tetraquentrum	**-0.493**	0.392	0.114	-0.247	0.360
Thomasia paniculata	-0.237	-0.063	**0.719**	-0.081	-0.243
Thomasia pauciflora	0.021	0.117	**-0.496**	**-0.562**	-0.313
Xyris lacera	0.135	0.425	-0.245	**0.639**	-0.020
Variance explained	15.0%	13.7%	12.6%	10.7%	10.0%

Table 3

Factor scores for the other habitat factors used to differentiate age classes within *Taxandria linearifolia* swamps and the variance they explained. Variables explained by each factor are illustrated in bold.

Variable	Factor 1	Factor 2	Factor 3
Species richness	0.066	**-0.858**	-0.016
Leaf litter	**-0.719**	0.060	0.301
Stags	**0.651**	0.364	-0.034
Logs	-0.075	-0.083	**0.900**
Open water	0.160	**0.612**	-0.010
Bare earth	0.678	-0.022	0.242
Variance explained	22.9%	15.8%	13.3%

Table 4

Comparisons between the various age classes of the *Taxandria* swamp shrubland habitat types based on ANOVA. The individual comparisons using Scheffe's test are shown in Table .

Factor	$F_{5, 165}$	Probability
Structural factor 1 (SF1)	0.914	0.4736
Structural factor 2 (SF2)	6.491	< 0.0001
Structural factor 3 (SF3)	2.148	0.6230
Structural factor 4 (SF4)	21.098	< 0.0001
Floristics factor 1 (FF1)	1.453	0.2080
Floristics factor 2 (FF2)	2.509	0.0321
Floristics factor 3 (FF3)	3.345	0.0066
Floristics factor 4 (FF4)	0.385	0.8589
Floristics factor 5 (FF5)	8.597	< 0.0001
Other habitat factors 1 (OF1)	31.108	< 0.0001
Other habitat factors 2 (OF2)	6.962	< 0.0001
Other habitat factors 3 (OF3)	1.228	0.2718

Table 5

Identification of the factors used to differentiate between the *Taxandria* swamp shrubland habitat units. The factor that differentiated each habitat unit is presented along with the Scheffe's post-hoc test significance level. The factors used were structural (SF1, SF2, SF3, SF4), floristic (FF1, FF2) and other habitat variables (OF1, OF2). A cross (X) signifies there was no direct differentiation possible between habitat units and so plots of two factor scores were subsequently used (Fig. 3).

Habitat unit	Fresh	5–9 years old (y.o.)	10–14 y.o.	15–19 y.o.	20–24 y.o.	> 25 y.o.
Fresh	–					
5–9 year old	OF1 [%] OF2 [%]	–				
10–14 year old	SF2 * OF1 * OF 2 *	X	–			
15–19 year old	SF2 [%] FF5 [%] OF1 [%] OF2 [%]	SF4 [%] FF5 [%]	SF4 [%] FF5 [%]	–		
20–24 year old	SF2 [%] OF1 [%]	SF4 * OF1 [%]	OF1 *	FF5 *	–	
> 25 year old	SF4 [%] OF1 [%]	SF4 [%] OF1 [%]	SF4 [%] OF1 [%]	SF4 [%] FF5 [%] OF1 [%]	X	–

* significant at less than 0.05 level.
[%] significant at less than 0.01 level.

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Towards monitoring rock-wallabies on Barrow Island, Western Australia

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ABSTRACT

The Black-flanked Rock-wallaby *Petrogale lateralis lateralis* is difficult to trap consistently on Barrow Island because of the prevalence of Common Brushtail Possums *Trichosurus vulpecula* and Golden Bandicoots *Isoodon auratus* in and near its shelter habitat. Three possible methods of monitoring were trialed: daytime searching, spotlighting and dusk watching. Daytime searching produced the best results, although numbers seen were low and varied between searches. In November 2004, 37 rock-wallabies were sighted during the first search of each 'site' and in August 2005, 43 were sighted. Repeated counts will be needed to demonstrate whether daytime searching could be used as a standard monitoring method. No estimate of the total population was possible, but it is clearly very small, consistent with previous research showing unprecedented low levels of genetic variation.

INTRODUCTION

The Black-flanked Rock-wallaby *Petrogale lateralis lateralis* is a listed threatened taxon under Western Australian and Commonwealth legislation. A formerly widespread distribution in the western deserts (Great Sandy, Little Sandy and Gibson, although the subspecies/race status of some of these populations is unclear), western and southern Pilbara, Cape Range and the south west of Western Australia has shrunk to a few isolated populations, largely due to predation by the introduced European Red Fox (*Vulpes vulpes*) (Burbidge et al. 1988; Kinnear et al. 1988; Pearson 1992; Pearson & Kinnear 1997; Kinnear et al. 1998). Historically, *P. l. lateralis* occurred on three offshore islands: Depuch and Barrow in the Pilbara and Salisbury in the Southern Ocean off Cape Arid (Abbott & Burbidge 1995; Pearson & Kinnear 1997). The invasion of Depuch Island by foxes in the first half of the 20th Century led to that population becoming extinct (Hall & Kinnear 1991; Pearson & Kinnear 1997). The Salisbury Island population is extant.

P. lateralis is the least abundant of the mammals occurring on Barrow Island. Two population estimates are available. Butler (1970, p. 154) stated 'I estimate there are 500+ individuals in the multiple cliff colonies which extend over some eight miles of coast and in places go two miles inland'. Hall et al. (1993) provided an estimate of 116 to 154 based on searching, trapping and spotlighting during one week in late February and early March 1993. Hall and Kinnear (1991, p. 6) in a draft recovery plan for *P. l. lateralis* stated that the subspecies was 'conspicuously abundant in suitable habitat, which is of restricted distribution'.

Barrow Island, despite being a nature reserve, has had an operating oilfield since the 1960s and the construction of a liquefied natural gas plant is proposed. Recent monitoring of mammal populations on Barrow Island by the Department of Environment and Conservation (DEC) and Chevron Australia (e.g. Burbidge et al. 2003) has concentrated on species that are captured in Sheffield cage, Elliott Type A or pit-fall traps, or that are readily detected by observers with hand-held spotlights from vehicles at night. *P. lateralis* is not consistently detected by any of these techniques and methods of monitoring this species need development. Attempts were made to trap rock-wallabies within and adjacent to their daytime shelter habitat on the west coast of the island; however, the prevalence of other mammals, particularly Common Brushtail Possums (*Trichosurus vulpecula*) and Golden Bandicoots (*Isoodon auratus*), in this habitat meant that while rock-wallabies were occasionally trapped, most traps captured possums early in the evening. The collection of reliable trap data with repeated recaptures, allowing mark-and-recapture population estimates, seemed unachievable during short duration monitoring visits. As well, adequate sampling of the linear shelter habitat would be problematical, as access to many shelter sites in steep and crumbling limestone cliffs is difficult and dangerous.

Conservation biologists are often presented with requests for quick, relatively cheap answers to conservation-related questions. Developing monitoring procedures for rock-wallabies on Barrow Island is one such example – neither the State conservation agency nor the oil company have biologists allocated primarily to monitoring mammals on Barrow Island and working on the island is expensive; yet rock-wallaby monitoring has been identified as important. This paper reports attempts to develop a basis for monitoring techniques where field time is limited, and discusses how best to proceed towards a monitoring method that can report on rock-wallaby relative abundance at selected time intervals.

There have been only limited studies on the biology and ecology of *P. lateralis*. Research in the southwest of Western Australia showed that breeding commences at

18 months and that some individuals may live longer than 12 years (Kinnear et al. 1988). Pearson (1992) reported that, in central Australia, *P. lateralis* 'MacDonnell Ranges race' was capable of moving long distances between rock outcrops, with Aboriginal informants reporting tracks up to 4 km from the nearest rockpile. In central Australia, there has been research on the diet, dietary competition with stock and euros and ranging behaviour of the related taxon, *P. lateralis* MacDonnell Ranges race (Blackbourn 1991; Capararo 1994).

METHODS

Short visits were made to Barrow Island in November 2003, November 2004 and August 2005 to trial three non-trapping methods of measuring rock-wallaby relative abundance:

- daytime searching of shelter habitat,
- dusk watching, and
- night time spotlight transects.

During the 2003 visit, only night time spotlighting was conducted. In the 2004 visit all three monitoring techniques were trialed and the first two were repeated in 2005.

Daytime searching

All prospective shelter habitat on and near the west coast was visited by two (occasionally three) people from 2–9 November 2004. To see whether more rock-wallabies would be sighted at a cooler time of the year, this method was repeated by two people from 3–10 August 2005. Search methods depended on the local topography: where possible one person walked below the cliff or scree while the other walked on the plateau above. Where topography prevented access below the cliff top, both persons walked near the cliff edge and, when safe to do so, looked below the cliff top. Search 'sites' were defined arbitrarily and marked onto colour air photographs (1:15 000, 7 August 1980). Digital copies of the air photographs with the sites marked on them are available in Burbidge and Thomas (2005) lodged in the Department of Environment and Conservation Western Australia, Wildlife Science library.

In 2004, all sites from Obe's Beach (20°42'25"S, 115°24'17"E) to Biggada Creek (20°46'52"S, 115°20'48"E) were visited twice. Areas north of Obe's Beach and south of Biggada Creek were visited once, as these areas showed little or no sign of rock-wallaby activity, as evidenced by the presence of only a few, scattered, mainly old scats, or none at all. In 2005, two searches were made of 'sites' south of Biggada Creek as far as Boggs Beach (20 47'30"E, 115 20'15"E). Searching commenced as soon as there was sufficient light to safely see when walking; this was usually at or near local sunrise. More effort was put into searching in the morning. Searchers left the search area at about 1130 hrs and restarted searching at about 1300 hrs; however, on some days searching did not recommence until about 1500 hrs. Searching ceased at about 1700 hrs. The time a rock-wallaby was first sighted was recorded only in 2005.

Because more rock-wallabies were usually sighted early in the morning (from about 0700 to about 1030 hrs), areas that were first searched late in the morning or during the afternoon were revisited in the early morning.

Dusk watching

At the isolated colony near Well Q21 (20°46'36"S, 115° 22'24"E, Site 27), we watched for rock-wallabies emerging from shelter to feed in the late afternoon and evening. On 7 November 2004 four people sat 150–200 m below the cliff face and watched from 1615 to 1900 (local sunset was at 1831 hrs), using 10x40 binoculars and a 20x–40x spotting telescope. On 8 November two people watched from the same position and one person watched from above the cliff from 1620 to 1900. This method was repeated on 4, 5 and 7 August 2005 by two people watching from below the cliff from 1600, 1625 and 1700 hrs respectively until 1825 by when it was too dark to see (local sunset was at 1801 hrs).

Spotlighting transects

Night time spotlight traverses were walked by two people along transects established during daytime in November 2003 and stored as 'routes' in a hand-held GPS receiver. One person carried a sealed lead acid battery on a backpack frame plus a 75 W spotlight, while the other, who walked immediately behind the spotlighter, navigated using the GPS receiver and where necessary identified any animals sighted with 10x40 binoculars. Two routes were walked: one from John Wayne Country (20°45'20"S, 115°21'55"E) to the coastal termination of a track passing well YS88 at 20°44'23"S, 115°22'56"E (ca 2.5 km long) and the other from above the Boodie Warren Cave (20°43'30"S, 115°23'26"E) to the headland just south of Obe's Beach (ca 2.0 km long). Walking time was 70–90 mins. Both transects were located a short distance inland from coastal cliffs (the northern transect) or cliffs with a narrow sandy coastal plain below (the southern transect); however, the southern transect also crossed white sand behind beaches and orange sand below cliff faces. The transects were walked south to north and searching commenced 30 minutes after local sunset. Search dates are given in Table 2. The habitat was recorded for all rock-wallabies sighted.

RESULTS

Daytime searching

Rock-wallabies were located in or near suitable shelter habitat from the headland immediately south of Obe's Beach south to near Boggs Beach, a distance of 11.2 km. Most sites where rock-wallabies were observed were very close to the coast; however, some sites south of Flacourt Bay (Site 17) and in and near John Wayne Country (Sites 19 to 22) and one site inland from Boggs Beach (Site 33)

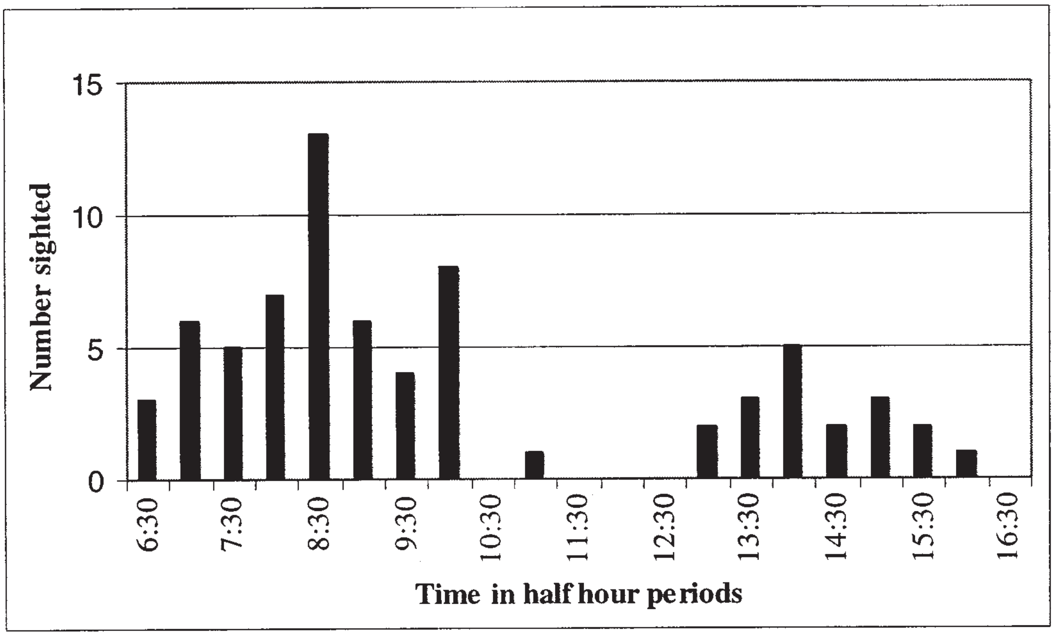

Figure 1. Number of rock-wallabies sighted in August 2005 in half-hour periods from 6:30 am to 4:30 pm. Note qualifications in text concerning searching times.

extended inland from 0.3 to 0.8 km. Rock-wallabies also shelter at an isolated cliff immediately southwest of Well Q21 (Site 27), 2.3 km from the west coast.

Table 1 shows the number of rock-wallabies recorded in each 'site' for each year for the two searches. Numbers seen were low and varied between searches. The total seen during the first search of each site was 37 in 2004 and 43 in 2005. The sum of the numbers seen during the first morning count was 50 in 2004 and 40 in 2005. The sum of the higher number of the two searches of at each site is 55 in 2004 and 50 in 2005.

Figure 1 shows the frequency of rock-wallaby sightings against the time of day in 2005. Searching effort was not uniform throughout the day (see Methods); but was similar between morning (about 0645 to 1130) and afternoon (about 1500 to 1700) on an intensity per hour basis. Even though effort was not uniform at all times of the day, Figure 1 suggests that more wallabies were sighted in the early morning (from about 7:00 am to 10:30 am) than immediately after dawn, in the late morning or in the afternoon.

Spotlighting

Table 2 shows the results of the spotlight traverses, as well as the wind and moon conditions prevailing during surveys. Numbers seen varied from zero to ten on the northern route (0 to 4/km) and from zero to three (0 to 1.5/km) on the southern route. Places where rock-wallabies were sighted were: among white sand dunes behind beaches among *Spinifex longifolius* (a rock-wallaby, possibly the same individual, was seen on consecutive nights feeding on *Cynanchum floribundum* growing among *S. longifolius*), a short distance inland among *Triodia*, and near the cliff edge with no vegetation.

Dusk watching

Five rock-wallabies were seen leaving shelter at the Q21 colony on the evening of 7 November 2004: at 1650, 1755, 1812, 1820 and 1838 hrs. On 8 November 2004 two rock-wallabies were sighted at 1725 and the same two were seen later. In 2005, two rock-wallabies were seen leaving shelter at 1800 and 1801 hrs on 5 August. No rock-wallabies were sighted on the other two nights.

DISCUSSION

Dusk watching did not produce useful results at the one site where it was trialed and the number of places where it could be used is limited. It does not appear to be a useful monitoring method.

Spotlighting also does not appear to be a useful monitoring method. When the same areas were compared, even the highest spotlighting total was lower than the number of rock-wallabies sighted during daytime searching. The spotlighting transects were located close to where rock-wallabies emerge from shelter and where they would be sighted if they moved inland to feed. Once rock-wallabies leave shelter they have been observed to move some distance inland, or in the case of the southern transect, also move towards the coast, and would not be detected by spotlighting. Daytime searching permitted all areas with shelter to be searched; this was not the case with spotlighting as some areas are too dangerous to walk at night. Spotlighting also did not produce consistent results.

Daytime searching, while locating rock-wallabies throughout almost all utilized shelter habitat on Barrow Island, resulted in low and variable numbers of animals at each 'site', making the development of standardized monitoring techniques difficult. Because of the low density of rock-wallabies and because their shelter habitat is spread over a long, narrow strip of the island, it appears to offer a better monitoring technique than other trialed methods. However, the low numbers seen prevents the use of the daytime searching technique as a reliable monitoring method without further work. Whether it is valid to add the numbers seen on the first and second searches, or total the larger number seen during the two searches can not be discussed without further information on the site fidelity and home ranges displayed by these rock-wallabies. Work in central Australia on the closely related taxon, *P. lateralis* MacDonnell Ranges race, found that most foraging activity occurred within 100 m of their rocky refugia based on the distribution of faecal material. In summer, they ranged slightly further, but not beyond 200 m from shelter (Blackbourn 1991, Capararo 1994). Mainland populations are subject to predation by foxes and dogs which may also alter behaviour. Given the lack of these predators on Barrow Island and the apparently higher levels of grazing competition with other mammals (pers. obs.), it could be hypothesized that Barrow Island rock-wallabies forage further from their refugia. Observations of rock-wallabies 1.4 km from cliff habitat during road spotlight transects (AA Burbidge & KD Morris, unpublished data), suggests this is likely.

During daytime searching, many of the wallabies sighted were flushed from low clumps of figs (*Ficus brachypoda* and/or *F. virens*) growing immediately below cliffs, on the slope below cliffs or, occasionally, just above cliffs; some were sighted among large rocks just below cliffs; some were seen in rockpiles at the base of slopes below cliffs, often very close to the ocean, and a few were first seen in the open above the cliff. On the west coast of Barrow Island, fig clumps provide the only dense, shaded shelter apart from rocks.

The aim of this study was to aid the development of a method for monitoring rock-wallabies on Barrow Island, not to provide an estimate of the total population. The method described as 'daytime searching' could provide a technique for monitoring relative abundance, and standardized monitoring methodology has been prepared and made available for future workers. However, in order to show that the technique could be used for detecting population trends, many further counts need be carried out.

Hall et al. (1993) sighted 38 animals in February–March 2003 and gave an estimate of the total population on Barrow Island of 116 to 154. This was derived by assuming that between 25% and 33% of the total population was sighted, a correction factor based on work by Kinnear and others (unpublished, cited in Hall et al. 1993) on isolated granite rocks in the southwest of Western Australia, where repeated trapping and spotlighting had been conducted. It is doubtful whether this correction factor can be validly applied to Barrow Island, where conditions and habitat are different.

There are two lines of evidence for an assumption that we did not sight all animals present within an area. Firstly, different numbers were often seen in one site when conducting the two searches. Secondly, in November 2004, dusk watching revealed five rock-wallabies in Site 27 (the isolated inland cliff near Well Q21), while only a single animal was sighted on each of the two daytime searches that year. It seems likely that some rock-wallabies were sheltering in deep, well-protected locations and did not move when we walked nearby.

Elsewhere, rock-wallabies tend to bask in the sun more in cool weather than in hot weather (Lim et al. 1992), and anecdotal information suggested that this is the case on Barrow Island. If this is the case, searches in winter should result in more rock-wallaby sightings than in early summer. The similar number of rock-wallabies sighted during August 2005 compared with November 2004 suggests that daytime temperatures do not greatly affect the number of animals sighted. However, November maximum temperatures are not high on Barrow Island compared with mainland sites at the same latitude. The mean maximum temperature during our visit in early November 2004 was 28.8°C compared with the long-term monthly average of 31.6°. The hottest month on Barrow Island is March with a mean maximum temperature of 34.7° and a highest recorded temperature of 44.0°. Barrow Island, with its tropical maritime climate, does not have very low winter minimum temperatures like inland desert areas on the mainland and these higher minima may reduce the tendency to bask in winter.

Local conditions may affect daytime searching. We had several cloudy days with strong winds, particularly during the mornings of 7–9 August 2005 when fresh to strong and gusty easterly winds prevailed. Fewer rock-wallabies were sighted at these times, but with low sighting figures overall no trends could be detected. Many more searches would be necessary to detect any relationship between weather and sightability.

A white-bellied sea-eagle (*Haliaeetus leucogaster*) nest with two small chicks was located in Site 22 in August 2005. No rock-wallabies were seen at the 'site' during the two searches. A single animal was seen at the extreme northern end of this site later after searching Site 21. In 2004, the maximum count for Site 22 was seven. Whether the rock-wallabies inhabiting this area in 2004 moved to another nearby site, whether they were sheltering out of sight of the eagles (and us) or whether they had been predated, is not known; however, it is likely the lack of rock-wallaby sightings near the nest can be attributed to the presence of the eagles. There were no rock-wallaby remains at the nest; only a Wedge-tailed Shearwater *Puffinus pacificus*, despite evidence that sea-eagles do take mammals of this size elsewhere (Marchant & Higgins 2003), although birds are a more important food item.

Overall, a very low number of rock-wallabies was sighted. This figure suggests a very small total population on Barrow Island. Eldridge et al. (1999, 2004) reported that the Barrow Island population of *P. lateralis* has unprecedented low levels of genetic variation and suffers from inbreeding depression (reduced fecundity, skewed sex ratio, increased levels of fluctuating asymmetry) and a small effective population size. Nevertheless, this population has survived a long period of isolation (*ca* 1600 generations).

CONCLUSIONS

Monitoring small wild animal populations is particularly difficult when a high proportion of the population can not be captured, marked and recaptured. The 'daytime searching' method described here may present an opportunity to develop relative abundance data between visits. However, many more searches will be necessary to ensure repeatability. Future work needs to take account of the time of year, time of day, number of repeat counts per trip needed to produce consistent data, and observation methods (number of observers, routes, walk speed and time spent in shelter habitat all need to be recorded to provide sightings/per unit time data). Standard routes may need to be documented and recorded.

Short term, low cost, reliable monitoring of rock-wallabies on Barrow Island seems not to be possible. As well as the need for many replicated counts, data on home range and whether animals move between the 'sites' designated during this study, are desirable.

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Table 1

Number of rock-wallabies sighted in defined 'sites' at Barrow Island Nature Reserve

Site No.	Nov 2004 search 1	Nov 2004 search 2	Nov 2004 first AM count	Aug 2005 search 1	Aug 2005 search 2	Aug 2005 first AM count
1	1	0	1	0	0	0
2	0	1	0	2	0	2
3	3	2	3	2	1	2
4	1	0	1	0	0	0
5	2	1	2	0	0	0
6	1	0	1	1	0	1
7	0	0	0	2	0	2
8	1	0	1	1	0	1
9	0	1	0	0	0	0
10	1	2	2	1	0	0
11	0	0	0	0	0	0
12	2	2	2	5	3	3
13	0	0	0	0	0	0
14	1	1	1	0	0	0
15	2	3	3	2	1	1
16	1	3	3	1	0	0
17	2	0	2*	4	1	1
18	1	1	1	1	0	1
19	2	2	2	4	2	4
20	4	2	4	0	0	0
21	4	4	4	8	5	8
22	1	7	7	0	0	0
23	1	7	7	3	8	8
24	2	2	2	1	2	2
25	1	0	0	1	1	1
26	2	0	0	0	0	0
27	1	1	1	1	2	2
28	0	–	0	0	0	0
29	0	–	0	0	0	0
31	0	–	0	1	0	0
30	0	–	0	0	0	0
32	0	–	0	1	0	1
33	–	–	–	1	0	0
Total	37	42	50	43	26	40

'–' designates that a site was not searched
* site searched once in 2004, in the afternoon

Table 2

Results of spotlighting traverses on the west coast of Barrow Island.

Date	No. of rock-wallabies sighted	Wind	Moon
Southern traverse			
24 October 2003	0	W, 25–30 knots	none
2 November 2004	2	SW, 5–10 knots	none
4 November 2004	10	W <3 knots	none
Northern traverse			
29 October 2003	3	W, 25–30 knots	1^{st} quarter, moonset at 10.41 pm
3 November 2004	3	SW, 10–15 knots	none
6 November 2004	0	W, 5 knots	none

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Improved bait and trapping techniques for chuditch (*Dasyurus geoffroii*): overcoming reduced trap availability due to increased densities of other native fauna

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ABSTRACT

The populations of several native medium-sized mammals have increased in abundance in response to an extensive fox control program in southwestern Australia. In particular, the woylie (*Bettongia penicillata*), established sufficient densities in some forest areas between 1996 and 2005, that they saturated the traps used in several long-term monitoring studies. As a consequence, less abundant and/or less readily caught species were likely to be excluded from traps and may have been inadequately represented in surveys.

In a series of comparative trials within several Western Australian native jarrah (*Eucalyptus marginata*) forests, this study tested an alternative lure for cage-traps that could be used in the presence of abundant woylies to improve capture rates of chuditch, *Dasyurus geoffroii*, and possibly other native vertebrates.

Compared with 'universal bait' (peanut butter and oat-based), the 'chuditch bait' (meat meal and fish oil-based) increased chuditch capture rates up to 800% by reducing woylie capture rates by about 50% or more: the species diversity and capture rates of several other vertebrates were also greater. Other associated trapping techniques to improve chuditch survey efficiency are also discussed.

INTRODUCTION

The chuditch (*Dasyurus geoffroii*: Family Dasyuridae) is the largest native carnivorous marsupial in Western Australia: adult males weigh 1175–2075 g and adult females weigh 705–1285 g (Serena & Soderquist 1995). As opportunistic nocturnal hunters, chuditch feed largely on small mammals, birds, reptiles and invertebrates but also consume some fruits, food scraps and carrion (Soderquist & Serena 1994). Early records suggest that the chuditch occupied a diverse range of habitats within a former distribution that covered much of the Australian continent, from Western Australia to western areas of Victoria, New South Wales and Queensland (Ride 1970; Serena et al. 1991). Since European settlement its distribution has substantially declined such that since the 1970s it has been largely confined to the southwest corner of Western Australia. By the late 1980s the conservatively-estimated 6000 individuals remaining in the wild were largely confined to the jarrah forests of southwestern Australia (Serena et al. 1991). In 1983 the species was listed under the WA *Wildlife Conservation Act 1950* as threatened and in 1991 it was listed as Endangered under the Commonwealth *Endangered Species Protection Act 1992*. A recovery plan for the species was prepared and implemented in 1992 (Orell & Morris 1994).

The decline of many species of native mammals, including the chuditch, was thought to be attributed in part at least to the introduction of the European red fox (*Vulpes vulpes*) (Burbidge & McKenzie 1989). A broad-scale fox control program was established in southwestern Australia after a series of studies demonstrated that with fox control, populations of many species of native mammals, including the chuditch, increased significantly (Friend 1990; Kinnear 1990; Kinnear et al. 1988; Morris et al. 1998, 2003). The 'Western Shield' fauna recovery program, initiated by the Western Australian Department of Conservation and Land Management (CALM, now Department of Environment and Conservation DEC), uses dried meat or sausage baits containing the toxin sodium monofluoroacetate (1080) to control fox numbers (Bailey 1996). This toxin occurs naturally in Western Australian endemic legumes in the genus *Gastrolobium*, and native fauna has evolved enhanced tolerance to 1080 (King et al. 1978, 1981, 1989; Mead et al. 1979). Introduced species such as the red fox, however, have very low tolerances to 1080 (McIlroy 1981; McIlroy & King 1990). Fox populations are now controlled in this manner on approximately 3.5 million hectares of DEC–managed land (Wyre 2004). This conservation program has resulted in population increases of several native species (Orell 2004). Three species, the woylie (*Bettongia penicillata*), quenda (*Isoodon obesulus*), and tammar wallaby (*Macropus eugenii*), recovered to such an extent that they were removed from the State and Commonwealth threatened fauna lists (Morris et al. 1998; Start *et al.* 1998).

The recovery of populations of medium-sized mammals within southwestern Australia has resulted in a unique challenge for researchers attempting to survey less common species such as the chuditch. In the period 1996 to 2005 within many forest systems the fox control program resulted in a dramatic increase in the density of medium-sized mammals. For example, within Kingston State Forest the trap success rates for mammals (all species combined) were less than 10% in 1992. Fox control began in 1993 and the corresponding increase in native mammals resulted in trap success rates greater than 70% since 1998 (Morris et al. 2001; Wayne unpublished data). The majority of these captures were woylies resulting from increased densities and their ease of capture. Trap saturation (i.e. greater than about 60% capture rate) and interference by animals reduces trap availability to less abundant species such as the chuditch. Similar problems have been encountered with other medium- to long-term studies within other jarrah forest sites such as at Batalling (Morris et al. 2003) and Perup (Burrows & Christensen 2002).

With the success of the Western Shield fox-baiting program, the problem of trapping rarer species in the presence of woylies may expand. Simply placing a greater density of traps than the density of woylies, to ensure that some traps remain available for other species incurs logistic and economic challenges that make this strategy impractical. This paper describes a trap-bait trial that sought to overcome this problem. The objective of this trial was to find an alternative lure that is less attractive to woylies than the extensively used 'universal bait', but provides a greater potential for capturing chuditch and possibly other less abundant native mammals.

MATERIALS AND METHODS

Kingston Study Area

Initial bait trials were conducted in Kingston, Winnejup and Warrup State Forests, 25 kilometres north-east of Manjimup, Western Australia. These field trials were conducted in association with the 'Kingston Project', a large-scale study into the impacts of timber harvesting and associated activities on the vegetation and fauna of the jarrah forest (Morris et al. 2001). The study area is approximately 15,000 hectares of open forest and woodland dominated by jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*). The area lies in the transition between high-quality and low-quality forest (Abbott & Loneragan 1983) within the intermediate rainfall zone (annual rainfall approximately 900 mm) and on primarily lateritic soils with deeper loams and sands lower in the valley profiles. Selective high quality jarrah timber harvesting was conducted in the area in the 1920s and during the 1940s to 1970s (Heberle 1997). Shelterwood creation and gap release harvest treatments (Stoneman et al. 1989) were also conducted within the area between 1994 and 1997. Fox control using 1080 impregnated dried meat baits has been maintained within the study area and surrounding forests using standardised baiting methods since 1993 (Morris et al. 2001).

Trapping trials of the alternative bait were conducted using 36 kilometres of road transects established for the Kingston Project (Morris et al. 2001). Sheffield wire cages (20.5 cm wide, 20.5 cm high, 55 cm deep; Sheffield Wire Co., Welshpool WA) were individually spaced 200 metres along these transects, and covered with thick hessian to protect trapped animals from weather exposure. The road transects were separated into two groups: northern transects (92 traps) and southern transects (88 traps). The shortest distance between the northern and southern transect traps was greater than two kilometres but was generally greater than five kilometres.

The principle of using a meat-based bait to catch chuditch had previously been used by Serena and Soderquist (1989) who used traps baited with raw meat or a mixture of peanut butter, tinned pet food, tuna and dried fish meal. The same authors also used similar bait variants on other occasions (e.g. Soderquist & Serena 2000). After we experimented with ingredients an alternative meat-meal based bait was developed along the same principles. Bait development criteria included it being primarily meat-based and practical considerations such as the ready supply and storage of ingredients, ease of bait preparation, bait longevity in the traps and ease of presentation (i.e. no packaging or containment required, suitable for hanging off trap 'hooks' to avoid soiling and reduce ant problems, etc). The final recipe used in these trials was as follows:

'Chuditch Bait'

3 kg	Dried meat meal (53% crude protein, 14.2–20.2% crude fat, 6.8–9.9% phosphorus, 5.9–9.2% calcium, 1.1% crude fibre, and 0.7–0.85% salts).
750 g	Sardines
500 mL	Fish oil (preferably tuna or something equally strong-smelling of fish)
<1 L	Chicken oil (95% chicken fat, previously used as cooking oil by a takeaway chicken outlet)
~1.5 kg	Quick-cooking rolled oats

All the dry and solid ingredients were combined with the fish oil and supplemented with enough chicken oil to produce a consistency that enabled a golf-ball-sized portion to hold together and remain attached to a closed wire bait hook. Occasionally a small amount of flour or cornflour was added to help as a binding agent and achieve the required consistency. Quantities are estimated to be sufficient to maintain about 100 traps for four nights.

'Eau de chuditch'

1 kg of low-fat red meat in 10 L of water was left to putrefy at room temperature in a well-sealed container for a minimum of two weeks. Strained of solids, the liquid was transferred into dispensing spray bottles.

Less than 5 mL was sprayed around (including on shrubs and forest debris < 1 m above ground) and within 150 cm radius of each trap and re-applied daily.

Chuditch bait trials in Kingston and surrounding State Forests

In August 1997 a preliminary paired comparison of the chuditch bait with the universal bait (peanut butter, rolled oats and sardines) was conducted by placing a trap with chuditch bait on the opposite side of the forest road/ track and at least 20 metres away from an identical trap with universal bait. A total of 180 paired traps were trialled over four consecutive nights.

The main comparative bait trial was conducted over four trapping sessions, approximately three months apart: December 1997, February 1998, May 1998 and August 1998. During each trapping session the northern and southern transects were operated synchronously, each transect with a different bait type. After four consecutive nights of trapping, there was a three to four day 'pause' before the traps and baits were alternated between the north and south and trapping recommenced for four consecutive nights.

Chuditch bait trials at Batalling and Honeymoon Pool forests

The Batalling forest area is 35 kilometres east-north-east of Collie, Western Australia. Batalling supports jarrah- and marri-dominated open forest and woodland on shallow sands and loams (Friend et al. 1994; Mathew 1996). The average annual rainfall is less than 700 mm. Timber harvesting in the area began in the early 1900s, woylies were re-introduced in 1983 in association with limited fox control. Regular fox control began in 1991 (Friend et al. 1994).

Three consecutive nights of trapping at Batalling were conducted in April 1999 in which a transect of 60 pairs of Sheffield cage traps (one for each bait type, placed on opposite sides of the forest transect tracks) were spaced 200 metres apart along forest tracks.

Honeymoon Pool in the Collie River valley (20 kilometres west-south-west of Collie, Western Australia) was used to test the preference of chuditch to the two bait types in the absence of woylies. Located on the Darling Scarp, Honeymoon pool (Lennard State Forest at the time of the study, now Wellington National Park) supports jarrah- and marri-dominated forest within the high-rainfall zone (average annual rainfall greater than 1200 mm) and is a popular recreation and camp site.

The preference trials at Honeymoon Pool involved 50 pairs of Sheffield traps with alternative baits, spaced less than one metre apart and roughly facing each other. Trap spacing between pairs was 200 metres apart in forest alongside Lennard Drive and River Road. These transects were surveyed for three consecutive nights in February 1998. 'Eau de chuditch' was not used in these preference trials.

At all study sites captured chuditch were individually marked with small titanium ear tags (National Band and Tag Company; Kentucky, USA) and details of their age, sex, reproductive condition, pes and head size, and body weight were recorded and the animals released. For all other animals captured, only their species, sex and age were recorded before they were released. From February 1998, the status of traps that did not capture animals were recorded (i.e. whether traps were open or closed, with or without bait).

RESULTS

The trapping results from comparative trials of the 'chuditch' and 'universal' baits at Kingston, Batalling and Honeymoon Pool are summarised in Table 1. In the preliminary comparison of the two bait types conducted at Kingston in August 1997, more than five times the number of woylies were captured on the universal bait than on the chuditch bait. Conversely, the chuditch bait caught eight times more chuditch than the universal bait. During the Kingston bait trial there were more chuditch and quenda, and fewer woylies and koomal (common brushtail possum, *Trichosurus vulpecula hypoleucus*) caught using the chuditch bait than the universal bait. These differences between the bait types were significant for all four species (Fishers Exact Test, two-tail: $p=3.73 \times 10^{-13}$, $p=0.0031$, $p=3.25 \times 10^{-73}$ and $p=0.0011$ respectively). Although more traps were disturbed (Fishers Exact Test, two-tail: $p=0.042$), substantially more traps remained available (Fishers Exact Test, two-tail: $p=2.04 \times 10^{-61}$) and potentially capable of capturing animals using the chuditch bait compared to the universal bait. Furthermore, the numbers of captures of 'other' species using the chuditch bait (nine species) were collectively double those caught in traps using the universal bait (5 species; Table 2).

A total of 39 individual chuditch were captured (from 87 chuditch captures) during the Kingston bait trial (Table 3). Of these, 36 were caught on the chuditch bait and nine were caught on the universal bait. Six individuals were caught on both bait types over the duration of the 12-month trial. Of these six, there were five instances where the same individual (three adult males, one sub-adult male and one adult female) was caught on both baits within the same trapping session. In all five cases, individuals were caught within the same area but in both four-day periods within a trapping session and therefore on different bait types in alternate periods. There was a significant male bias among the chuditch caught with a 32:7 male:female ratio ($X^2=42.2$, $p<0.0001$). It was not possible to determine whether the sex bias was unique to the chuditch bait due to the small sample size of individuals caught on universal bait. There were only five sub-adult captures, four of which were male. Each individual was trapped during the trial between one and seven times and between zero and five times within any one of the four trapping sessions. During the trial females were caught on average 3.57 times each and significantly more frequently (p=0.0133; 2-tail unpaired Students t-test) than males (mean 1.84 captures each).

Results from the 'Kingston Project' (Morris et al. 2001, 2003) indicate that between 1994 and 1998, the average annual trap success rate for chuditch on the road transects using universal bait was 0.74% (SE± 0.20; annual mean of 2902 trap nights). Chuditch captures from identical traps and bait on associated trapping grids (3 x 3 traps spaced 80 m apart; Morris et al. 2001) resulted in an annual average trap success rate of 0.26% (SE± 0.10; annual mean of 2840 trap nights). The difference in the trap success rates between transects and grids was significant (p=0.0304; one-tail paired Students t-test).

The results from the chuditch bait trial at Batalling forest were generally similar to those from Kingston: substantially more chuditch, and fewer woylies and koomals were caught using the chuditch bait than using the universal bait. Quenda captures were equally very low on both bait types (Table 1). The extent of trap disturbance did not differ greatly between the two bait types, however the number of empty traps remaining potentially available to capture animals was more than five times greater with chuditch bait. Formal statistical tests on the differences between the bait types were not conducted on the Batalling data (or Honeymoon Pool data) because of the relatively small datasets and absence of repeated trials as in the case with the Kingston trials.

At the bait preference trial at Honeymoon Pool, there were 13 chuditch captures using chuditch bait and 14 captures using universal bait. Twenty-one chuditch individuals were involved. A total of 19 reptiles (predominantly *Egernia kingii*), a *Rattus rattus* and a koomal were also captured.

DISCUSSION

Traps using chuditch bait resulted in about half the woylie captures of traps using universal bait at both Kingston and Batalling forests. Trap availability and chuditch captures were substantially greater using chuditch bait. The chuditch bait is thus more efficient at surveying chuditch in the presence of large numbers of woylies than universal bait.

Although the number of chuditch captures at Honeymoon Pool was small, the results suggest that there may not be a clear preference by wild chuditch for either bait. Further preference tests would determine the role of the 'Eau de chuditch' given that this was not tested at Honeymoon Pool. Additional preference trials elsewhere would also more rigorously assess whether there are population differences in bait preferences. This has been difficult given that sites where chuditch are abundant and woylies are sparse or absent have been extremely limited. Despite the limitations of the Honeymoon Pool dataset, it may be deduced that the increased chuditch captures using chuditch bait at Batalling and Kingston were likely a result of substantially increased trap availability through decreased woylie captures, rather than a difference in bait preference by chuditch.

The male sex bias in chuditch captures and the tendency for females to be caught more frequently over time than males may be explained by the species having a solitary nature, gender differences in territorial behaviour and the gender differences in the extent of movement and home-rages. Females are intrasexually territorial and occupy smaller home-ranges (3–4 km^2), whereas males tend to range further (5–15 km^2) and have greater range overlap with other males and females (Mathew 1996; Morris et al. 2003; Serena & Soderquist 1989). As a consequence, a series of well-spaced traps within the landscape are likely to be within the home-range of more males than females. By virtue of female home-ranges being smaller, the chance of a female chuditch encountering a limited number of traps is greater than that for a male individual within its larger home range. These differences highlight the general principal that it is not possible to comment on what the actual sex ratio may be within a population without first having detailed information on their home-ranges and density – a commonly made mistake.

There is some indication that the chuditch bait may also be useful in surveying a greater number and diversity of other small and medium-sized vertebrate species that are sympatric with abundant woylie populations. In particular, the results from Kingston suggest that quenda and larger lizards may be trapped more effectively using chuditch bait. The extent to which the increased trap availability and species-specific preferences for bait types accounts for this trend, remain to be quantified. The chuditch bait may not be an appropriate alternative to universal bait for other species such as those that are predominantly herbivorous. These species might be expected to be attracted more by vegetable based lures rather than meat based products. This could explain why, compared with the peanut-based universal bait, the meat-based chuditch bait caught significantly fewer woylies, which are mainly mycophagous and herbivorous (Christensen 1995). Similarly and as expected, the generalist and herbivorous koomal (How & Kerle 1995), was also trapped less frequently on the chuditch bait at Kingston and Batalling.

In this context, the capture of three ngwayir (western ringtail possum, *Pseudocheirus occidentalis*) on chuditch bait at Kingston was particularly interesting and unexpected. This specialist arboreal herbivore was rarely caught on universal bait at Kingston over six years despite the trapping intensity and their local abundance (Morris et al. 2001; Wayne unpublished data). On all three occasions during the bait trial, it was not apparent that the trapped ngwayir had consumed any of the chuditch bait. Therefore, their captures may possibly be explained by a combination of an increased opportunity to be trapped, a curiosity for the strong smelling chuditch bait and perhaps a limited attraction to the universal bait. Differences in the effectiveness of lures and survey methods for the ngwayir and koomal are provided in Wayne et al. (2005).

This study demonstrated that where woylies were abundant, the chuditch bait generally favoured trapping greater numbers of a more diverse array of vertebrate species while the universal bait was more efficient in capturing the woylie and koomal. When using universal bait, however, there needs to be consideration for having sufficient trap density to avoid 'trap saturation' problems that may subsequently affect the ability to interpret and analyse the results.

The importance of the spatial distribution of traps being appropriate for the target species is highlighted by the difference in trap success rates for chuditch caught on grids and transects at Kingston (i.e. trap density should correspond to density and movement patterns of the target species). For example, given that chuditch typically have low densities and large home ranges (Mathew 1996; Morris et al. 2003; Serena & Soderquist 1989), the most efficient trap densities will be relatively low (e.g. 200 metres between traps along transects). There is also the possibility that the association of trapping transects with roads and tracks may improve the capture of chuditch if they favour travelling along them. This may be a preferred strategy for predators in habitats with a dense understorey. However, in the case of chuditch in the Kingston jarrah forest, the vegetation is unlikely to be dense enough for this to be a major factor.

An additional improvement to trapping technique is the use of free-swinging bait 'hooks' made of fencing wire. These are an effective means of reducing potential problems associated with ants. The 'hooks' should, however, be a completely closed loop rather than a hook in order to avoid injury to trapped animals, which has been observed (A. Wayne personal observation).

The quality of the meat meal used in the 'chuditch' bait is also particularly important. Meat meals may be highly variable between suppliers in their content, texture, consistency, smell and look. Darker coloured, strong smelling meat meal was thought to be more effective in deterring woylies and capturing chuditch than lighter coloured less pungent meals that appeared to have a higher fat and/or bone content.

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Table 1

Comparative trap success rates (%) for medium-sized mammals between 'chuditch bait' and 'universal bait' at Kingston, Batalling and Honeymoon Pool forests, Western Australia: Kingston bait trial percentage data are presented as the mean and standard error of four trapping sessions; ^ calculated from three trapping sessions; * 'Eau de chuditch' applied with chuditch bait; Chuditch/Universal (C/U) ratio of captures from traps with different bait.

	PRELIMINARY KINGSTON TRIAL			**KINGSTON BAIT TRIAL**			**BATALLING**			**HONEYMOON POOL**		
Bait type	Chuditch	Universal	C/U ratio	Chuditch	Universal	C/U ratio	Chuditch	Universal	C/U ratio	Chuditch	Universal	C/U ratio
Number of trap nights	720	720		2859	2895		180	180		150	150	
	%	%		%	%		%	%		%	%	
D. geoffroii	1.1	0.1	**8.00**	2.6 ± 0.7	0.4 ± 0.1	**7.00**	9.4	1.7	**5.67**	8.7	9.3	**0.93**
B. penicillata	7.0	42.9	**0.18**	25.5 ± 2.5	48.5 ± 2.5	**0.53**	37.8	67.2	**0.56**	0.0	0.0	
T. vulpecula	4.0	10.6	**0.38**	13.3 ± 1.4	15.8 ± 2.5	**0.84**	5.6	6.7	**0.83**	0.7	0.0	
I. obesulus	7.8	4.9	**1.60**	6.5 ± 0.8	4.6 ± 0.6	**1.42**	0.6	0.6	**1.00**	0.0	0.0	
Other captures	0.1	0.1	**1.00**	2.3 ± 0.7	1.1 ± 0.7	**2.05**	0.0	0.0		8.0	5.3	**1.50**
Total trap success	21.0	58.6	**0.36**	50.2 ± 3.0	70.3 ± 2.2	**0.71**	53.3	76.1	**0.70**	17.3	14.7	**1.18**
Traps disturbed	not recorded			^22.7 ± 1.3	^18.6 ± 1.1	**1.22**	17.8	18.3	**0.97**	not recorded		
Traps available	not recorded			^24,8 ± 3.8	^9.1 ± 2.0	**2.72**	28.9	5.6	**5.20**	not recorded		

Table 2

The number of trap captures for species caught during the comparative trial between 'chuditch' and 'universal' baits conducted in Kingston forest, Western Australia.

BAIT TYPE		**CHUDITCH BAIT**	**UNIVERSAL BAIT**
TRAP NIGHTS		**2859**	**2895**
Woylie	*Bettongia penicillata*	730	1403
Koomal	*Trichosurus vulpecula*	379	453
Quenda	*Isoodon obesulus*	183	133
Chuditch	*Dasyurus geoffroii*	76	11
Southern Heath Monitor	*Varanus rosenbergi*	32	10
Bobtail Skink	*Tiliqua rugosa*	16	18
King's Skink	*Egernia kingii*	4	3
Black Rat	*Rattus rattus*	3	1
Wambenger	*Phascogale tapoatafa*	0	1
House Mouse	*Mus domesticus*	4	
Ngwayir	*Pseudocheirus occidentalis*	3	
Splendid Fairy-wren	*Malurus splendens*	2	
Feral Cat	*Felis catus*	1	
Gould's Monitor	*Varanus gouldii*	1	

Table 3

Gender and age distribution of chuditch individuals caught during the comparative bait trial ('chuditch bait' versus 'universal bait'), conducted in Kingston forest, Western Australia.

CHUDITCH CAPTURES	**CHUDITCH BAIT**	**UNIVERSAL BAIT**	**BOTH BAITS (C & U)**	**OVERALL**
No. Individuals	**36**	**9**	**6**	**39**
No. Male individuals	31	5	4	32
No. Femal individuals	5	4	2	7
No. Adult individuals	33	6	5	34
No. Subadult individuals	3	3	1	5

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Home range overlap of the quokka *Setonix brachyurus* (Macropodidae: Marsupialia) suggests a polygynous mating system

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ABSTRACT

The home range overlap of the quokka was investigated with the aim of elucidating the mating system of the species on mainland Australia. Fifty adult quokkas from five sites were radio collared for long enough to obtain stable home range estimates and the percentage that individual home ranges overlapped those of other conspecifics was calculated. Two sites were found to be anomalous due to a low population density and the threat of introduced predators, and were excluded from several comparisons and consequently there were no significant differences between sites. There was no significant difference in the degree of overlap of overall ranges, although male home ranges overlapped other males less than they overlapped females and less than females overlapped either sex. Female core home ranges overlapped other females significantly more than males. Because of the lack of significant results conclusions are tentative, however the fact that female home ranges overlap other ranges more than males do, combined with the male, weight-based dominance hierarchy, suggests the quokka operates a polygynous mating system, however variation in mating strategies may occur due to variations in prey density. Genetic analysis is recommended to confirm this hypothesis. The clumping behaviour of quokkas at the excluded Victor Road site is probably a predator-avoidance strategy.

Keywords: breeding strategy, mating system, predation, predator avoidance, polygyny, vulnerable, *Vulpes vulpes*

INTRODUCTION

The mating systems of the larger macropodids are generally well understood, however those of the smaller members of the family are largely unknown due to their cryptic nature. The quokka (*Setonix brachyurus* Quoy & Gaimard 1830) is a medium-sized, macropodid marsupial that is listed as vulnerable according to IUCN criteria (Hilton-Taylor 2000). Despite extensive study on Rottnest Island in the 1950s, '60s and '70s (Kitchener 1972; Main et al. 1959; Packer 1965, 1969; Storr 1961) and on the mainland at the end of the last millennium (Hayward et al. 2005a; Hayward et al. 2005b; Hayward et al. 2007), the mating system of the quokka remains unknown (Hayward 2002).

Mating systems can be viewed as the outcomes of the behaviour of individuals competing to maximise their reproductive success (Davies 1991). Male mating behaviour varies among species according to four characteristics of females: 1) the extent to which female reproductive rate can be increased by male assistance in caring for the offspring; 2) the size of female home range; 3) the size and stability of female groups, and 4) the density and distribution of females in space (Clutton-Brock 1989).

Males can better monopolise several females when their assistance raising offspring is unnecessary, when females have small home ranges or when females live in small, stable groups (Davies 1991). Conversely, when females are solitary and use large home ranges, occur in unstable groups or where density is high, males are more likely to be monogamous or monopolise individual females successively (Davies 1991).

When male assistance is required for successful rearing of the young and females are territorial and solitary, obligate monogamy (e.g. gibbons *Hylobates sp*., black-backed jackal *Canis mesomelas* and klipspringer *Oreotragus oreotragus*) or polyandry occurs (e.g. African wild dog *Lycaon pictus*) (Davies 1991). Considering the parental investment typical of macropodids (Russell 1974) where forage is readily available and so assistance in food provisioning is unnecessary, it is unlikely that this form of mating system would apply to the quokka.

When male assistance is not required to rear the young, there are several options that have evolved. One male defending solitary females with small ranges leads to monogamy (e.g. bushbabies *Galago sp.*) or several females with small home ranges leads to polygyny (e.g. tiger *Panthera tigris*) (Davies 1991). Variations in the number of males defending the ranges of several females lead to uni-male polygyny (e.g. black-tailed prairie dog *Cynomys ludovicianus*) or multi-male polygyny (e.g. lion *Panthera leo* and chimpanzee *Pan troglodytes*) (Davies 1991).

Alternatively, where males are not required to successfully raise the young and females occur in stable groups and undefendable ranges, harem polygyny may evolve. In red deer *Cervus elaphus* and gelada baboon *Theropithecus gelada*, one male defends a small, stable group of females (Clutton-Brock et al. 1985; Hill & Dunbar 1998), while in the multi-male polygynous African buffalo *Syncerus caffer* several males associate with large stable groups and individually defend receptive females (Sinclair 1977).

Finally, where males are not required to successfully raise their young and females occur in unstable groups in poorly defendable home ranges, three mating systems may result. Polygynous males may defend large, resource-based territories and mate with females from large unstable groups as they pass through (e.g. white rhinoceros *Ceratotherium simum*) (Davies 1991; Owen-Smith et al. 1997). Alternatively males may lek and defend small, clustered mating territories which females visit solely for mating (e.g. Uganda kob *Kobus kob*) (Clutton-Brock et al. 1993; Davies 1991). Scramble competition polygyny may arise when males search widely for solitary or small groups of receptive females which they may guard temporarily (e.g. polar bear *Ursus arctos* and African savannah elephant *Loxodonta africana*) (Davies 1991; Moss 2001). Finally, large unstable migratory herds where males may defend and mate with individual females or harems, or where they create temporary territories when the migration halts results in polygyny (e.g. blue wildebeest *Connochaetes taurinus*) (Davies 1991).

Evidence of similarity in home range size between male and female quokkas suggests monogamy may be the mating system (Hayward et al. 2004), although the male, weight-based dominance hierarchy (Kitchener 1972; Kitchener 1981; Packer 1969) indicates polygyny may be operating. I hypothesised that the degree of home range overlap of one sex on the same and other sex (as discussed) would indicate the type of mating system the species has. If male home ranges overlapped females extensively, but hardly overlapped those of other males, then polygyny is likely to be in operation (Fig. 1a). If female home ranges overlapped males extensively, but hardly overlapped those of other females then polyandry may be in operation (Fig. 1b). If home ranges of males and females overlapped equally, then the mating system may be monogamous (Fig. 1c).

METHODS

Quokkas were trapped at five sites in the northern half of the jarrah forest bioregion (Hayward et al. 2003) (Fig. 2). Each of these sites was a swamp in the upper reaches of creek systems dominated by *Taxandria linearifolia* (Hayward et al. 2008). These sites are effectively isolated from other sites because the habitat changes in the lower reaches of creeks to become unsuitable for quokkas. Quokkas are almost entirely restricted to the swamps or their near surrounds (Hayward et al. 2004; Hayward et al. 2005b). Four of these sites were baited monthly with sodium monofluoroacetate poisoned dried meat baits targeting the European red fox (*Vulpes vulpes*), while the Victor Road site remained unbaited (Hayward et al. 2003).

Over 21,000 trap nights conducted seasonally at these five sites (range 2592 – 4976 trap nights), yielded 62 captures of new adult individuals and 186 recaptures (Hayward et al. 2003). Mark-recapture estimates suggested there were 10 individuals at Chandler (6

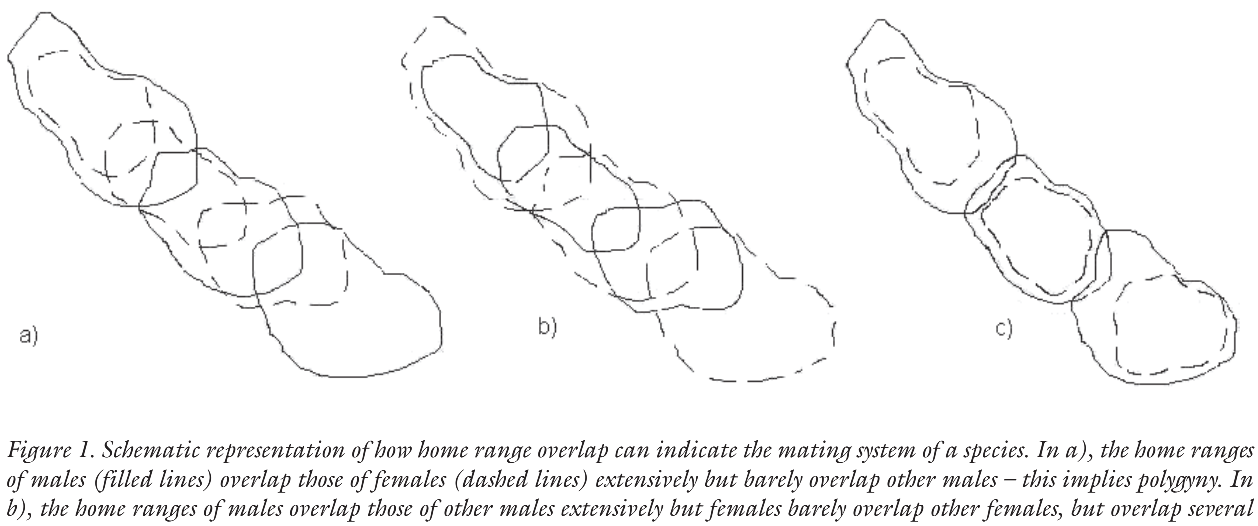

Figure 1. Schematic representation of how home range overlap can indicate the mating system of a species. In a), the home ranges of males (filled lines) overlap those of females (dashed lines) extensively but barely overlap other males – this implies polygyny. In b), the home ranges of males overlap those of other males extensively but females barely overlap other females, but overlap several males – this implies polyandry. In c), the home ranges of one male and one female overlap but are largely separate from adjoining home ranges indicating monogamy.

collared), 21 individuals at Hadfield (15 collared), 36 individuals at Kesners (18 collared) and nine individuals at Victor Road (all collared)(Hayward et al. 2004; Hayward et al. 2003). Only one quokka was trapped at the Rosella Road site despite 4607 trap nights (Hayward et al. 2003) so overlap analyses were not possible there. The study was conducted from spring 1998 until spring 2000, which was a period of average temperature and rainfall conditions (Hayward 2002).

Almost all captured quokkas were fitted with radio collars (50 of 62 captured adults) (Hayward et al. 2004). As such, we feel justified in using a simple percentage overlap measure as a predictor of mating system because it should be representative of the entire population, when compared with a null model of random distribution of individuals.

The dense vegetation of the quokkas' swampy habitat meant triangulation was used to locate individuals using the Locate II computer program (Nams 1990). Locations were taken both day and night, as nocturnal home ranges are significantly larger than diurnal ranges (Hayward et al. 2004). Entire home ranges were estimated using 95 percentile kernel estimates in the Ranges V computer program (Kenward & Hodder 1992) for individuals with more than the 40 locational fixes, as this number was found to provide accurate home range estimates (Hayward et al. 2004). Core home ranges were estimated using 50 percentile kernel estimates following identification by incremental area analysis (Hayward et al. 2004). Digitised boundaries of these home ranges were then exported into the MapInfo Professional Version 5.5 geographic information system (MapInfo Corporation 1985–1999) and the percentage overlap (O) of home ranges was calculated by dividing the area that one home range covered another home range (a_1) by the area of the original home range (a_o) using the equation

$$O = \frac{a_1}{a_o} \times \frac{100}{1}.$$

Overlap was calculated for male home ranges overlapping other males, males overlapping females, females overlapping other females and females overlapping males, due to the differences in home range sizes of individual male and female quokkas (Hayward et al. 2004). The mean number of individuals of each sex overlapping other ranges is also reported.

Data analysis

Non-parametric statistics were used after transformation attempts failed to normalise the data. The Kruskal-Wallis test was used to test differences between sites and the Mann-Whitney test was used to test differences between Kesners and Hadfield, after the eventual exclusion of the Chandler and Victor Road sites, and between the sexes. Chandler was excluded from subsequent analyses because the small population size meant that very few of the five animals collared overlapped one another. Individuals at the unbaited Victor Road site, where predation pressure is considered higher than other sites, were excluded due to the high degree of home range overlap that has been hypothesised as being due to clumping associated with predator avoidance (Hayward 2002). Relationships between home range overlaps and population density and body mass were investigated using Spearman rank correlations. All tests were conducted in Statview for Windows V5.0 (SAS Institute 1992–1998) and sample means are presented with standard errors.

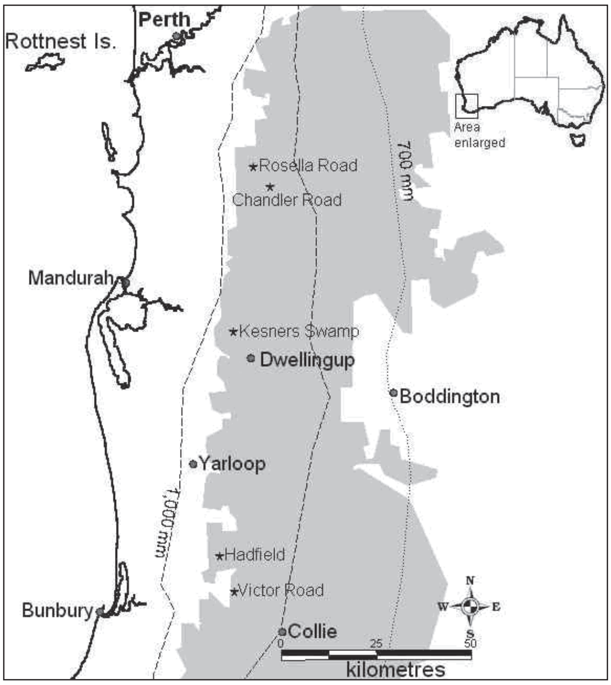

Figure 2. Map of the five study sites (stars) within the northern jarrah forest study region (shaded grey) of south-west Australia where quokkas were trapped and radio collared. Rainfall isohyets (700 and 1,000 mm) are also shown.

RESULTS

Fifty-two percent of the average quokka home range is overlapped by home ranges of other quokkas. This home range overlap is substantially enlarged by individuals at the Victor Road site, where both males and females overlap significantly more than at other sites (Table 1; Fig. 3). Differences between sites arose through a significant negative relationship between home range overlap and population density, that is, as population density increases overlap decreases (Table 2). There is no such relationship between overlap and body mass (Table 2).

The average male quokka overlapped the ranges of four other males and eight females. The average female quokka overlapped the ranges of three other females and eight other males (Table 3). When we look at extensive home range overlaps (i.e. >50%), the average male overlapped the ranges of one other male and three females, while the average female overlapped the range of one other female and three males (Table 3).

The exclusion of the Chandler site, due to its low population density, and Victor Road site, due to clumping behaviour thought to be associated with the higher risk of predation there (Hayward 2002), removes these between sites differences (Table 4). In this case, the mean home range overlap is 14.8 ± 2.7%. The mean male home range of 6.92 ha (Hayward et al. 2004) overlaps other male ranges by 9.0 ± 1.5% and females by 14.5 ± 2.7% (Fig. 3). The mean female home range of 5.91 ha (Hayward et al. 2004) overlapped other females by 20.4 ± 3.8% and males by 15.0 ± 2.7% (Fig. 3). These differences were not significant (Table 5) and are illustrated by the real home range overlaps of three male and three female quokkas at the Hadfield site (Fig. 5). There are no changes

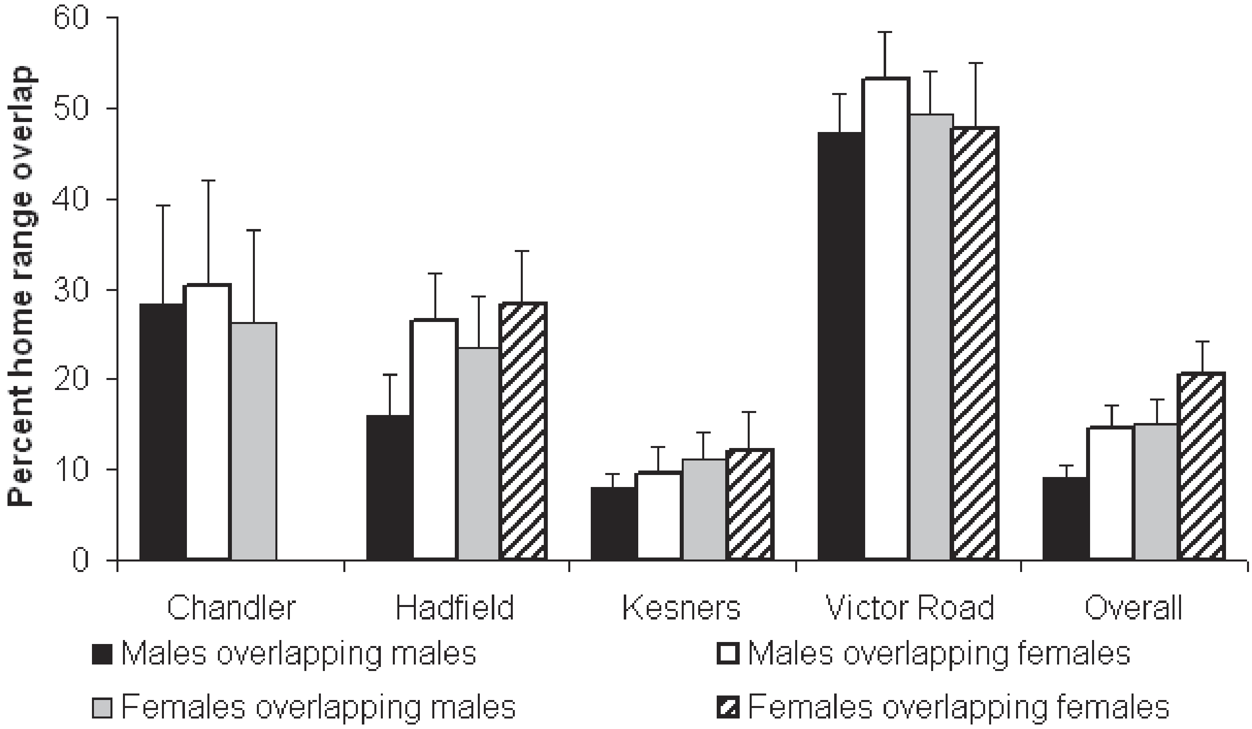

Figure 3. Mean (± s.e.) home range overlap for male and female quokkas at each site and overall (Hadfield and Kesners).

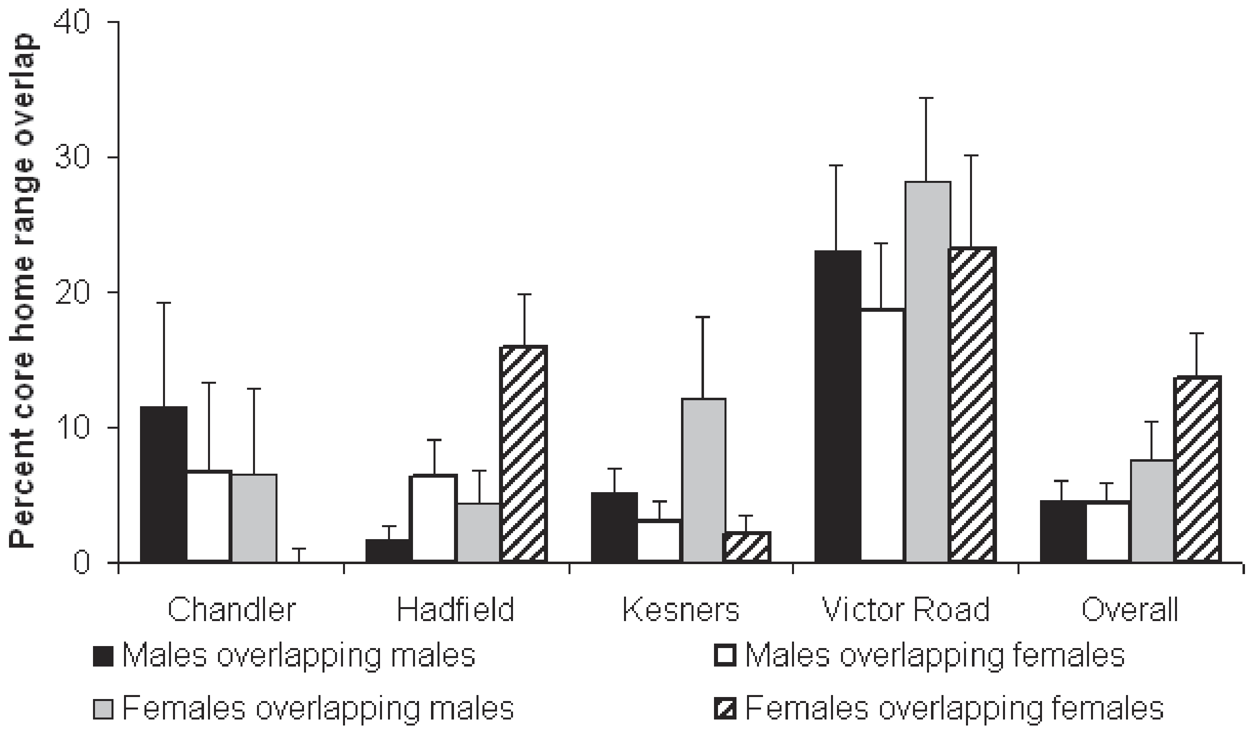

Figure 4. Mean (± s.e.) overlap of core home ranges of male and females quokkas at each site and overall (Hadfield and Kesners).

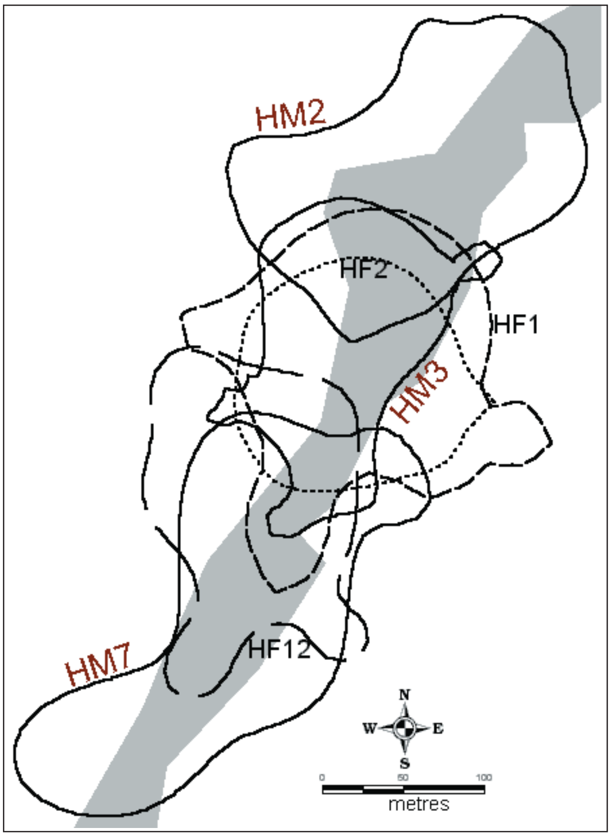

Figure 5. Home ranges of three male (solid lines) and three female (broken lines) quokkas at the Hadfield site showing a typical level of home range overlap for quokkas in the northern jarrah forest. The identification code beside each range refers to Hadfield (H), sex (M/F) and an individual number.

in the number of individual ranges overlapped by each sex with the exclusion of Chandler and Victor Road data.

The core home range overlap is similarly biased by the small population size and lack of abutting home ranges at Chandler and the clumping behaviour of quokkas under increased predation pressure at the Victor Road site, with significant differences existing amongst the sites (Table 1; Fig. 4). These differences cease to be significant with the exclusion of quokkas at these two sites in further analysis (Table 4) and the mean core home range is overlapped by conspecifics by 7.5 ± 2.3%. The mean male core home range of 1.47 ha (Hayward et al. 2004) is overlapped by other males by 4.5 ± 1.6% and by females by 4.5 ± 1.4% (Fig. 4). The mean female core home range of 0.97 ha (Hayward et al. 2004) is overlapped by core ranges of other females by 13.6 ± 3.4% and by males by 7.5 ± 2.9% (Fig. 4). This increased overlap of female core ranges with other females is significantly larger than the degree of overlap of female core ranges with males (Table 5).

DISCUSSION

Quokkas on the mainland are essentially solitary creatures unless threatened with high levels of predation (Hayward 2002). Such social behaviour is typical of the small macropodids (Jarman 1989; Jarman & Coulson 1989).

The results from the overlap of entire home ranges revealed little about the mating system of the quokka, until the Chandler and Victor Road sites were excluded. The exclusion of these sites is justified by the small population size at Chandler (5 collared individuals over 11.3 ha and the high degree of overlap occurring at Victor Road which probably stems from the higher predation risk there than at the other sites due to the lack of introduced predator control there. Although not significant, the smaller degree of overlap of males on males, once these sites were removed, compared to overlaps of females suggests males are avoiding each other.

With the Chandler and Victor Road sites excluded, the core home ranges of males overlapped other males and females almost equally, whereas core ranges of females overlapped those of other females significantly more than other males. The degree to which males are located by themselves suggests that they are not simply avoiding other males but females as well.

Based on the original hypotheses of this study and the male weight-based dominance hierarchy (Kitchener 1972; Kitchener 1981; Packer 1969), the more extensive home range overlap of males on females than on other males indicates polygyny may be the mating system of the quokka. Multi-male polygyny seems unlikely given the small degree of home range overlap amongst males. Similarly, the lack of observations of overlap between one male and several females suggests harem polygyny is not occurring. There was no evidence of lekking or migration so these forms of unstable group polygyny are also unlikely. The most likely mating system of the quokka is therefore uni-male polygyny where one male defends the ranges of a small number of females (e.g. Fig. 4). The lack of significant results however, means firm conclusions on the quokka mating system cannot be drawn.

An alternative hypothesis is that quokkas at the excluded sites (Chandler and Victor Road) were behaving naturally and reflect the natural flexibility in mating systems practiced by the quokka. At low population densities, the small population sizes might force quokkas to become monogamous due to the lack of mating opportunities, whereas at higher population densities polygyny may occur, and this may break-down at the highest population densities.

The only way to elucidate this feature of the ecology of the quokka with certainty is by conducting genetic analysis at sites of different densities to ascertain the relatedness of pouch young. If one male is siring the majority of offspring then polygyny is confirmed; if each male produces an equal number of offspring then monogamy may be occurring; and if one female has produced offspring from several different males over several breeding seasons then polyandry may be occurring.

The significant negative relationship between overlap and population density is interesting considering the similar significant negative relationship between home range size and population density (Hayward et al. 2004). Home ranges decreased in size and overlap together, rather than the degree of overlap increasing with population density as more home ranges are fitted into the same bounded area of the swamp vegetation. In such circumstances, polygyny might break down.

The lack of a significant relationship between overlap and body mass is also interesting. For polygyny to occur, one might anticipate that heavier, dominant males would overlap a greater proportion of female home ranges and inhibit the overlap of other males. This is not the case.

The exceptionally high degree of home range overlap amongst individuals at the unbaited Victor Road site was anomalous compared to other sites and is considered a predator avoidance strategy. At Victor Road, the mean home range is overlapped by 49.3 ± 5.4% compared to 16.9 ± 4.1% at the other sites (Hadfield and Kesners). Proximity to conspecifics was found to minimise the risk of mortality in the quokka (Hayward 2002). Hence, this clumping behaviour is likely to be a feature used by quokkas to reduce predation risk from the introduced, European red fox.

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Table 1

Kruskal-Wallis test statistics for comparison between sites of the percentage of male, female and all home ranges that are overlapped by home ranges of other quokkas. *N* is the aggregate total of each individual's home range overlap with every other individual.

Comparison	Kruskal-Wallis H	d.f.	n	Probability
Sites (All)				
– % of all home ranges overlapped	41.371	3	602	<0.001
– % of male home ranges overlapped	31.476	3	366	<0.001
– % of female home ranges overlapped	36.153	3	236	<0.001
Core home ranges with sites (All)				
– % of all core home ranges overlapped	184.775	3	602	<0.001
– % of male core home ranges overlapped	76.402	3	366	<0.001
– % of female core home ranges overlapped	106.489	3	236	<0.001

Table 2

Spearman rank order correlations between the percentage of home range overlap and a) population density and b) body mass. Population density was calculated using the Jolly-Seber method (Hayward *et al.* 2003). *N* is the aggregate total of each individual's home range overlap with every other individual.

Comparison	Spearman rank correlation rho	Z-value	n	Probability
a) Overlap against population density (all sites)				
– % of all home ranges overlapped	-0.411	-3.701	602	<0.001
– % of male home ranges overlapped	-0.309	-2.783	366	<0.001
– % of female home ranges overlapped	-0.259	-2.333	236	0.003
b) Overlap against body mass				
– % of all home ranges overlapped	0.012	0.096	602	0.941
– % of male home ranges overlapped	0.021	0.176	366	0.915
– % of female home ranges overlapped	0.065	0.536	236	0.639

Table 3

Data on the number of individuals with overlapping home ranges. Overlaps of entire ranges are presented, along with extensive overlaps (i.e., overlaps of greater than 50% of the entire home range).

Site	Male – male	Female – female	Male – female	Male – male >50%	Female – female >50%	Male – female >50%
Number of individuals with overlapping ranges						
Chandler	4	0	3	2	0	1
Kesners	5	3	6	1	1	2
Victor Road	6	4	12	2	2	6
Hadfield	4	3	9	0	1	3
Mean	4	3	8	1	1	3
Percentage of individuals at a site with overlapping ranges						
Chandler	100%	0%	56%	50%	0%	22%
Kesners	39%	47%	35%	4%	8%	11%
Victor Road	70%	80%	95%	27%	36%	43%
Hadfield	72%	56%	83%	8%	22%	27%
Weighted average	62%	54%	65%	17%	19%	25%
S.E.	12%	17%	14%	10%	8%	7%

Table 4

Mann-Whitney test statistics for comparisons of the percentage of male, female and all home ranges that are overlapped by those of other quokkas between the sites when the anomalous Victor Road and Chandler sites are excluded.

Comparison between sites	Mann-Whitney U	d.f.	n	Probability
Entire home range				
– % of all home ranges overlapped	275.5	1	417	0.154
– % of male home ranges overlapped	284.5	1	255	0.205
– % of female home ranges overlapped	235.5	1	162	0.032
Core home ranges				
– % of all core home ranges overlapped	4952.0	1	367	0.195
– % of male home ranges overlapped	3994.0	1	176	0.623
– % of female home ranges overlapped	45724.0	1	191	0.179

Table 5

Mann-Whitney test statistics for comparisons of the percentage of male, female and all home ranges that are overlapped by those of other quokkas between the sexes with animals at Victor Road and Chandler excluded.

Comparison	Mann-Whitney U	d.f.	n	Probability
Sex – overall home range				
– % of all home ranges overlapped Male mean rank 41.935; female 40.944	848.000	1	82	0.851
– % of male home ranges overlapped Male mean rank 41.989; female 40.875	850.5	1	82	0.832
– % of female home ranges overlapped Male mean rank 42.891; female 39.722	892.000	1	82	0.547
Sex – core home ranges				
– % of male home ranges overlapped Male mean rank 64.838; female 69.262	2357.000	1	133	0.346
– % of female home ranges overlapped Male mean rank 62.309; female 71.908	2529.000	1	133	0.044

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BiblioRakali: the Australian water rat, *Hydromys chrysogaster* Geoffroy, 1804 (Muridae: Hydromyinae), a subject-specific bibliography

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ABSTRACT

Eighty-six references relating to the Australian water rat or Rakali (*Hydromys chrysogaster* Geoffroy*)*, have been collated to create this bibliography. References were taken from available written literature (published and unpublished, with or without peer review) to provide a comprehensive resource for researchers. Using these references we present a summary of the distribution, status and biology of the species. In addition, each reference has been sorted into the following groups: behaviour, conservation status, description, diet, distribution, ecology, evolution, general, genetics, species management, parasites, physiology, reproduction and threatening processes.

DESCRIPTION

The Australian water rat, or Rakali, *Hydromys chrysogaster*, was described by Geoffroy (1804) and is part of the Family Muridae (Vernes 1998) within the order Rodentia (Olsen 1983). The Hydromyinae includes all the native Australian rodents in the Muridae, except for the genus *Rattus* (Hinds et al.,2002).

Hydromys chrysogaster is thought to have radiated from New Guinea to Australia (Vernes 1998), and is one of the few amphibious mammals found in Australia (Hinds et al. 2002). Water rats have effectively colonised a niche which few mammals have successfully colonised, and have evolved adaptations to live a semi-aquatic and semi-nocturnal lifestyle (McKenzie, 1998). Water rats have a flattened head with small ears and eyes, dorsally located nostrils on a blunt nose and a large number of whiskers (Australian Museum, 2003). Their hind feet are broad and partially webbed for efficient swimming (Olsen 1983). The fur of the water rat is waterproof and the colouring depends on where it is found in Australia. It varies from black to grey on the dorsal surface and white to orange on the ventral surface (Olsen, 1983). Its tail is covered by dark fur and usually terminates with a white tip (Olsen, 1983). In south-eastern Australia, adult males ranged in length (head and body) from 231 – 345 mm (mean 310 mm), with a weight range of 400 – 1275 g (mean 755 g), while adult females were on average slightly smaller with head and body lengths of 245–370 mm (mean 290 mm) and weights from 340–992 g (mean 606 g; Olsen 1983). Olsen (1983) also reported that mean tail lengths were very similar between males and females at 275 and 272 mm respectively.

DISTRIBUTION

Water rats live near permanent water whether it is fresh, brackish or marine (Olsen 1983). Water rats can be found in wetlands, rivers, estuaries and along beaches and on islands. Natural areas are not the only places offering suitable habitat, as artificial water sources and even polluted urban water bodies can support water rat populations (Watts & Aslin 1981).

Water rats are found in suitable habitats throughout Australia, New Guinea and the offshore islands. In Australia, *H. chrysogaster* is a widespread species (Vernes 1998), and can be found in all states and territories (Olsen, 1983, 1995). In Western Australia, they can be found along water courses and in wetlands on the Swan Coastal Plain, and along rivers in the Darling Range (Kitchener, Chapman & Barron 1978). The abundance of water rats in suitable habitats within Australia ranges from sparse to common (Olsen 1983).

A specimen list originally constructed by Kitchener et al. (1978) and updated by the Western Australian Museum (Ric How pers. comm., 2005[1]) gives an indication of the distribution of water rats in Western Australia from the late 1800s to 2002. Specimens have been sent to the Western Australian Museum from various places such as Kununurra, Shark Bay, Balingup and Albany. The majority of specimens were from regional country towns with only 13 specimens from Perth (all collected prior to 1983). A specimen was recently recovered from Lake Goollelal in Perth (Mike Bamford pers. comm. 2005[2]). The distribution

1 Ric How, Curator of Survey, Western Australian Museum, Perth

2 Mike Bamford, MJ and AR Bamford, Consulting Ecologists, Perth

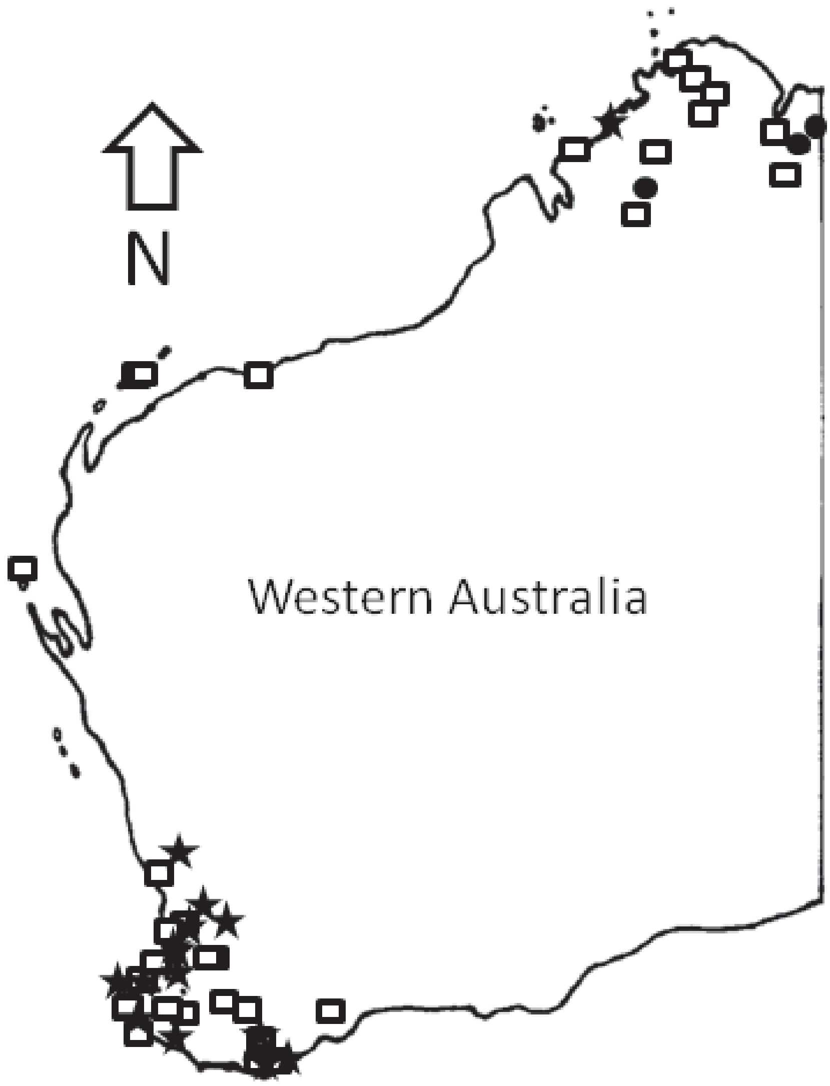

Figure 1. Distribution of Hydromys chrysogaster *(records prior to 1850 indicated by ★, 1950–1999 by □ and 2000 onwards by ●) in Western Australia based on specimens located in Australian museums (adapted from BioMaps (http://www.biomaps.net.au/biomaps/ Retrieved 20/6/07) and FaunaBase (http://www.museum.wa.gov.au/faunabase/prod/index.htm Retrieved 20/6/07).*

of water rats in Western Australia as compiled from national, state and territory Museum records (FaunaBase and BioMap Databases) is shown in Figure 1.

Conservation Status

Along rivers, water rat populations appear to be sparsely distributed. However in Victorian irrigated areas and drainage swamps, water rat populations have been found to be quite dense (Olsen, 1983). In these areas water rats are said to be a pest by some as they profit on the easy availability of prey and their burrows are thought to cause damage to irrigation structures (McNally 1960). However, they prey upon the burrowing freshwater crayfish (*Cherax destructor*), which could cause more damage if not kept in check by the water rat (Olsen 1983).

In the past, particularly in south-eastern Australia, the water rat was hunted to almost extinction for its fur, as it was highly prized for use in clothing manufacture (McKenzie 1998). It is now a protected species across Australia and this is believed to have led to a recovery in abundance.

The current range of the water rat in Australia is similar to that occupied prior to European settlement (Watts & Aslin 1981). However, this does not reflect localised losses associated with clearing, pollution and secondary salinisation (Lee 1995). Lee (1995) believed that degradation and salinisation of southwestern Australian waterways had resulted in a substantial decline in populations. Water rats are considered to be secure nationally, however little is known of abundance and health of Western Australian populations. Water rats are not listed as a threatened species in the 2000 IUCN Red List of Threatened Species, the *Wildlife Conservation Act 1950* (Western Australian Government), or the *Environmental Protection and Biodiversity Conservation Act 1999*

(Commonwealth Government). However in Western Australia, it is listed as a Priority 4 species (Department of Environment and Conservation), that is, one that is not threatened at this time, but is in need of monitoring.

Oral histories (Sanders 1991) suggest that in the wheatbelt of Western Australia water rats declined during the 1950s and then the species disappeared from wetlands. This may have come about through falling numbers of the prey species (fish, frogs and crustaceans), which resulted from the increased salinity in the region (Sanders 1991; Lee 1995; Scott & Grant 1997).

The natural predators of the water rat are birds of prey, snakes and large fish but they are also taken by feral cats and foxes (Scott & Grant 1997). The impact of feral predators and cane toads on water rats is poorly understood.

Barrett (1950) controversially described the Western Australian populations as a different species to the eastern populations. Olsen (1983) however stated that subspecies had been described but were unlikely to be valid. Genetic studies are required to determine the taxonomic relationships between the various Australian populations as this may affect the imperatives for conserving each of these populations.

Despite the broad distribution and abundance of the species in Australia, it has attracted comparatively little scientific interest with only 85 publications found compared to the 294 for Chuditch (Smith et al. 2004). The possibility of a subspecies in Western Australia and the few publications available on western populations suggests that more research on this species is needed in the west.

DIET

Water rats are not completely nocturnal and are most active around sunrise and sunset but can also be seen foraging during the day. Occasionally they climb trees in search of food but mainly forage in the water (Olsen 1983). Water rats will take captured prey to consume at feeding middens to allow their bodies to warm up between hunts, especially when the water temperature is low, as they don't have insulated fur (Scott & Grant 1997). Water rats are opportunists and will feed on fish, aquatic insects, mussels, crustaceans, small waterbirds, small mammals, lizards, frogs and even household rubbish. They consume little plant material and will only do so if their preferred prey is unavailable (Olsen 1983).

REPRODUCTION

Water rats have been recorded as breeding at anytime of the year but according to Olsen (1983) the most common times are spring and summer. Any regional differences in breeding times are unknown. Females can start breeding at four months of age but usually begin at eight months. Nests generally consist of tunnels dug into a river bank, or occasionally logs. The gestation period lasts for 34 days and 3–4 young are born. Typically one or two litters are produced a year but more litters are possible if conditions are optimal. The young are suckled for approximately four weeks but stay with the mother for another four weeks gaining independence before dispersing (Olsen 1983). A single male water rat will keep a large home range which may contain several female home ranges within it (Scott & Grant 1997). Water rats are territorial animals and will fight in overcrowded areas often resulting in damaged tails (Olsen, 1983).

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BIBLIORAKALI

This bibliography of information on the Rakali or Australian water rat, *Hydromys chrysogaster*, lists the majority of known and available references that focus solely on the water rat and relevant literature that contains some information on the water rat.

The bibliography was built using titles extracted from the Web of Science and Streamline Online Databases at Edith Cowan University and the Department of Environment and Conservation (Western Australia) library at Woodvale. Some references have been taken from the World Wide Web and although useful may not be completely reliable sources of information. The URLs have been included in the reference but may change over time.

The references have been listed in alphabetical order and given a number. These numbers have been placed under 14 broad subject groups in relation to the information given in each reference.

BEHAVIOUR:

2, 3, 10, 14, 21, 26, 28, 35, 40, 41, 44, 48, 49, 51, 54, 55, 56, 57, 60, 71, 75, 76, 79, 80, 81, 86

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1, 2, 3, 5, 8, 10, 14, 15, 18, 24, 25, 26, 28, 31, 34, 40, 41, 42, 49, 50, 51, 54, 57, 60, 64, 70, 71, 74, 75, 79, 80, 81

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THREATENING PROCESSES:

5, 8, 10, 24, 30, 37, 38, 40, 41, 44, 50, 51, 52, 59, 60, 71, 79, 80

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Flora and vegetation of banded iron formations of the Yilgarn Craton: Koolanooka and Perenjori Hills

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ABSTRACT

A study of the flora and plant communities of Koolanooka and Perenjori Hills, east of Morawa, recorded 238 taxa, with 217 native and 21 weeds. Nine priority taxa were found and five new species were identified and are considered endemic to the hills. Fifty quadrats were established to cover the major geographical, geomorphologic and floristic variation across the hills. Data from 48 of these quadrats were used to define five community types, with two subtypes in one community. Differences in communities were strongly correlated with landform and soil fertility. Patterns of high plant endemicity and restricted communities are similar to those found on other ranges within the Yilgarn Craton. None of the plant communities found on the Koolanooka and Perenjori Hills is reserved in the conservation estate.

INTRODUCTION

Banded iron formation ranges within the Yilgarn Craton are highly prospective for iron ore exploration and mining. Previous studies on greenstone and banded ironstone ranges in the Goldfields have found high plant endemicity and restricted vegetation types (Gibson et al. 1997; Gibson & Lyons 1998a,b; Gibson & Lyons 2001a,b; Gibson 2004a,b). It is hypothesised that similar patterns would also be found on the ironstone ranges in the Yilgarn Craton. The current knowledge of the vegetation and flora that occur on these ranges is poor and based on Beard's pioneering vegetation mapping (Beard 1976).

The Koolanooka Hills, Aboriginal for hill of wild turkeys (Rogers 1996), is located approximately 20 km east of Morawa. Perenjori Hills is located 10 km southeast of Koolanooka and 12 km to the northeast of Perenjori (Figure 1). Both hills are located near the boundary of the agricultural and pastoral zones in Western Australia, which roughly correlates with the boundary of the Eremaean and Southwest IBRA provences (Figure1).

The Koolanooka and Perenjori Hills are part of the Koolanooka synform, one of several Archaen belts within the Yilgarn Craton. The hills strike NNW–SSE and N–S respectively. The banded iron formation within the Koolanooka synform is part of the middle sedimentary association. The association contains siltstones, sandstones, conglomerates interbedded with banded iron formation and shale. This in turn is intruded by granitoids and bounded by upper and lower volcanic associations (Baxter & Lipple 1985). Historically, iron ore was mined in the northern part of Koolanooka Hills between 1966 and 1975 (Baxter & Lipple 1985). Currently, there is interest in further exploiting the iron ore resources of Koolanooka Hills.

The climate of the region is dry warm mediterranean (Beard 1990) with a mild wet winters and hot dry summers. Mean annual rainfall recorded at Morawa is 333.8 mm, but not as variable in more arid regions (227.8 mm 1st decile; 453.7 mm 9th decile; recorded 1911 to 2004). Rain primarily falls in winter, derived mainly from cold fronts moving in an easterly direction over the Indian Ocean. Summer rains are unpredictable and tend to occur later in the season. Summer rains originate from troughs and depressions and sometimes tropical cyclones off the northwest coast of Western Australia (Rogers 1996).

The highest maximum temperatures occur during summer, with the January as hottest month (mean maximum temperature 36.7 °C with mean of 7.4 days above 40 °C). Winters are mild with lowest mean maximum temperatures recorded for July of 18.1 °C. Temperatures rarely fall below 0 °C in winter (a mean of 0.2 days below 0 °C), with a mean minimum of 6.2 °C in July.

The Koolanooka and Perenjori Hills were described by Beard (1976) as a single vegetation system, the Koolanooka system, consisting of *Allocasuarina huegeliana*, *Eucalyptus ebbanoensis*, *Acacia acuminata*, *Dodonaea inaequifolia* interspersed with communities of *Allocasuarina campestris*, *Acacia acuminata*, *Grevillea paradoxa*, *Melaleuca cordata*, *Melaleuca nematophylla* and *Melaleuca radula*. The footslopes grade into *Eucalyptus loxophleba* woodlands interspersed with the thickets.

Koolanooka vegetation system was endorsed by the Minister for Environment as a Threatened Ecological Community (TEC) in 2001. The TEC, plant assemblages of the Koolanooka system, is based upon Beard's (1976) vegetation system described above, covering the entire extent of both hills, approximately 4500ha. It is currently ranked vulnerable following English and Blythe (1999).

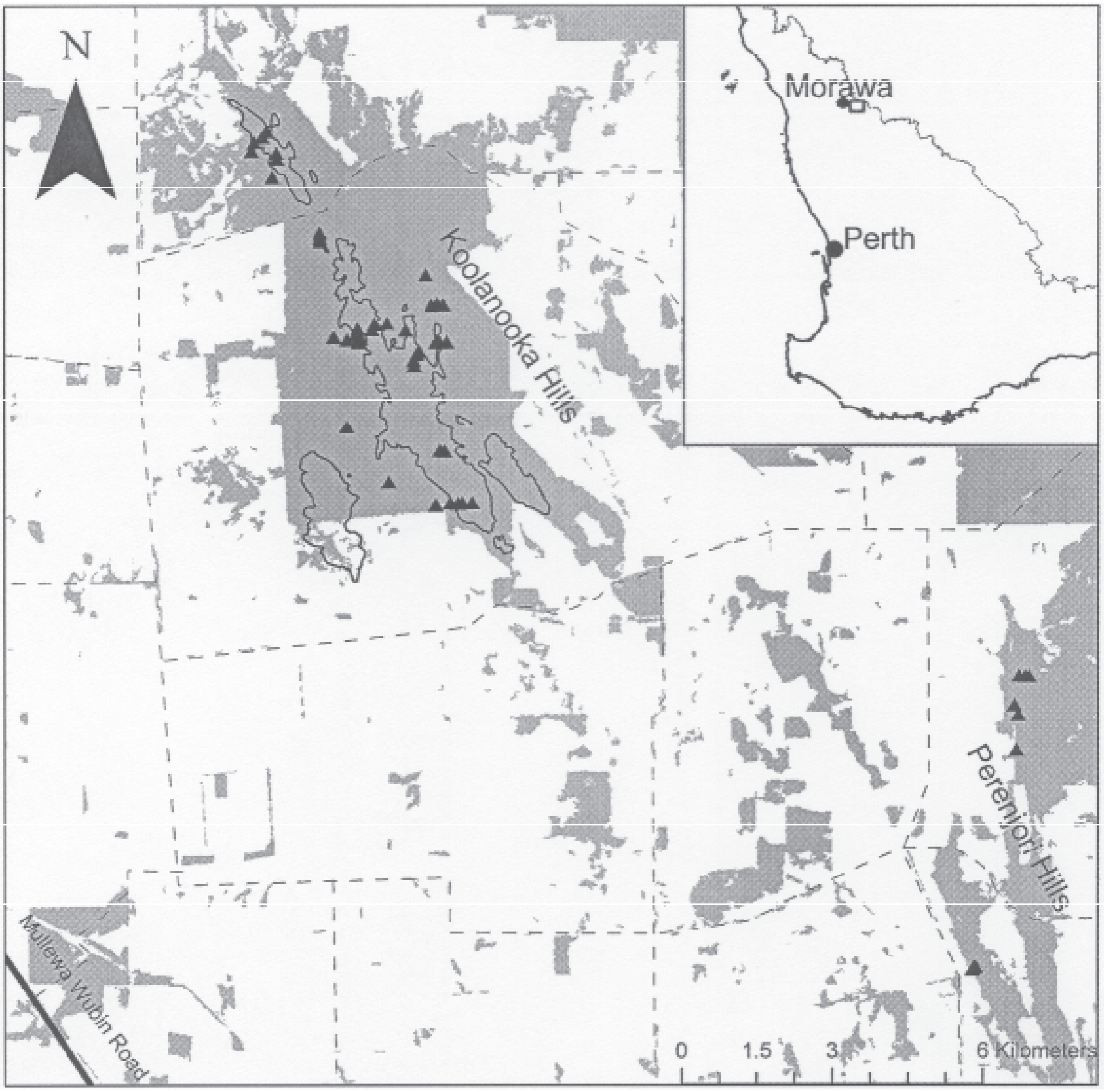

Figure 1. Location of survey and distribution of quadrats (▲) on Koolanooka and Perenjori Hills. The 340 m contour is shown, with remnant vegetation represented by shaded areas represent, dashed lines represent roads. In the inset, the grey line represents the zone between the Southwest and Eremaean provinces.

The aim of the present work was to undertake a detailed floristic survey of the Koolanooka and Perenjori Hills and to identify the plant communities that occur on the ranges. This was achieved by detailed flora lists, and description of plant communities based on a series of permanently established quadrats. Ultimately, the aim is to place these communities in a regional context with other banded ironstone ranges throughout the Yilgarn Craton.

METHODS

Fifty 20 x 20 m quadrats were established on the crests, slopes and foot slopes of Koolanooka and Perenjori Hills in October 2005 (Figure 1). These quadrats were established to cover the major geographical, geomorphologic and floristic variation found in the study area. Each quadrat was permanently marked with four steel fence droppers and their positions determined using a GPS unit. All vascular plants within the quadrat were recorded and collected for later identification at the Western Australian Herbarium.

Data on topographical position, disturbance, abundance, size and shape of coarse fragments on the surface, the amount of exposed bedrock, cover of leaf litter and bare ground were recorded following McDonald et al. (1990). Additionally, growth form, height and cover were recorded for dominant taxa in each stratum (tallest, mid- and lower).

Twenty soil samples were collected from the upper 10 cm of the soil profile within each quadrat. The soil was bulked and the 2 mm fraction analysed for B, Ca, Cd, Co, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S and Zn using the Mehlich No. 3 procedure (Mehlich 1984). The extracted samples were then analysed using Inductively Coupled Plasma – Atomic Emission Spectrometer (ICP-

AES). This procedure is an effective and cost efficient alternative to traditional methods for evaluating soil fertility and has been calibrated for Western Australian soils (Walton & Allen 2004). pH was measured in 0.01M $CaCl_2$ at soil to solution ratio of 1:5. Effective cation exchange capacity (eCEC) was calculated from the sum of exchangeable Ca, Mg, Na and K (Rengasamy & Churchman 1999). Exchangeable Ca, Mg, Na and K were obtained by multiplying the values of Ca, Mg, Na and K obtained from ICP-AES by a standard constant.

Quadrats were classified on the basis of similarity in species composition on perennial species only, to be consistent with other analyses of banded ironstone ranges (Gibson 2004 a, b). Perennials were also more consistent across season and amount of pre-survey rainfall. Life form followed Paczknowska and Chapman (2000), where perennial is defined as a plant whose life span extends over 2 or more growing seasons. The quadrat and species classifications were undertaken using the Bray and Curtis coefficient and Flexible UPGMA (Unweighted pair-group mean average; â = -0.1; Belbin 1989). Indicator species and species assemblages characterising each community were determined following Dufrene and Legendre (1997) using the INDVAL routine in PC-ORD (McCune & Mefford 1999). Quadrats were ordinated using SSH (semi-strong hybrid multidimensional scaling), correlations of environmental variables were determined using the PCC (Principal Component Correlation) routine and significance determined by the MCAO (monte-carlo attributes in ordination) permutation test in PATN (Belbin 1989).

Statistical relationships between quadrat groups were tested using Kruskall-Wallis non parametric analysis of variance (Siegel 1956), followed by non-parametric comparison (Zar 1999). Correlations between environmental parameters were analysed using Spearman Rank correlation coefficient.

Nomenclature generally follows Paczkowska and Chapman (2000).

RESULTS

Flora

A total of 237 taxa from 53 families were recorded from the 50 established quadrats and adjacent areas. Of these 237 taxa, 216 were native and 21 weeds. The dominant families in order were Asteraceae (39 species, 3 weeds), Myrtaceae (21), Poaceae (21 species, 11 weeds), Mimosaceae (19) and Chenopodiaceae (11).

Rare and Priority Flora

Nine priority taxa (designated P1, P2, P3) were found during the survey of Koolanooka and Perenjori Hills.

- *Acacia acanthoclada* subsp. *glaucescens* (P3) is an intricately branched shrub to 2 m with pungent branchlets and glaucous phyllodes. It was found growing in open forests and mallee woodlands and of *E. ebbanoensis* or *E. loxophleba* subsp. *supralaevis*. It has been previously found on Koolanooka Hills.
- *Baeckea* sp. Perenjori (J.W. Green 1516) (P2) is a small myrtaceous shrub to 1.5 m with pink flowers. This taxon is restricted to the Morawa and Perenjori region. In this survey, it was found growing on the crests and slopes of Perenjori and Koolanooka Hills.
- *Gunniopsis rubra* (P3) is a small succulent herb to 10 cm growing on water gaining sites in sandy loam. A single collection was made of this taxon from a colluvial outwash site, growing under mallee woodlands of *Eucalyptus subangusta subsp. pusilla* and *Eucalyptus ebbanoensis* subsp. *ebbanoensis*.
- *Melaleuca barlowii* (P1) is a myrtaceous shrub to 1.8 m known mainly from the Mullewa and Morawa area growing on roadside reserves. It has been collected previously from Koolanooka Hills. In this survey, it was collected from two sites on Koolanooka Hills, growing in shrublands of *Allocasuarina acutivalvis* on a lower and mid slope.
- *Millotia dimorpha* (P1) is a small yellow flowered daisy characteristically with two rows of glandular involucral bracts. This species is poorly collected, and originally known only from Koolanooka Hills and Kadji Kadji Station. It has recently been found growing on the slopes of Mount Karara, east of Kadji Kadji (Markey and Dillon, 2008).
- *Mribelia sp.* Helena and Aurora (B.J. Lepschi 2003) (P3) is a perennial, leaf less but pungent shrub to 3m. Originally found only on the Helena and Aurora Ranges in the western Goldfields, it was found growing on the mid to upper slopes of Koolanooka Hills with *A. acutivalvis* and *E. ebbanoensis*. This is a new record for Koolanooka Hills and a range extension of over 400km for the species.
- *Persoonia pentasticha* (P2) is a proteaceous shrub to 2 m with pungent five ribbed leaves. In this survey, it was found at two sites on crests of Koolanooka Hills, growing in open forests of *A. acutivalvis* and *E. ebbanoensis*.
- *Rhodanthe collina* (P1) is an annual daisy with small delicate flowers. It is known mainly from the pastoral stations near Paynes Find on flats and water gaining sites. A single specimen was found on Koolanooka Hills on a rocky midslope. This is a new record, range extension and population for the area.
- *Stenanthemum poicilum* (P2) is small shrub to 50 cm that was found growing on the crests and upper slopes of Koolanooka Hills in open mallee forests and woodlands of *E. ebbanoensis* and *A. acutivalvis*. It has been previously collected from rocky sites in the Morawa area. This a new record for Koolanooka Hills.

New Species

During the survey, six new species were identified. These taxa are apparently endemic to the Koolanooka and

Perenjori Hills. Further surveys are required to determine the distribution and population size of each taxon. Further taxonomic work is also required to determine taxonomic rank of several of the taxa.

- *Acacia muriculata* is a shrub to 2 m found growing only on the slopes and crests of Koolanooka Hills in open mallee forests and woodlands of *E. ebbanoensis* and *A. acutivalvis*. It characterised by hairy verruculose-ribbed branchlets and falcate phyllodes with solitary globular flowers (Maslin & Buscomb 2007). It has recently been listed as Priority One species and is known only from Koolanooka Hills.
- *Acacia graciliformis* is an openly branched shrub to 2 m with slender stems and short pungent phyllodes. It was found at four sites growing in *Eucalyptus* woodlands crests and slopes of Koolanooka Hills. This species is closely allied to *Acacia mackeyana* and *A. dissona* which differ significantly from the species in their phyllode nervature (Maslin & Buscomb 2007). It has been listed as a Priority One species due to its restricted habitat and location.
- *Caesia* sp. Koolanooka Hills (R.Meissner & Y.Caruso 78) is a geophyte to 30 cm with pale yellow flowers growing on crests and slopes of Koolanooka and Perenjori Hills. The species is closely related to *Caesia* sp. Wongan (K.F. Kenneally 8820) but with smaller, pallid flowers and spreading anthers. It may belong to a sub-group of the genus that is endemic to ironstone ranges, including such species as *Caesia* sp. Ennuin (N.Gibson & M.N.Lyons 2737) (G. Keighery[1], pers. comm.). The occurrence on the ranges is unusual as most *Caesia* spp. grow in deep clay soils on flats and plains.
- *Dodonaea scurra* is a dioecious shrub to 1 m with verticillate leaves and solitary flowers. It is closely allied to *Dodonaea caespitosa* but is distinguished by relatively more clustered leaves per node and distinctly rounded capsules with simple scattered hairs (Shepherd et al. 2007). It was found only on the slopes and crests of Koolanooka Hills in several different communities. There was one previous collection in the Western Australian Herbarium of this taxon, which was misidentified, from the Koolanooka Hills. It is has recently been listed as Priority One due to its limited distribution to Koolanooka Hills.
- *Drummondita rubroviridis* is a spindly shrub to 1.5 m with glandular clavate leaves, held recurved to horizontal, and subsessile, solitary flowers that possess red petals with green tips (Meissner & Markey 2007). It is closely related to *D. wilsonii* and *D. ericoides*, both taxa with restricted distributions (Mollemans 1993). This species was only found on the slopes and crests of Koolanooka Hills, growing mainly in open mallee forests and woodlands of *E. ebbanoensis* and *A. acutivalvis*.
- *Lepidosperma* sp. Koolanooka (K. Newbey 9336) is a sedge to 50 cm found growing on the slopes of Koolanooka and Perenjori Hills in open forests and shrublands of *A. acutivalvis* or *A. campestris*. Although previously collected from Koolanooka, it was not recognised as a new species until the current survey collected sufficient material for the status to be determined with confidence. It is closely related to another newly discovered granite endemic, *Lepidosperma* sp. Karara (H.Pringle 3865) found growing on granite outcrops on Karara Station.

Flora of taxonomic interest

- *Hibbertia* aff. *exasperata* belongs to a complex, including *Hibbertia rostellata*, *Hibbertia nutans* and *Hibbertia uncinata*, of unresolved taxonomy (Wheeler 2004). Further work needs to be undertaken to elucidate the taxonomic relationships within this complex. The species was collected only from the slopes and crests of Koolanooka Hills, mainly from mallee woodlands of *E. ebbanoensis* and *A. acutivalvis*.
- *Eucalyptus ebbanoensis* subsp. *glauciramula* is a mallee to 3 to 6m and was collected from both ranges. It was commonly the dominant *Eucalyptus* and was found across the landscape, from crests to lower slopes and plains. It has previously been collected from the range. The nearest populations are nearly 400 km to the east in the Goldfields.
- *Labichea lanceolata* subsp. *brevifolia* is a shrub to 3m. It was found growing at single site on a midlsope of Koolanooka Hills, in an open forest of *A. acutivalvis*. The taxon is found in three discreet areas; around Esperance, York and an outlying northern population. The specimen collected in this survey belongs to the northern variant of the taxon, found in scattered populations between Geraldton and Morawa. These collections have narrow leaves and look superficially more like *Labichea eremaea* than *L. lanceolata*, but differ from the former as they have 4 rather than 5 sepals. Revision of this taxon is required.
- *Tetraria* aff. *capillaris* is a sedge with curly leaves growing to 50 cm. It was found growing at a single site on Koolanooka Hills in *Allocasuarina acutivalvis* subsp. *acutivalvis* woodland with *M. nematophylla*, *H.* aff. *exasperata* and *L.* sp. Koolanooka (K.Newbey 9336). It is closely allied to *Tetraria capillaris* and this complex is in need of taxonomic revision (R. Barrett[2], pers. comm.).

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Plant Communities

Initial analysis of the data with all species excluding singletons (species which occurred in only one plot) compared to an analysis of data with only perennial species revealed little difference in the groupings and ordination. Ninety eight perennial taxa were included in the final analysis. Subspecies of *E. ebbanoensis* and *A. acutivalvis* were reduced to species level for the analysis, due to the difficulty in differentiating between subspecies without sufficient flowering or fruiting material.

Forty eight quadrats out of the fifty established on the ranges were used in the final analysis. In the initial analysis, two quadrats were outliers and subsequent removal improved the ordination stress. Quadrat KOOL26 was a species poor *Eucalyptus salmonophloia* woodland occurring over limestone and KOOL36 was an open shrubland of *Acacia tetragonophylla* and *Calycopeplus paucifolius* and had a high percentage of weeds present, probably due to high levels of disturbance. Both sites had high levels of calcium, magnesium and high pH.

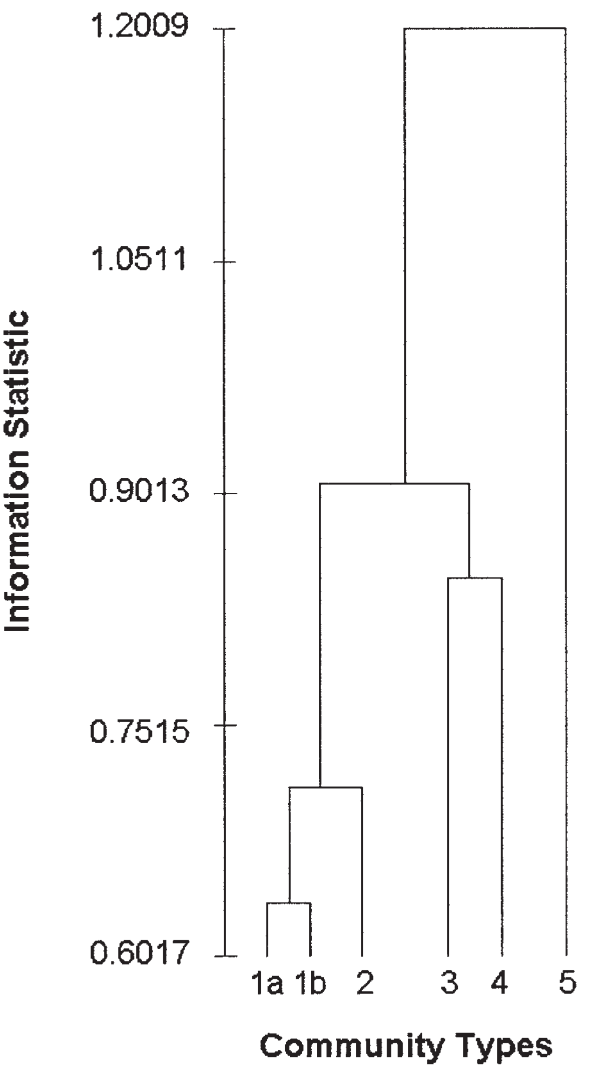

Figure 2. Dendrogram of 6 group level classification of 48 quadrats established at Koolanooka and Perenjori Hills.

Community groups were separated into 5 groups, based upon clear pattern in the final dendrogram. This pattern was also the first division separates the *Allocasuarina* shrublands and thickets (Communities 1-4) from the more fertile woodland sites (Community 5; Figure 2). The second division separates communities restricted mainly to the crests, upper and mid slopes of Koolanooka Hills (Communities 1 and 2) from communities common between Perenjori and Koolanooka Hills (Community 3) and communities found on the lower slopes of Koolanooka (Community 4). These divisions can also be clearly seen in the sorted two-way table of the sites and species classification (Table 1).

In total, five community types, one with two subtypes, were recognised.

Community 1 – Woodlands, mallee shrublands and shrublands of *A. acutivalvis*, *E. ebbanoensis* over shrublands of *Acacia* spp. and Myrtaceae spp. The community occurs only on crests and slopes of Koolanooka Hills and can be further divided into 2 subtypes.

Community type 1a – This community is found only on Koolanooka Hills on all landforms except colluvial outwashes. It is described as mallee shrublands, shrublands and woodlands of *A. acutivalvis*, *E. ebbanoensis* and *Melaleuca* spp. over shrublands with *Micromyrtus racemosa*, *G. paradoxa* and *M. sp.* Helena and Aurora (B.J. Lepschi 2003) present. The community had the lowest mean species richness (annuals and perennials) of all communities (mean 32.3 ± 0.6 species per quadrat). The best indicator species are *Acacia neurophylla* subsp. *neurophylla*, *Cheiranthera filifolia* var. *simplicifolia*, *D. rubroviridis*, *E. ebbanoensis*, *G. paradoxa*, *Micromyrtus racemosa* subsp. *racemosa*, *Melaleuca atroviridis*, *M. sp.* Helena and Aurora (B.J. Lepschi 2003) and *Thysanotus manglesianus* (Table 1).

Community type 1b – This community is only found on the slopes of Koolanooka Hills. It is best described as woodlands and shrublands of *A. acutivalvis* with an understorey of *L.* sp. Koolanooka (K.Newbey 9336), *Pimelea avonensis,* and *Acacia nigripilosa* subsp. *nigripilosa*. Mean species richness was 34.0 ± 0.5 species per quadrat. Indicator species were *A. nigripilosa* subsp. *nigripilosa, Austrostipa hemipogon*, *C.* sp. Koolanooka Hills (R.Meissner & Y.Caruso 78), *L.* sp. Koolanooka (K. Newbey 9336), *M. nematophylla, P. avonensis* and *Tricoryne elatior*. This community is characterised by taxa from Species groups D and G (Table 1).

Community type 2 – This community occurs only on Koolanooka Hills, mainly on crests and upper slopes and contains taxa from Species group A (Table 1). It can be described as mallee woodlands and shrublands of *E. ebbanoensis* and *A. acutivalvis.* This community had the second highest species richness with a mean of 38.6 ± 1.3 species per quadrat. Indicator species were *S. poicilum*, *H.* aff. *exasperata*, *A. acutivalvis* and *Ptilotus obovatus* subsp. *obovatus.*

Community type 3 – This community occurs on midslopes and crests of Koolanooka and Perenjori Hills. It can be described as open woodlands, shrublands and open shrublands of *Allocasuarina* spp., *M. nematophylla,* and

C. paucifolius over a mixed shrubland of *D. inaequifolia* and *Philotheca brucei* subsp. *brucei*. The community had the highest species richness with a mean of 39.4 ± 0.6 species per quadrat. Indicator species for this community are *Acacia exocarpoides*, *C. paucifolius*, *D. inaequifolia* and *P. brucei* subsp. *brucei*. Taxa in the community are mainly from species groups A, D, F and G (Table 1).

Community type 4 – This community was found mainly on low fertility lower slopes of Koolanooka Hills. The vegetation is shrublands and open shrublands of *Allocasuarina* spp., *M. cordata*, *Hemigenia* sp. Paynes Find (A.C. Beauglehole 49138) and *Mirbelia microphylla*. This community had a mean species richness of 34.4 ± 1.6 species per quadrat and is comprised of taxa from species group D, I and J (Table 1). The Best indicator species are *Acacia stereophylla* var. *stereophylla*, *A. campestris*, *Drosera macrantha* subsp. *macrantha*, *Grevillea obliquistigma* subsp. *obliquistigma*, *H.* sp. Paynes Find (A.C. Beauglehole 39138), *Hibbertia arcuata*, *M. cordata*, *M. microphylla*, *Monachather paradoxus* and *Stypandra glauca*.

Community type 5 – This community was found on both ranges. It occurs on colluvial outwash soils from the ranges, and sites occurring in pockets of fertile soil within community type 1. The vegetation is woodlands and mallee woodlands of *Eucalyptus* spp. (*E. loxophleba*, *E. ebbanoenisis* or *E. salmonophloia*) over *Acacia* spp. and chenopods. The community had a mean species richness of 34.2 ± 0.8 species per quadrat. The best indicator species are *Acacia andrewsii*, *Acacia erinacea*, *Austrodanthonia caespitosa*, *Austrostipa trichophylla*, *Enchylaena lanata*, *Maireana carnosa*, *Maireana georgei*, *Rhagodia drummondii*, *Scaevola spinescens*, *Sclerolaena diacantha* and *Senna charlesiana*. The community is characterised by taxa from species groups A and C (Table 1), which are typical of soils of high pH.

Physical parameters

The soil chemistry showed significant intercorrelations with other soil parameters. Iron had the most correlations with physical site parameters. It was positively correlated with slope, aspect, maximum surface rock fragment size and rock outcrop abundance, but negatively with leaf litter cover (Table 2).

There were few correlations between physical site characters. Slope, rock outcrop abundance, maximum surface rock size and run off were positively intercorrelated (Table 2).

Phosphorus, pH, magnesium and cobalt were all high in Community 5, indicating sites of higher fertility. Low phosphorus and magnesium separated Communities 1 and 4 from the other communities (Table 3).

Communities 2 and 5 showed similar values in phosphorus, cobalt, magnesium and pH. Community 3 differed from the latter with the highest phosphorus values but significantly lower pH (Table 3).

Community 3 had significantly greater coarse fragment size and abundance than Community 5, which occurred on the colluvial outwashes and deeper fertile soils (Table 4). The remaining communities did not differ from Communities 3 and 5 in these site characters. Community 4 occurred on lower slopes and differed only from Community 3, which occurred predominantly on crests and midslopes. The cover of surficial rock (rock outcrop abundance) was greatest in Community 2, followed by Community 3 (Table 4).

The three dimensional ordination (stress = 0.17) clearly separated the majority of the communities (Figure 3). The most common community type found on Koolanooka Hills (Community 1a) is on the left side of the ordination, characterised by lower fertility (low phosphorous and potassium). Community 1b occurred in the upper left quadrant with lower pH and an increase in coarse fragment abundance. The woodlands on colluvial soils and on the slopes of the hills (Community 5) also clearly separated out from the other communities. This community was found in the lower right quadrant and was characterised by higher pH and Co and occurrences on predominantly lower slopes and flats. Community 3, common between Koolanooka and Perenjori Hills, occurred in the upper right quadrant. This community can be characterised by the higher abundance of rocky outcrops and steeper slopes, and high phosphorus. Community 2 and 4 occur in the centre of the ordination but separate in the third dimension (not shown). The soil of Community 4 has characteristically lower fertility and is found on gently inclined slopes, while Community 2 was on soils of intermediate fertility.

DISCUSSION

Flora

The total of 238 taxa and the pattern of dominant families recorded for Koolanooka Hills are similar to other ironstone and greenstone ranges surveyed in the Eastern goldfields (see Gibson 2004a). Six endemic species were identified during the survey, similar to the number of endemics found on other ironstone ranges (Gibson 2004b).

The patterns of endemism and priority species on ironstone ranges are high. A concurrent survey in the Central Tallering found 15 priority species and 9 endemic taxa (*cf.* 8 species and 6 taxa, respectively, in this survey) (Markey & Dillon, 2008). The Central Tallering survey covered a greater area and sampled twice the number of quadrats, making it even more significant the high number of endemic species found in this survey.

Three of the endemic species, *A. muriculata*, *C.* sp. Koolanooka (R. Meissner & Y. Caruso 78) and *D. rubroviridis* (R. Meissner & Y. Caruso 69), were collected for the first time. *Acacia muriculata*, *A. graciliformis*, *D. scurra* and *D. rubroviridis* appear to be restricted to Koolanooka Hills and were not found on Perenjori Hills, while *Caesia* sp. Koolanooka (R. Meissner & Y. Caruso 78) and *L.* sp. Koolanooka (K. Newbey 9336) occur on both.

Recent taxonomic work has discovered several

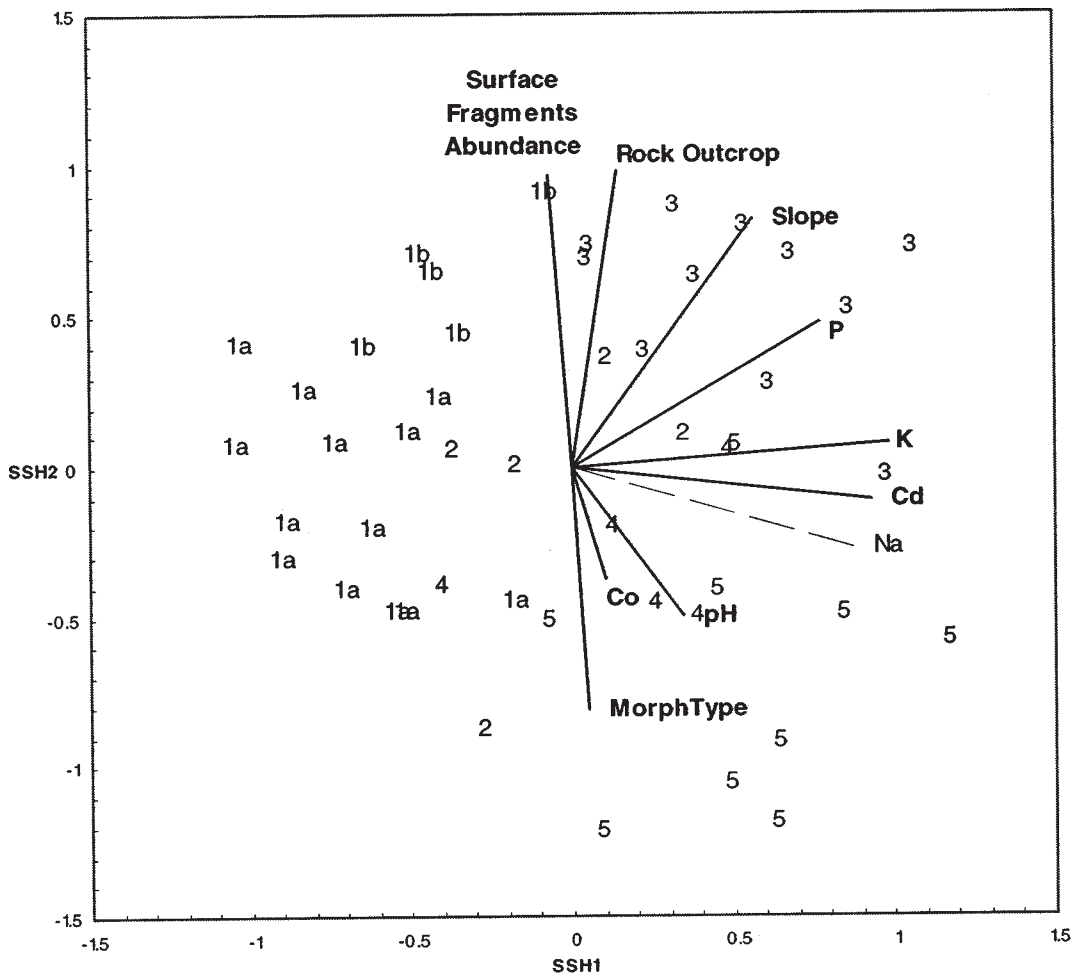

Figure 3. Two dimensional representation of a three dimensional ordination showing only axis 1 and 2 of the 48 quadrats established on Koolanooka and Perenjori Hills and represented by community type. Lines represent the strength and direction of the best fit linear correlated variables. Unbroken and dashed lines represent significance at P < 0.01 and P < 0.05 respectively. Abbreviations as in Table 4.

additional taxa of *Lepidosperma* that are endemic to banded ironstone ranges, such as *Lepidosperma gibsonii*, *L. ferricola* and *Lepidosperma* sp Karara (Markey and Dillon 3468) (R. Barrett[3], pers. comm., Barrett 2007). This group is currently undergoing a much needed revision.

Koolanooka and Perenjori Hills occurs close to the boundary between two provinces, Southwest and Eremaean (Beard 1990). The flora found within this survey showed a greater affinity to the Southwest flora (e.g. *Ptilotus drummondii*, *Alyxia buxifolia*, *Hibbertia* spp. and *Allocasuarina* spp.) than Eremaean. Those Eremaean taxa present at Koolanooka and Perenjori Hills showed considerable range extensions, especially *Eucalyptus ebbanoenis* subsp. *glauciramula* and *Mirbelia* sp. Helena & Aurora (B.J. Lepschi 2003), found in the eastern goldfields.

[3] Science Directorate, Botanic Gardens & Parks Authority, Kings Park and Botanic Garden, Western Australia

Communities

Vegetation on Koolanooka and Perenjori Hills is described by Beard (1976) as the same system; however, there were differences in communities between Koolanooka and Perenjori Hills. Three of the communities, 1, 2 and 4 were found only on Koolanooka Hills while Communities 3 and 5 were found on both Koolanooka and Perenjori Hills. Perenjori Hills is smaller in extent than Koolanooka, and in some places the vegetation has been cleared up to the lower slopes. In addition, there is a history of sheep grazing in Perenjori Hills, but only feral goat grazing is known at Koolanooka.

Community types were found to be correlated with soil fertility, landscape position, soil depth and surface rockiness. Low phosphorus and potassium separate Communities 1 and 4, restricted to Koolanooka Hills, from the more fertile sites. The two communities occur on very different landforms with Community 1 occurring on skeletal soils on crests and slopes, while Community 4 is found on the lower slopes of the ranges. In contrast, Community 2, which is also restricted to Koolanooka Hills, shows higher levels of phosphorus. It is found on a similar landform to Community 1 but mainly on sites with laterised banded ironstone and with higher cover of surficial rocks.

Community 3 is found on both Perenjori and Koolanooka Hills and showed highest phosphorus levels, but had lower pH. It was commonly found on steeper slopes and crests and often with a higher cover of surficial rocks, some weakly metamorphosed banded ironstone but no tertiary laterites.

Community 5 is typical of the woodlands surrounding many of the greenstone and ironstone ranges in the Yilgarn Craton (see Gibson 2004b). At Koolanooka it occurred on the colluvial flats at the bases of both hills and also on pockets of fertile soils on slopes and small valleys between hills. The communities are likely to be responding to the higher nutrients and pH, and possibly deeper soils required for larger trees to survive.

Gradients in the floristics and associated environmental variables occur in the study area. Communities 1b and 3 occurred on rockier sites which were always associated with a higher position in the landscape. The soils in these areas are often shallower with higher phosphorus, a characteristic of soils derived from the ironstone (Gray & Murphy 2002). In contrast, the lower colluvial and lower slope communities (4 and 5) the soils were relatively higher in nutrients, and in the case of the woodlands, possessing deeper soil. This is the likely result of the enrichment by leachates and colluvium from the surrounding ridges.

Beard (1976) mapped Koolanooka and Perenjori Hills as a single vegetation system, the Koolonooka system. A vegetation system encompasses a series of plant communities recurring in a catenary sequence or mosaic pattern linked to topographic, pedological and or/ geological features (Beard 1981). This present study shows the broad vegetation system as comprised of five plant communities. The current definition of the Koolanooka TEC should be re-evaluated and incorporate these communities.

In Beard's (1976) description of the Koolanooka system, he notes *Allocasuarina huegeliana* as the dominant taxon (*cf. A. acutivalvis* in this survey). There is no record of *A. huegeliana* from Koolanooka or Perenjori Hills in the Western Australian Herbarium, and is probably a misidentification. Furthermore, within the vegetation system he also mapped two structural units that largely correspond to Communities 1 and 5.

The plant communities on Koolanooka and Perenjori Hills, especially the three restricted to Koolanooka, are currently under increasing threat from mining and none of the area is currently reserved.

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Table 1

Sorted two-way table of quadrats established Koolanooka and Perenjori Hills showing species by community type. Taxa shaded grey within a community are indicator species identified by INDVAL > 17 (Dufrene & Legendre 1997) at the 6 group level (* indicates P< 0.05; ** indicates P<0.01; statistical significance tested by randomisation procedures).

	Community Types					
	1a	1b	2	3	4	5
SPECIES GROUP A						
Acacia acanthoclada subsp. *glaucescens*			••			•••
** *Scaevola spinescens*	•			•••		**•••••••**
* *Senna charlesiana*			•	•		**••••**
Acacia acuminata	•••••••••	•	••••	•••••	••	••••••
* *Austrostipa trichophylla*	••••		•	•••	••	**•••••••**
Austrostipa elegantissima	••••••••	•	•••••	•••	•••	••••••••
** *Acacia andrewsii*	•		**••••**	••		**•••••••••**
** *Rhagodia drummondii*			**•••**	•		**•••••••**
Austrostipa scabra		•	••••	••••••	•	••••
Ptilotus obovatus var. *obovatus*	••		•••	••••••		••••••
Acacia anthochaera	•	•	••			•••
Austrodanthonia sp. Goomalling (A.G. Gunness et al. OAKP 10/63)	•			•		•
SPECIES GROUP B						
* *Bulbine semibarbata*			**••**			
Senna artemisioides subsp. *filifolia*	•		•			
Maireana planifolia			•			•••
Olearia humilis	•		•	••		•
SPECIES GROUP C						
Acacia graciliformis			••			••
** *Acacia erinacea*						**••••**
Maireana marginata						••
** *Austrodanthonia caespitosa*						**••••**
Sclerolaena fusiformis						••
** *Sclerolaena diacantha*						**•••••**
** *Maireana carnosa*						**•••••**
** *Maireana georgei*						**•••••**
* *Enchylaena lanata*						**•••**
Olearia muelleri						••
Eucalyptus subangusta subsp. *pusilla*			•			••
SPECIES GROUP D						
Acacia assimilis subsp. *assimilis*	•••••••••	••••	••	•••	•••••	
Amphipogon caricinus var. *caricinus*	••••••••••	•••••	••	••••	••••	•
* *Allocasuarina acutivalvis*	**••••••••••••**	**••••**	**•••••**	••••••••	•	••
Arthropodium dyeri	•••••••••••	•••••	•••••	•••••••	•••	••••••
* *Eucalyptus ebbanoensis*	**•••••••••••••**	**••••**	**•••••**	•••	•	•••••
** *Grevillea paradoxa*	**•••••••••••••**	**•••••**	•••	**•••••••••••**	••	
* *Thysanotus manglesianus*	**•••••••••••••**	**•••••**	••	••••	**••••**	•
Astroloma serratifolium	•••••••••	•••	••••	••	•••	
** *Hibbertia* aff. *exasperata*	••••••••	•••	**•••••**	•		
Dianella revoluta var. *divaricata*	••••••••	••••	••••	•••	•	•
* *Melaleuca nematophylla*	•••••	**•••••**	**••••**	**••••••••••**	•	
** *Acacia nigripilosa* subsp. *nigripilosa*	••••••••	**••••**	•			
Dodonaea scurra	••••••••	•	••	•		•
** *Micromyrtus racemosa* var. *racemosa*	**•••••••••••**	•	•			
Aluta aspera subsp. *hesperia*	••••••••	•		•	••	
Stylidium confluens	••••••••••	•••	••	••	•	
* *Hibbertia arcuata*	•••••	•		••	**•••**	
Acacia coolgardiensis subsp. *coolgardiensis*	••••			•••	••	
** *Melaleuca atroviridis*	**•••••••**					••
* *Melaleuca cordata*	•••••••				**•••**	
Schoenus nanus	•••	•		•	•	•
Melaleuca eleuterostachya	••		••			••
** *Stenanthemum poicilum*	••••	•	**•••••**	••		

Table 1 (cont.)

	1a	1b	2	3	4	5
SPECIES GROUP E						
Acacia daviesioides	••					
Acacia muriculata	••••		•			
* *Drummondita rubroviridis*	••••					
* *Mirbelia* sp. Helena & Aurora (B.J. Lepschi 2003)	•••••			•		
* *Acacia neurophylla* subsp. *erugata*	•••••					
* *Cheiranthera filifolia* var. *simplicifolia*	••••					
Westringia cephalantha	•					•
Malleostemon tuberculatus		•			•	
Santalum acuminatum	•	•				
SPECIES GROUP F						
** *Acacia exocarpoides*				•••••		
Allocasuarina dielsiana				•••		
Acacia tetragonophylla			•	•••		••
Eremophila latrobei subsp. *latrobei*				••		
Solanum ellipticum				•	•	
Hakea recurva			••	••		
Persoonia pentasticha		•	•			
SPECIES GROUP G						
** *Austrostipa hemipogon*	•	•••••	•••	•		
** *Lepidosperma* sp. Koolanooka (K.Newbey 9336)		•••••		•••		
* *Tricoryne elatior*	•	•••	•	•••		
** *Pimelea avonensis*	•	•••				
Baeckea sp. Perenjori (J.W. Green 1516)		••		•••	•	
Comesperma integerrimum	•••••	••••	•	••••••••	•••	
Xanthosia bungei	•	•••		••••••••	•••	
Caesia sp. Koolanooka Hills (R.Meissner & Y.Caruso 78)	•	••		••••••	•	
** *Calycopeplus paucifolius*				••••		
Melaleuca radula	••••	••		••		
Chamaexeros macranthera			•	•••••		••
** *Dodonaea inaequifolia*		•	••	••••••••••	•	••••
** *Philotheca brucei* subsp. *brucei*			••	••••••••••	•	••
Eremophila clarkei	•••		•••	••••••••	•	••••
Daviesia hakeoides subsp. *hakeoides*		•	•	••••	•••	
Dioscorea hastifolia	•	••	••	••••••	•	
* *Mirbelia microphylla*	•	••	••	••••••	•••••	
Sida atrovirens	••	•	•••	•••••	•	
SPECIES GROUP H						
* *Caesia* sp. Wheatbelt (AJM Hopkins 353)		••				
Eucalyptus loxophleba subsp. *supralaevis*	•	•	•			•••
Melaleuca hamata	•	•		•		
SPECIES GROUP I						
* *Acacia stereophylla* var. *stereophylla*	•			•	••	
Thysanotus pyramidalis					••	••
* *Grevillea obliquistigma* subsp. *obliquistigma*					••	
Alyxia buxifolia				•		••
Arthropodium curvipes			•	•		
SPECIES GROUP J						
** *Allocasuarina campestris*	•••	•			••••	
** *Drosera macrantha* subsp. *macrantha*	•••	•••			•••••	
** *Hemigenia* sp. Sticky Terete (B.H. Smith 449)	•				•••	
* *Monachather paradoxus*	•			••	•••	••
Melaleuca barlowii		•			•	
* *Stypandra glauca*					••	

Table 2
Spearman's rank correlation of soil chemistry parameter and physical site characters. Cells with numbers present represent significant correlation at P < 0.05.

	eCEC	pH	B	Ca	Cd	Co	Cu	Fe	K	Mg	Mn	Mo	Na	Ni	P	Pb	S	Zn	Aspect	Slope	Disturbance	Surface Rock Abundance	Surface CF Size
eCEC																							
pH																							
B	0.20	0.41																					
Ca	0.99	0.58																					
Cd																							
Co	0.31	0.39			0.48																		
Cu					0.34	0.53																	
Fe	0.51			0.54																			
K	0.63	0.33		0.57	0.31	0.30	0.39																
Mg	0.90	0.60	0.31	0.85		0.34	0.31	0.45	0.58														
Mn	0.39	0.42		0.37	0.52	0.68	0.30			0.29													
Mo			0.57																				
Na	0.42		0.30	0.34			0.50		0.69	0.50													
Ni	0.74	0.41		0.71	0.41	0.47	0.30	0.45	0.52	0.71	0.51												
P							0.34		0.33				0.33	0.08									
Pb		-0.30			0.33		0.33						0.29										
S		-0.56											0.41			0.45							
Zn					0.41		0.52		0.47		0.31		0.40		0.35	0.51	0.29						
Aspect								0.30															
Slope								0.31		0.29				0.38				0.34	0.41				
Disturbance																							
Surface Rock Abundance							-0.37																
Surface CF Size								0.38					0.32				0.34			0.42			
Rock Outcrop Abundance								0.50												0.45			0.61
Runoff														0.31						0.73		0.41	0.29
%Litter					0.39	0.43	0.33	-0.39			0.35												
%Bare															-0.43								

Table 3

Plant community mean values for soil chemistry parameters (measured in mg/kg except eCEC and pH). Differences between ranked values tested using Kruskall-Wallis non-parametric analysis of variance. Standard error in parentheses. Parameters in bold indicate significance at P<0.01. a, b and c represent significant differences between community types at P < 0.05 (n = number of quadrats, P = probability, ns = not significant).

			Community Type			
	1	**2**	**3**	**4**	**5**	**P**
eCEC	4.7 (0.5)	4.9 (0.9)	4.3 (0.7)	2.6 (0.3)	5.5 (0.9)	ns
pH	**4.9 (0.0)[b]**	**5.0 (0.1)[ab]**	**4.8 (0.1)[b]**	**4.7 (0.1)[b]**	**5.3 (0.1)[a]**	**0.01**
P	**4.3 (0.2)[a]**	**7.2 (1.0)[bc]**	**9.1 (1.5)[b]**	**3.4 (0.4)[a]**	**7.0 (0.6)[c]**	**<0.01**
Ca	636.7 (60.5)	660.0 (148.0)	565.5 (112.7)	336.0 (57.3)	658.9 (112.5)	ns
K	116.4 (6.3)	132.0 (17.4)	139.4 (13.2)	112.8 (11.9)	144.4 (9.9)	ns
Mg	**140.0 (20.3)[a]**	**144.0 (21.6)[a]**	**115.9 (17.4)[ab]**	**69.8 (7.6)[b]**	**199.7 (36.2)[a]**	**<0.01**
B	**0.6 (0.0)**	**0.7 (0.1)**	**0.8 (0.1)**	**0.5 (0.0)**	**0.9 (0.2)**	**0.05**
Cd	0.01 (0.00)	0.01 (0.00)	0.01 (0.00)	0.01 (0.00)	0.02 (0.01)	ns
Co	**0.4 (0.1)[ab]**	**0.8 (0.3)[ab]**	**0.3 (0.1)[b]**	**0.2 (0.1)[b]**	**0.8 (0.2)[a]**	**<0.01**
Cu	**1.7 (0.3)**	**3.2 (0.4)**	**1.6 (0.2)**	**1.3 (0.3)**	**2.8 (0.7)**	**0.01**
Fe	**77.3 (3.7)**	**73.2 (5.0)**	**69.5 (7.2)**	**53.6 (3.4)**	**66.9 (9.6)**	**0.04**
Mn	121.1 (17.1)	170.8 (40.0)	94.8 (16.7)	90.6 (29.1)	147.0 (27.8)	ns
Mo	**0.01 (0.00)**	**0.01(0.00)**	**0.01(0.00)**	**0.01(0.00)**	**0.01(0.00)**	**0.05**
Na	**20.3 (2.1)**	**28.4 (4.2)**	**40.6 (8.4)**	**16.0 (1.9)**	**47.1 (15.4)**	**0.03**
Ni	0.3 (0.1)	0.4 (0.1)	0.3 (0.0)	0.2 (0.0)	0.3 (0.0)	ns
Pb	1.4 (0.5)	1.7 (0.7)	1.7 (0.4)	5.9 (2.9)	1.7 (0.4)	ns
S	9.8 (0.8)	10.4 (1.0)	14.5 (2.4)	11.0 (2.2)	8.0 (1.1)	ns
Zn	2.3 (0.9)	2.4 (0.5)	2.2 (0.3)	2.3 (0.7)	2.9 (1.2)	ns
n	18	5	11	5	9	

Table 4

Plant community mean values for physical site parameters; aspect (16 cardinal directions), slope (degrees), coarse fragment (CF) abundance (0 – no coarse fragments to 6 very abundant coarse fragments), Maximum size of coarse fragments (CF) (1 – fine gravelly to 7 – large boulders), Morph type (landscape morphology; 1 – crest, 2 – midslope, 3 – simple slope, 4 – flat, 5 – lowerslope), rock outcrop (RO) abundance (0 – no bedrock exposed to 5 – rockland), runoff (0 – no runoff to 5 – very rapid), % leaf litter and bare ground (1 – >70% to 4 – <10%). Differences between ranks tested using Kruskall –Wallis non-parametric analysis of variance. Standard error in parentheses. Parameters in bold indicate significance, a and b represent significant differences between community types at P < 0.05 (n = number of quadrats, P = probability, ns = not significant).

			Community Type			
	1	**2**	**3**	**4**	**5**	**P**
Aspect	5.4 (1.1)	6.4 (2.1)	6.5 (1.7)	9.0 (2.7)	8.2 (2.0)	ns
Slope	5.0 (1.1)	1.2 (2.5)	9.4 (2.4)	17.0 (4.1)	6.6 (1.8)	ns
CF Abundance	**3.6 (0.3)[ab]**	**4.2 (0.4)[ab]**	**3.8 (0.4)[a]**	**4.4 (0.2)[ab]**	**2.6 (0.5)[b]**	**0.01**
CF Max. Size	**3.8 (0.4)[ab]**	**3.6 (1.1)[ab]**	**4.2 (0.6)[a]**	**5.0 (0.3)[ab]**	**3.4 (0.5)[b]**	**0.02**
MorphType	**2.2(0.31)[ab]**	**1.8 (0.6) [ab]**	**1.5 (0.2)[b]**	**4.4 (0.6)[a]**	**2.9 (0.4) [ab]**	**<0.01**
RO Abundance	**1.0 (0.3)**	**2.4 (0.9)**	**1.5 (0.6)**	**1.6 (0.7)**	**0.4 (0.3)**	**0.01**
Runoff	1.4 (0.2)	2.0 (0.3)	1.5 (0.3)	2.6 (0.4)	1.6 (0.3)	ns
%Leaf Litter	**2.3 (0.3)**	**2.6 (0.4)**	**3.0 (0.2)**	**3.0 (0.3)**	**3.1 (0.3)**	**0.05**
% Bare Ground	**1.6 (0.2)**	**1.0 (0.0)**	**1.4 (0.2)**	**1.6 (0.6)**	**1.1 (0.1)**	**0.02**
n=	18	5	11	5	0	

APPENDIX 1

Flora list for Koolanooka and Perenjori Hills, including all taxa from the sampling quadrats and adjacent areas. Nomenclature follows Paczkowska and Chapman (2000), * indicates introduced taxon.

Adiantaceae

Cheilanthes adiantoides

Aizoaceae

* *Cleretum papulosum*
Gunniopsis rubra
* *Mesembryanthemum nodiflorum*

Amaranthaceae

Ptilotus drummondii
Ptilotus exaltatus var. *exaltatus*
Ptilotus gaudichaudii var. *gaudichaudii*
Ptilotus gaudichaudii var. *parviflorus*
Ptilotus grandiflorus var. *grandiflorus*
Ptilotus holosericeus
Ptilotus obovatus var. *obovatus*
Ptilotus polystachyus var. *polystachyus*

Anthericaceae

Arthropodium curvipes
Arthropodium dyeri
Caesia sp. Koolanooka Hills (R.Meissner and Y. Caruso 78)
Thysanotus manglesianus
Thysanotus pyramidalis
Tricoryne elatior

Apiaceae

Daucus glochidiatus
Platysace cirrosa
Trachymene cyanopetala
Trachymene ornata
Trachymene pilosa
Xanthosia bungei

Apocynaceae

Alyxia buxifolia

Asphodelaceae

Bulbine semibarbata

Asteraceae

Actinobole uliginosum
* *Arctotheca calendula*
Bellida graminea
Blennospora drummondii
Brachyscome ciliocarpa
Brachyscome perpusilla
Calocephalus multiflorus
Calotis hispidula
Calotis multicaulis
Cephalipterum drummondii
Ceratogyne obionoides
Erymophyllum ramosum subsp. *ramosum*
Gilberta tenuifolia
Gilruthia osbornei
Hyalosperma demissum
Hyalosperma glutinosum subsp. *glutinosum*
* *Hypochaeris glabra*
Lawrencella davenportii
Lawrencella rosea
Millotia dimorpha
Millotia myosotidifolia
Myriocephalus guerinae
Olearia dampieri subsp. *eremicola*
Olearia humilis
Olearia muelleri
Podolepis canescens
Podolepis lessonii
Podotheca gnaphalioides
Rhodanthe battii
Rhodanthe chlorocephala subsp. *rosea*
Rhodanthe collina
Rhodanthe laevis
Rhodanthe maryonii
Rhodanthe polycephala
Schoenia cassiniana
Senecio pinnatifolius var. *pinnatifolius*
* *Sonchus oleraceus*
* *Urospermum picroides*
Waitzia acuminata var. *acuminata*

Brassicaceae

* *Brassica tournefortii*
Lepidium oxytrichum
* *Sisymbrium erysimoides*
Stenopetalum filifolium
Stenopetalum lineare
Stenopetalum salicola

Caesalpiniaceae

Labichea lanceolata subsp. *brevifolia*
Senna artemisioides subsp. *filifolia*
Senna charlesiana
Senna sp. Austin (A. Strid 20210)

Campanulaceae

Wahlenbergia gracilenta
Wahlenbergia tumidifructa

Caryophyllaceae

* *Petrorhagia dubia*
* *Silene nocturna*
Spergularia sp.

Casuarinaceae

Allocasuarina acutivalvis subsp. *acutivalvis*
Allocasuarina acutivalvis subsp. *prinsepiana*
Allocasuarina campestris
Allocasuarina dielsiana

Chenopodiaceae

Enchylaena lanata
Maireana carnosa
Maireana georgei
Maireana marginata
Maireana planifolia
Maireana planifolia x *villosa*
Maireana thesioides
Rhagodia drummondii
Rhagodia preissii subsp. *preissii*
Sclerolaena diacantha
Sclerolaena fusiformis
Sclerolaena sp. Koolanooka Hills (R. Meissner & Y. Caruso 437)

Crassulaceae

Crassula closiana
Crassula colorata var. *acuminata*
Crassula colorata var. *colorata*
Crassula tetramera

Cuscutaceae

* *Cuscuta epithymum*

Cyperaceae

Lepidosperma sp. Koolanooka (Newbey 9336)
Schoenus nanus
Tetraria aff. *capillaris* (R.Meissner & Y.Caruso 51)

Dasypogonacea

Chamaexeros macranthera

Dilleniaceae

Hibbertia aff. *exasperata* (R.Meissner & Y.Caruso 56)
Hibbertia arcuata

Dioscoreaceae

Dioscorea hastifolia

Droseraceae

Drosera macrantha subsp. *macrantha*

Epacridaceae

Astroloma serratifolium

Euphorbiaceae

Calycopeplus paucifolius
Euphorbia boophthona
Poranthera microphylla
Ricinocarpos muricatus

Geraniaceae

Erodium cygnorum

Goodeniaceae

Brunonia australis
Goodenia berardiana
Goodenia mimuloides
Goodenia occidentalis
Goodenia pinnatifida
Scaevola spinescens
Velleia cycnopotamica
Velleia hispida
Velleia rosea

Haloragaceae

Gonocarpus nodulosus
Haloragis trigonocarpa

Lamiaceae

Hemigenia sp. Sticky Terete (B.H. Smith 449)
Westringia cephalantha

Lauraceae

Cassytha nodiflora

Lobeliaceae

Lobelia winfridae

Loganiaceae

Phyllangium sulcatum

Malvaceae

Sida atrovirens

Mimosaceae

Acacia acanthoclada subsp. *glaucescens*
Acacia acuminata
Acacia acuminata (narrow phyllode variant)
Acacia andrewsii
Acacia anthochaera
Acacia assimilis subsp. *assimilis*
Acacia cf. *coolgardiensis*
Acacia coolgardiensis subsp. *coolgardiensis*
Acacia daviesioides
Acacia erinacea
Acacia exocarpoides
Acacia graciliformis
Acacia lineolata subsp. *lineolata*
Acacia muriculata
Acacia neurophylla subsp. *erugata*
Acacia nigripilosa subsp. *nigripilosa*
Acacia ramulosa var. *ramulosa*
Acacia stereophylla var. *stereophylla*
Acacia tetragonophylla

Myoporaceae

Eremophila clarkei
Eremophila deserti
Eremophila latrobei subsp. *latrobei*
Eremophila oldfieldii subsp. *oldfieldii*
Eremophila oppositifolia subsp. *angustifolia*

Myrtaceae

Aluta aspera subsp. *hesperia*
Baeckea sp. Perenjori (J.W. Green 1516)
Calothamnus gilesii
Chamelaucium micranthum
Eucalyptus ebbanoensis subsp. *ebbanoensis*
Eucalyptus ebbanoensis subsp. *glauciramula*

Eucalyptus subangusta subsp. pusilla
Eucalyptus kochii subsp. *borealis*
Eucalyptus loxophleba subsp. *supralaevis*
Eucalyptus wubinensis
Eucalyptus oldfieldii
Eucalyptus salmonophloia
Malleostemon tuberculatus
Melaleuca atroviridis
Melaleuca barlowii
Melaleuca cordata
Melaleuca eleuterostachya
Melaleuca hamata
Melaleuca nematophylla
Melaleuca radula
Micromyrtus racemosa var. *racemosa*

Orchidaceae

Diuris porrifolia

Papilionaceae

Daviesia benthamii subsp. *benthamii*
Daviesia hakeoides subsp. *hakeoides*
Mirbelia microphylla
Mirbelia sp. Helena & Aurora (B.J. Lepschi 2003)

Phormiaceae

Dianella revoluta var. *divaricata*
Stypandra glauca

Pittosporaceae

Cheiranthera filifolia var. *simplicifolia*

Plantaginaceae

Plantago aff. *hispida* (R.Meissner & Y.Caruso 512)

Poaceae

Amphipogon caricinus var. *caricinus*
Aristida contorta
Austrodanthonia caespitosa
Austrodanthonia sp. Goomalling (A.G. Gunness et al. OAKP 10/63)
Austrostipa elegantissima
Austrostipa eremophila
Austrostipa hemipogon
Austrostipa scabra
Austrostipa trichophylla
* *Avena fatua*
* *Bromus madritensis*
* *Bromus rubens*
* *Ehrharta longiflora*
* *Lamarckia aurea*
* *Lolium perenne* x *rigidum*
Monachather paradoxus
* *Pentaschistis airoides* subsp. *airoides*
* *Rostraria pumila*
* *Elymus* sp.
* *Vulpia muralis*
* *Vulpia myuros*

Polygalaceae

Comesperma integerrimum

Polygonaceae

* *Acetosa vesicaria*

Portulacaceae

Calandrinia aff. *eremaea* (R.Meissner & Y.Caruso 533)
Calandrinia calyptrata
Calandrinia eremaea complex
Calandrinia sp. Blackberry (D.M. Porter 171)
Calandrinia sp. Bungalbin (G.J. Keighery & N. Gibson 1656)

Proteaceae

Grevillea levis
Grevillea obliquistigma subsp. *obliquistigma*
Grevillea paradoxa
Hakea minyma
Hakea recurva
Persoonia pentasticha

Rhamnaceae

Stenanthemum poicilum

Rutaceae

Drummondita rubroviridis
Phebalium tuberculosum
Philotheca brucei subsp. *brucei*

Santalaceae

Santalum acuminatum

Sapindaceae

Dodonaea adenophora
Dodonaea inaequifolia
Dodonaea scurra

Solanaceae

Nicotiana rosulata subsp. *rosulata*
Solanum ellipticum
Solanum sp.

Stylidiaceae

Levenhookia stipitata
Stylidium confluens

Thymelaeaceae

Pimelea avonensis

Urticaceae

Parietaria cardiostegia

Zygophyllaceae

Zygophyllum apiculatum
Zygophyllum eremaeum

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Flora and vegetation of banded iron formations of the Yilgarn Craton: Jack Hills

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ABSTRACT

A study of the flora and plant communities of Jack Hills, 140 km WNW of Meekatharra, found 208 taxa, with 205 native and 3 weeds. Two priority taxon was found and two new species identified. Fifty quadrats were established to cover the major geographical, geomorphologic and floristic variation across the hills. Data from these quadrats were used to define six community types. Differences in communities were strongly correlated with altitude and soil fertility. Several communities had restricted distributions. None of the plant communities found on the Jack Hills is reserved in conservation estate.

INTRODUCTION

Banded iron formation ranges within the Yilgarn Craton are highly prospective for iron ore exploration and mining. Previous studies on greenstone and banded ironstone ranges in the Goldfield have found high plant endemicity and restricted vegetation types. It is hypothesised that these patterns may also be found on the ironstone ranges in the Yilgarn (Gibson et al. 1997; Gibson & Lyons 1998a,b; Gibson & Lyons 2001a,b; Gibson 2004a,b). The current knowledge of the flora and vegetation that occur on these ranges is poor and based primarily on the structural description of the dominant vegetation (Speck 1963; Beard 1976; Curry et al. 1994) rather than the community composition.

The study area is located approximately 140 km WNW of Meekatharra and covers the major extent of Jack Hills, approximately 40 km from the Berringarra-Cue Road to Mount Taylor. The range runs in a prominent NE-SW direction (Figure 1). The south west part of the range extends across Berringarra-Cue Road, but this area was not surveyed.

The climate of the region is arid with mild winters and hot summers. Mean annual rainfall at Meekatharra is 235.9 mm, with much variation in rainfall (112.9mm 1st decile; 368.9 9th decile; recorded 1994 to 2004). Annual rainfall has a bimodal distribution with summer and winter rainfall. Summer rainfall, peaking in January and February, is influenced by cyclonic activity off the Pilbara coast of Western Australia. Cyclones that cross the coast dissipate and develop into rain bearing depressions which may bring rain inland. In addition, thunderstorm may develop from convectional activity (Curry et al. 1994). Winter rainfall is often the result of cold frontal activity associated with low pressure systems in the south west of Western Australia. These systems often weaken as they move inland and result in isolated showers and strong winds (Curry et al. 1994). The highest maximum temperatures occur during summer, with the January as hottest month (mean maximum temperature 38.9 °C and mean 11.3 days above 40 °C). Winters are mild with lowest mean maximum temperatures recorded for July of 18.9 °C. Temperatures rarely fall below 2 °C in winter, with mean minimum of 7.4°C in July.

Jack Hills is located in the Murchison geological province in the northwest part of the Yilgarn Craton. It differs locally from the Weld Range, 90 km south, although formed during the same tectonic phase, as it mainly contains metasedimentary rock rather than the metavolcanics of the Weld Range (Elias 1982). Jack Hills is dominated by pelitic and psammitic metasediments such as quartz-mica schists, banded iron formations and chert. The latter two form units several centimetres to several hundred metres thick as prominent strike ridges within the range (Elias 1982).

The area surrounding Jack Hills is topographically flat, with the more erosion resistant range of Banded Ironstone prominent in the landscape. Colluvial deposits are present in a valley between a divide in the range, resulting in deeper sandier soils, than the colluvial deposits exterior to the range. This is probably a result of sheetwash across a larger area exterior to the hills, rather than the smaller constricted area between two ridges. Skeletal soils are found on the crests and hill slopes of the range. The shallow soils are formed when erosion is greater than the weathering process resulting in relatively thin soil profile and extensive rock outcrop (Gray & Murphy 2002)

Jack Hills occurs in the Murchison IBRA region, which is characterised by open mulga (*Acacia aneura*) woodlands and a rich diversity in ephemerals (Environment Australia 2000). Beard (1976) describes the dominant cover of *Acacia aneura* and *A. grasbyi*.

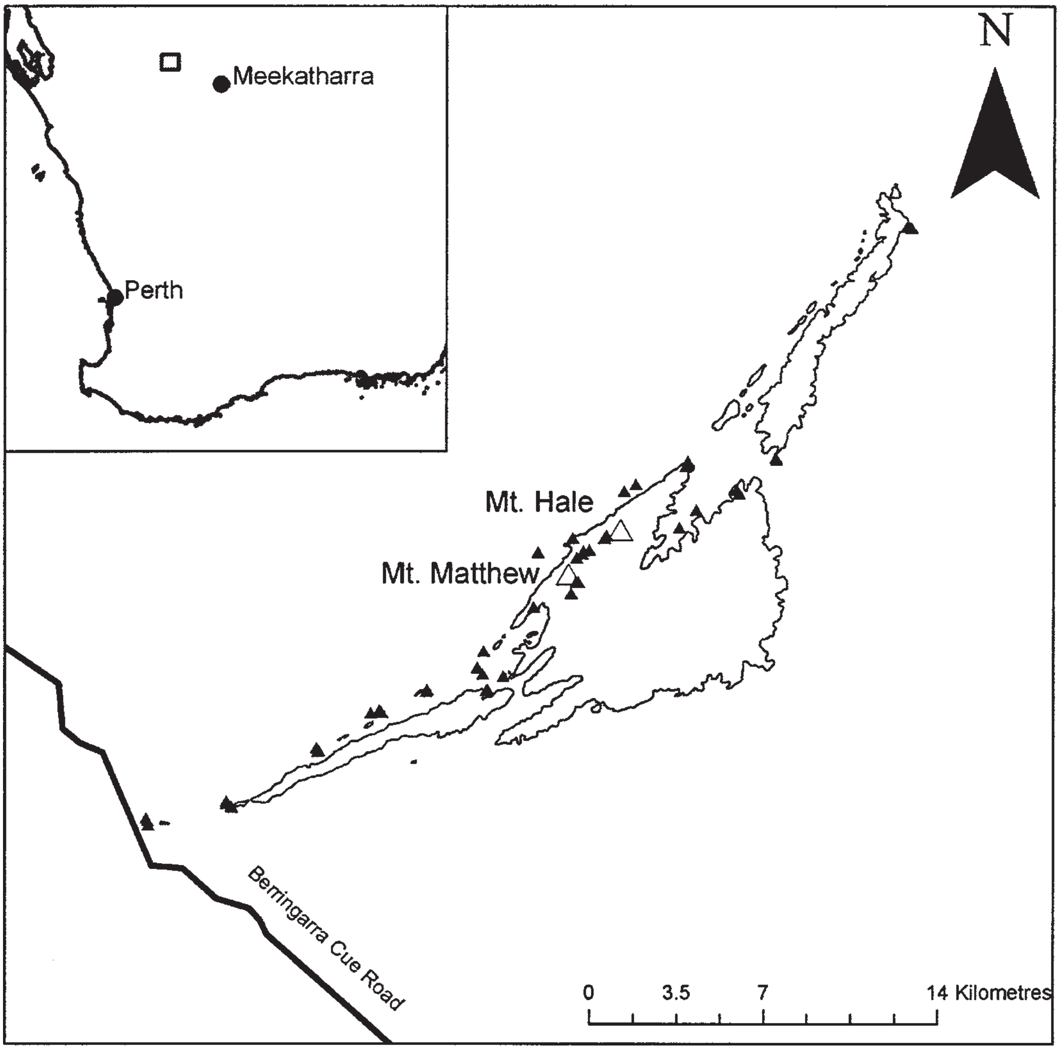

Figure 1. Location of the study area and distribution of the 50 quadrats (▲) along the Jack Hills. Mount Matthew and Mount Hale are the highest peaks (Δ) on the range. The 340m contour is shown.

Speck (1963) and later Curry et al. (1994) mapped land systems at a similar scale. Jack Hills is in the Weld land system, which covers the Weld Range to the south. The vegetation consists of rocky hills with mixed shrubland, minor areas of stony soils with mulga mixed shrubland, and shrublands on valley floors.

The aim of this work was to undertake a detailed floristic survey of the Jack Hills and to identify the plant communities that occur on the range. This was achieved by detailed flora list, and description of plant communities based on a series of permanently established quadrats. The survey of the Jack Hills will be part of a larger regional study of flora and plant communities of banded ironstone formations of Yilgarn Craton.

METHODS

Fifty 20 x 20 m quadrats were established on Jack Hills in August 2005 (Figure 1). The location of quadrats attempted to cover the major geographical, geomorphologic and floristic variation found on the hills in the study area. Each quadrat was permanently marked with four steel fence droppers and their positions determined using a GPS unit. All vascular plants within the quadrat were recorded. Data on topographical position, disturbance, abundance, size and shape of coarse fragments on surface, the amount of exposed bedrock, cover of leaf litter and bare ground were recorded following McDonald et al. (1990). Additionally, growth form, height and cover were recorded for dominant taxa in each strata (tallest, mid- and lower).

Twenty soil samples were collected from the upper 10 cm of the soil profile within each quadrat. The soil was bulked and the 2mm fraction analysed for B, Ca, Cd, Co, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S and Zn using the Mehlich No. 3 procedure (Mehlich 1984). The extracted samples were then analysed using Inductively Coupled Plasma – Atomic Emission Spectrometer (ICP-AES). This procedure is an effective and cost efficient alternative to traditional methods for evaluating soil fertility and has been calibrated for Western Australian soils (Walton & Allen 2004). pH was measured in 0.01M $CaCl_2$ at soil to solution ratio of 1:5. Effective cation exchange capacity (eCEC) was calculated from the sum of exchangeable Ca, Mg, Na and K (Rengasamy & Churchman 1999). Exchangeable Ca, Mg, Na and K were obtained by multiplying the values of Ca, Mg, Na and K obtained from ICP-AES by a standard constant.

Quadrats were classified on the basis of similarity in species composition on perennial species only, to be consistent with other analyses of banded ironstone ranges (see Gibson 2004 b). Taxa identified to species level and occurring in more than one quadrat were used in the floristic analysis. Life form followed Paczknowska and Chapman (2000), where perennial is defined as a plant whose life span extends over 2 or more growing seasons.

The quadrat and species classifications were undertaken using the Bray and Curtis coefficient and Flexible UPGMA (Unweighted pair-group mean average; â = - 0.1; Belbin 1989). Indicator species and species assemblages characterising each community were determined following Dufrene and Legendre (1997) using INDVAL routine in PC-ORD (McCune & Mefford 1999). Quadrats were ordinated using SSH (semi-strong hybrid multidimensional scaling), correlations of environmental variables were determined using the PCC (Principal Component Correlation) routine and significance determined by the MCAO (monte-carlo attributes in ordination) permutation test in PATN (Belbin 1989). PCC is a routine that runs multiple linear regressions on the variables and the ordination coordinates, resulting in a vector for each variable within the ordination plot. The MCAO is a monte-carlo test determining the robustness of the PCC results by randomly assigning values of variables to objects and then running the PCC routine (Belbin 1989).

Statistical relationships between quadrat groups were tested using Kruskall-Wallis non parametric analysis of variance (Siegel 1956) followed by non-parametric comparison (Zar 1999). Correlations between environmental parameters were analysed using Spearman Rank correlation coefficient.

Nomenclature generally follows Paczkowska and Chapman (2000).

RESULTS

Flora

A total of 209 taxa, from 98 genera and 43 families as recorded from the 50 established quadrats or adjacent areas. The best represented families were Asteraceae (41 taxa), Poaceae (17), Mimosaceae (16), Malvaceae (12) and Myoporaceae (12).

Rare and Priority Flora

Two priority three (P3) species were found during the survey of Jack Hills, *Gunniopsis propinqua* and *Homalocalyx echinulatus* .

- *Gunniopsis propinqua* (P3) is a small prostrate succulent herb growing on low outwash areas or flats. Only one collection was made from an open drainage channel in a valley.
- *Homalocalyx echinulatus* (P3) is a low growing myrtaceous shrub to 1m, growing on breakaways, sandstone hills and laterite in the northern area of the Murchison IBRA region. A single collection was made from a colluvial outwash.

New taxa

Three new taxa, *Prostanthera ferricola*, *Lobelia heterophylla* subsp. Pilbara (R.Meissner & Y.Caruso 1), and *Acacia* sp. Jack Hills (R. Meissner & Y. Caruso 4) were collected during the Jack Hills survey.

- *Prostanthera ferricola* is a highly aromatic shrub to 1 m with purple mauve flowers. The shrubs are highly palatable and were heavily grazed by feral goats. Initially, the collections at Jack Hills were matched to a specimen collected by G. Byrne from Doolgunna station in 2003, approximately 100 km north of Meekatharra. Subsequent taxonomic work identified the Doolgunna specimen as a distinct new species, *P. ferricola*. Its taxonomic affinities remain unclear, but it is morphologically similar to *P. centralis*, but differs significantly by having smaller leaves and short, patent indumentum (Conn & Shepherd 2007).
- *Lobelia heterophylla* subsp. Pilbara (R.Meissner & Y.Caruso 1) was identified as a subspecies of *L. heterophylla*, previously collected in the Pilbara. This taxon is a small herb to 20 cm with bright blue flowers, and serrated leaves. It has been found growing in two localities on Jack Hills. In this survey, it was found growing abundantly on a small ironstone outcrop approximately 5 km east of the Berringarra-Cue Road. Additional collections were recorded from *Triodia* shrubland between Mount Matthew and Mount Hale. Further work and collections need to be made to determine the taxonomic rank of this herb.
- *Acacia* sp. Jack Hills (R. Meissner & Y. Caruso 4) is a multi-stemmed shrub to 2.5 m with bright green phyllodes. Initially it was thought to be *Acacia cockertoniana* on account of the generally features of its phyllodes and flowers, but it differs significantly in having elongated flowering spikes and less resinous phyllodes (Maslin 2007).

Range extensions

- *Actinobole drummondianum* is a small prostrate daisy to 10 cm with small white to cream flowers. It was collected from a valley flat growing in red sandy loam soil. It is known from the Carnarvon IBRA region, growing in creeklines and hillsides. The single collection extends its range east by approximately 200 km.
- *Calandrinia disperma* is a prostrate succulent annual

to 10 cm. It has been poorly collected with only 11 collections in the Western Australian Herbarium. This survey collected *C. disperma* from two locations, a valley flat and a small crest. The survey has extended the range by nearly 400 km eastward.

- *Petalostylis labicheoides* is an erect shrub to 4 m with bright yellow flowers. A single specimen was collected during the survey growing in the spinifex community between Mount Matthew and Mount Hale. This species is common in the Pilbara region and this collection extends it southern range by approximately 200km.
- *Rhodanthe polycephala* is an annual daisy with small yellow flowers to 10 cm. It was found growing on the slopes between Mount Hale and Mount Matthew, in the spinifex community. It is known mainly in the southwest of Western Australia and has been previously recorded growing on ironstone hills. The collections extend its range north east by nearly 300 km.
- *Trachymene ceratocarpa* is a small annual herb to 10 cm with white to blue flowers. A single specimen was collected during the survey from a low valley flat occurring between the two strike ranges in the main area of Jack Hills. This species is mainly known from the northern Geraldton Sandplains but has also been collected from pastoral stations within Yalgoo and Coolgardie IBRA regions. The single collection extends it range north east by approximately 300 km.
- *Triodia melvillei* is a perennial hummock grass to 0.5 m with resinous culms. It is well collected and is found growing in a range of habitats, such as sandplains, dunes and rocky hills. This a range extension of approximately 200 km based upon herbarium records. It has been previously reported by (Speck 1963 cited in Beard 1976). This species was common on the upper slopes of Mount Matthew and Mount Hale.

Taxa requiring further study

Several taxa collected during the survey are of taxonomic interest for several reasons: they could not be identified beyond genus, even with sufficient floral and fruiting material; the species was a hybrid; or the current taxonomy of the genus needs revision. Only species from the first two reasons are described below. Further taxonomic work and additional collections need to be made to determine their significance and status.

- *Abutilon* sp. (R.Meissner & Caruso 136) is a short lived perennial collected from 4 quadrats in a variety of different communities. It was collected from midslope, breakaways and rocky outcrops. The species could not be identified to species level even though floral material was present.
- *Glycine* sp. (R.Meissner & Y.Caruso 110) is a leguminous climber to 20 cm found growing in a creekline. This collection could not be determined further than genus and showed no affinity to currently known taxa.
- *Gunniopsis* aff. *divisa* (R.Meissner & Y.Caruso 125) is small succulent herb collected from a lower slope/flat. It could not be matched to any collection but exhibits affinity to *G. divisa*. This taxon has been collected previously and misidentified under *G. divisa*. Further taxonomic work and additional collections need to be undertaken.
- *Hibiscus* sp. (R.Meissner & Y.Caruso 123) is a small short lived perennial to 20 cm with purple flowers. Two collections were made of this species from a creekline and a small ironstone crest. It was not possible to identify it beyond genus, and it did not show affinity to known species.
- *Indigofera* aff. *australis* is a small herb to 30 cm found growing on a banded ironstone outcrop. Taxonomically closest to *I. australis* but differs in leaf morphology, possessing five instead of eight leaflets.
- *Senna stricta* x *artemesioides* subsp. *petiolaris* (E.N.S. Jackson 2888) is a shrub to 1.5 m collected from sites in close proximity to each other. This hybrid was recognised as a new entity of *Senna* following collections from the Weld Range and this study. These collections were also matched to an earlier misidentified collection within the Western Australian Herbarium. Hybridisation within *Senna* is common (Randell 1989) and several other *Senna* hybrids were found within the survey.

In the survey area, the dominant acacia is *Acacia aneura* (mulga). This species shows a large amount of variation in morphology, within and between populations, readily hybridises and is a taxonomically diverse group (Miller et al. 2002). This causes a great deal of difficulty in identification in the field and the herbarium. Due to the difficulty in identification, the collections were placed in morphological groups consisting of 3 varieties; *Acacia aneura* cf. var. *aneura*, *A. aneura* cf. var. *tenuis* and *A. aneura* cf. var. *microcarpa*.

Plant Communities

Sixty perennial species, perennial taxa identified to species level and species occurring in more than one quadrat were in the final analysis. A preliminary analysis between the full and perennial data set showed a correlation of 0.63.

Community groups were separated into 6 groups, based upon clear patterning in the final dendrogram (Figure 2). The first split in the dendrogram separates Community 6 from the remaining community types, indicating that this community is distinctly different from the other plant communities found on Jack Hills. Community 6 also had a restricted distribution between Mount Hale and Mount Matthew while the other community types were more widely distributed across the range. These divisions can also be clearly seen in the sorted two-way table of the sites and species classification (Table 1).

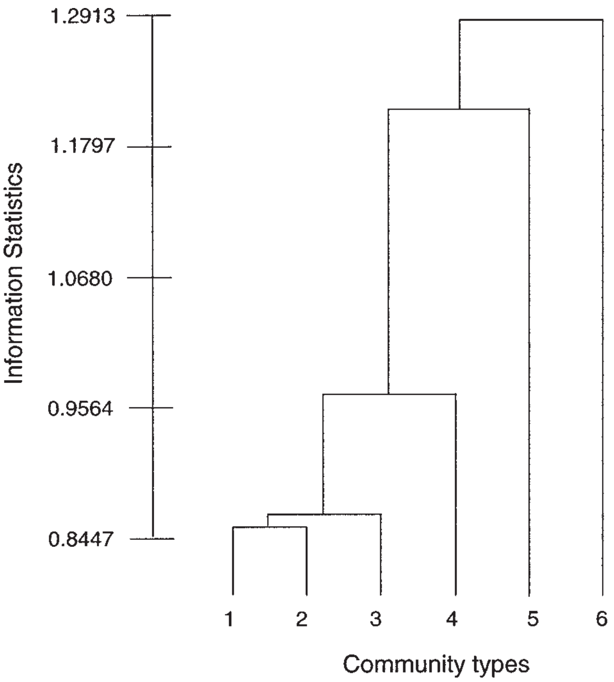

Figure 2. Dendrogram of 6 group level classification of the 50 quadrats established on Jack Hills.

Community 1 – Open woodlands and woodlands of *Acacia* spp. (dominants are *Acacia aneura cf.* var. *aneura*, *Acacia ramulosa* var. *linophylla*, *Acacia rhodophloia*) over shrublands of *Ptilotus obovatus* subsp. *obovatus* or *Eremophila* spp. This community is found along the entire range and across a variety of landscapes but mainly on creeklines and lower slopes. Mean species richness (including annual taxa) was 31.9 ±0.6 taxa per quadrat. Taxa from species group A characterise this community (Table 1). There were only two indicator species, *Enneapogon caerulescens* and *P. obovatus* subsp. *obovatus*.

Community 2 – Woodlands and shrublands and of *A. aneura* cf. var *aneura* or *A. aneura* cf. var. *tenuis* occasionally associated with *A. rhodophloia* woodlands over shrublands of *P. obovatus* subsp. *obovatus* and *Dodonaea petiolaris*. The community was found along the entire range mainly on crests and midslopes and was very similar to Community 1. However, it has lower species richness (mean taxa per quadrat 24.2 ±0.4) and *D. petiolaris* was characteristically present (Table 1).

Community 3 – Open woodlands, woodlands and shrublands of *A. aneura* cf. var. *aneura* and *Acacia citrinoviridis* over *P. obovatus* subsp. *obovatus*. This community was found on crests and midslopes of rocky outcrops on the entire range. Its main species are from Species Group A and species richness was similar to community 2 (mean 25.6 ±0.6 taxa per quadrat) (Table 1). Indicator species for this community are *A. citrinoviridis*, *Cheilanthes brownii*, *E. caerulescens*, *Neurachne minor* and *Sida chrysocalyx*.

Community 4 – Isolated trees of *Acacia stowardii* or woodlands of *A. aneura* cf. var. *tenuis*, *A. stowardii* and *Acacia kempeana* over sparse shrublands. This community was represented by only 2 quadrats, one on colluvial outwash and the other on a small ironstone crest, respectively. Both quadrats are low in perennial species and are represented by taxa in Species Group C and D (Table 1). The quadrats had low species richness of 23.0 ± 1.0 taxa per quadrat. The low number of species, the absence of species in Group A and the few species in common likely resulted in the quadrats grouping together. Indicator species were *A. kempeana*, *A. stowardii*, *Maireana villosa* and *Senna glaucifolia*.

Community 5 – Open woodlands, woodlands and isolated trees of *A. aneura cf.* var. *aneura* over shrublands of *Eremophila* spp. The community consisted of 5 quadrats of species poor (mean richness 20.8 ± 0.9 taxa per quadrat) colluvial outwashes and one low crest in the south west end of the range. The community was characterised by species from Group G and two indicator species, *A. aneura* cf. var. *aneura* and *Eremophila macmillaniana* (Table 1).

Community 6 – Shrublands of *Acacia* sp. Jack Hills (R. Meissner & Y. Caruso 4), *Philotheca brucei* subsp. *cinerea*, *Eremophila* spp. over hummock grasslands of *T. melvillei.* Occasionally present in the community are isolated trees of *A. citrinoviridis, Acacia pruinocarpa* and *Grevillea berryana*. This community is found on the slopes of Mount Matthew and Mount Hale. It had one of the highest species richness of all the communities (mean of 30.4 ± 0.6 taxa per quadrat), and is especially rich in perennial species. It is characterised by species in group H (Table 1). Indicator species were *A.* sp. Jack Hills (R. Meissner & Y. Caruso 4), *Cheilanthes sieberi* subsp *sieberi*, *Eremophila exilifolia*, *Eremophila jucunda* subsp. *jucunda*, *G. berryana*, *Halgania gustafsenii* var. *gustafsenii*, *Hibiscus sturtii* var. *sturtii*, *P. brucei* subsp. *cinerea, Thysanotus manglesianus* and *T. melvillei.*

Physical Parameters

The soil parameters showed significant intercorrelations ($P < 0.05$). Iron showed significant positive correlations with all physical site characters except aspect and leaf litter cover ($P < 0.05$). Altitude was strongly correlated with all physical site character except aspect and runoff. Slope also correlated strongly with most of the physical site characters apart from aspect, rock outcrop abundance and % bare ground (Table 2).

Community 2 and 6 were lower in pH than Community 1 but similar to Community 3 and 5. However, Community 6 has significantly higher levels of iron than Community 2 (Table 3). Communities 1, 2 and 3 had the highest levels of phosphorus and differed significantly from Community 5, with the lowest phosphorus values (Table 3). Community 5 also differed from Community 3 and 6 in higher nickel levels but had lower sulphur levels than Community 3 (Table 3). Community 4 was excluded from the post-hoc analysis due to low sample size (2 quadrats).

Altitude separates Community 6 from Communities 1, 2 and 5, which all occur lower in the landscape (Table 4). Community 3 is the only community similar in altitude to Community 6, while Community 5 is the lowest in the landscape (Table 4). Community 5 had occurred on sites with gentle inclines, located on lower slopes and creeklines. Community 2 and 6 have higher coarse fragment abundance than Community 1, but similar to Community 3 and 5 (Table 4).

The three dimensional ordination (stress = 0.21) clearly separated the spinifex community (Community 6) from the other 5 communities. Community 6 sites plot in the lower left quadrant ordination (Figure 3). The species poor communities 4 and 5 are spread across the ordination indicating large variability in species composition between the quadrats, a result of low numbers of perennial species. Sites from the most common plant communities (1 and 2) across Jack Hills occur on the upper and lower right quadrants respectively, and overlay each other slightly with Community 3 occupying the centre of the ordination.

Altitude was strongly correlated with the communities ($P < 0.01$; Figure 3). Community 6 occurred higher in the landscape on the slopes and gullies between the highest peaks of the range, while at the opposite end of the gradient, Community 1 was found mainly on lower slopes and outwashes of the range. Magnesium and pH were strongly correlated in the ordination ($P<0.01$), with Community 1 having higher pH and magnesium than Communities 2 and 6, while Communities 3 and 5 showed intermediate values. Although significant in the post-hoc analysis, phosphorus was not correlated with the position of the sites in the ordination as the relationship was non-linear.

DISCUSSION

Flora

The number of taxa recorded was lower at Jack Hills, as was the occurrence of the Myrtaceae, when compared to

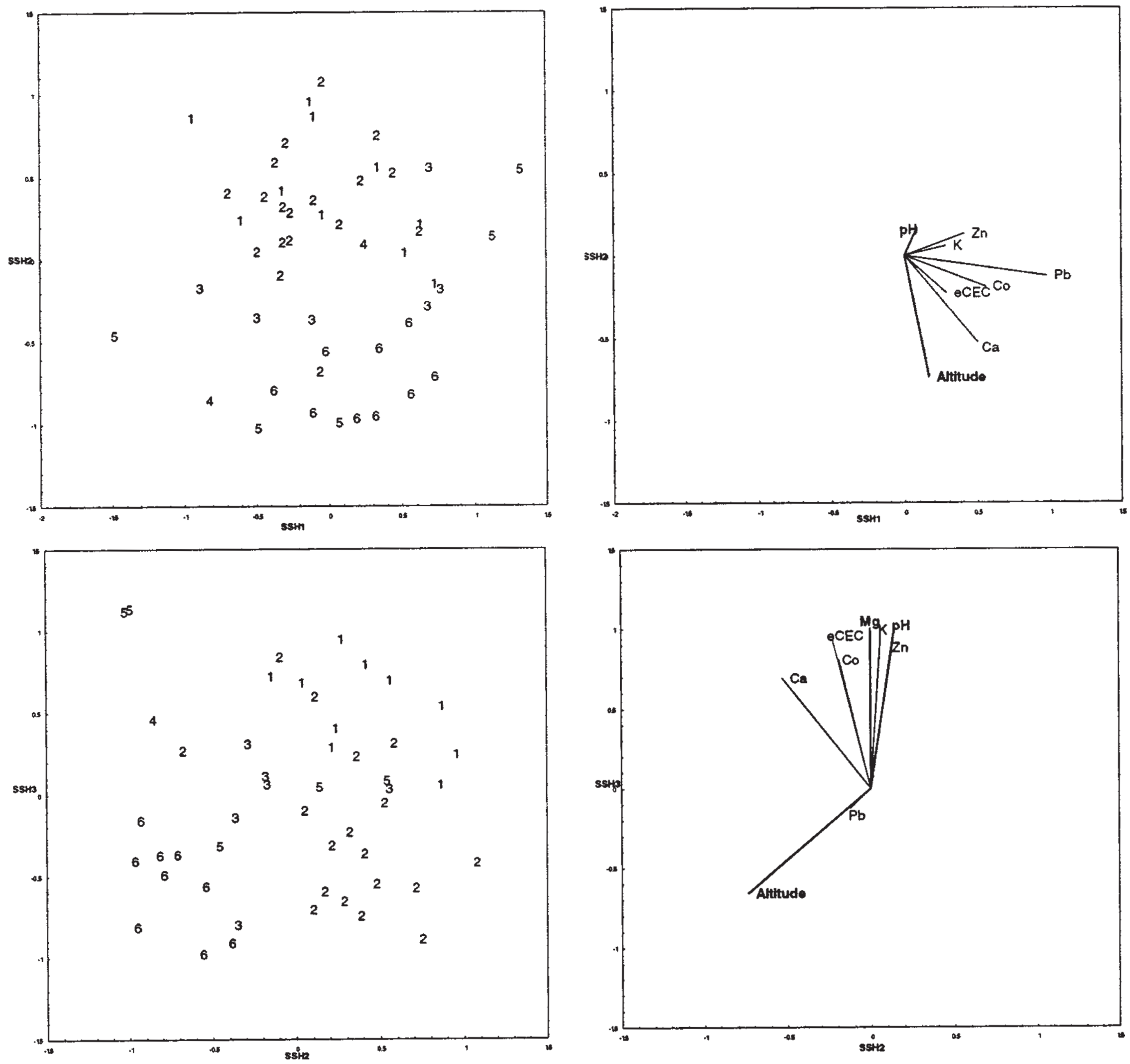

Figure 3. Three dimensional ordination showing Axis 1, 2 and 3 of the 50 quadrats established on Jack Hills and represented by community type. Lines represent the strength and direction of the best fit linear correlated variables. Bold and plain lines represent significance at P < 0.01 and P < 0.05 respectively.

studies on ranges in the eastern Goldfields (see Gibson et al. 2004b). The concurrent survey of the banded iron communities at Weld Range found 243 taxa (*cf.* 209 at Jack Hills) and similar patterns in dominant perennial families (Markey & Dillon, 2008). The shift in dominance of the perennial families from Myrtaceae in the goldfields to Mimosaceae and Myoporaceae reflects the greater aridity of Jack Hills (Beard 1976).

Annuals were a large component of the flora of Jack Hills, comprising over 50% of the species recorded, and this is similar to composition found at the Weld Range (Markey & Dillon, 2008). The season was good due to early rainfall, which encouraged the abundance of ephemeral species, indicated by the dominance of Asteraceae (41 taxa).

In the Jack Hills region, rainfall is bimodal resulting in different annual communities, grasses predominating following summer rainfall, and Asteraceae dominate the annuals following winter rain (Mott 1972). At any given time, perennials will always be present, but the abundance and composition of annuals will differ between years. Annuals were a significant component of the 2005 season because of above average rainfall and showed a different pattern from the perennial dataset.

Three new taxa were identified during the survey, a small herb, *L. heterophylla* subsp. Pilbara (R.Meissner & Y.Caruso 1), an aromatic shrub, *P. ferricola* and *A.* sp. Jack Hills (R. Meissner & Y. Caruso 4), with the latter found only on Jack Hills. *Lobelia heterophylla* subsp. Pilbara (R.Meissner & Y.Caruso 1) is found at several sites in the Pilbara and this complex is currently being reviewed. *Prostanthera ferricola* appears to be restricted to a smaller area from Weld Range to Doolgunna station. The current mining proposal would impact on several populations of these taxa.

Acacia sp. Jack Hills (R. Meissner & Y. Caruso 4) was the only endemic taxon to Jack Hills. This taxon was mainly found growing on ironstone in the spinifex community between Mount Matthew and Mount Hale (Community 6) and is currently known from only a few flowering specimens. Further taxonomic and genetic work needs to be undertaken to determine the relationship with *Acacia cockertoniana*, an ironstone endemic and its closest relative.

Plant Communities

Altitude appears to be the strongest environmental variable correlated with the distribution of the communities on the Jack Hills. Communities 1, 2 and 5 were all lower in the landscape. Community 1 occurred mainly on lower slopes and creeklines on soils of intermediate fertility, while Community 5 was found on colluvial outwashes of Jack Hills on lower phosphorus soils. Community 2 occurred, on crests and midslopes slightly higher in the landscape than 1 and 5. Community 3 was found at a higher altitude than Community 1, 2 and 5. This community was found mainly on the crests and midslopes sites, with high cover of surficial rock.

Altitude is possibly a correlate for other variables not recorded or recognised in the survey, such as soil depth and rock type. Skeletal soils and poor nutrients have previously been correlated with at higher elevations and topographic class (ie. crests and upper slopes) (Gibson & Lyons 1998a, 1998b). The presence of the communities (3 and 6) on the upper slopes and crests, and associated with higher surficial rock, may be related to the nutrient poorer soils, as indicated on the ordination (Figure 3).

Community 6, the species rich spinifex community, was restricted to higher elevations in the range, between Mount Matthew and Mount Hale. This community had the highest perennial species richness of all the communities found on the range. In addition, a number of species found in this community were not recorded elsewhere on the range. The community has a lower pH and nickel, but these values were not significantly different to several of the other communities. *Triodia* grasslands are the dominant vegetation in arid regions, occurring across the landscape in the Pilbara region to the north and in the eastern parts of the Murchison on sandplains (Beard 1976). Recent preliminary surveys have found spinifex communities on the upper slopes of Mount Gould and Robinson Ranges. All these communities are dominated by *T. melvillei*, but have different suites of perennial species e.g. *Acacia* sp. Jack Hills (R.Meissner & Y.Caruso 4) and *Halgania gustafsenni* occur only in the Jack Hills community (R. Meissner, unpublished data). Further surveys are needed to clarify their relationships to Community 6 on Jack Hills.

Early vegetation mapping in the Murchison region described the vegetation at a broad scale. Beard (1976) mapped the Weld Range and Jack Hills as the same vegetation unit, while Speck (1963) and Curry et al. (1994) mapped the ranges within the same landsystem. Vegetation on the Weld Range is quite distinct from Jack Hills with only 57% of the taxa recorded on Jack Hills found on the Weld Range, and the majority of the common taxa were annuals (Markey & Dillon, 2008). The landforms are morphologically similar, but geologically different, with the Weld Range dominated more by basalt.

The Weld Range had a higher number of perennial species and greater species richness than Jack Hills. There were no communities in common between the two ranges (Markey & Dillon, 2008). Both ranges are dominated by mulga (*Acacia aneura*) communities; however, the associated dominant species were different. For example, the dominant community (1b) on Weld range was characterised by *A. aneura*, *Acacia* sp. P129 and *G. berryana* over a shrub layer of *Eremophila* spp. (Markey & Dillon, 2008). Notably, *Acacia* sp. 129 and *Eremophila georgei* were not recorded on Jack Hills.

Mining exploration is continuing in the Jack Hills area. This is focussed especially in the area where the restricted upland spinifex community is found. If the current mining proposal proceeds approximately 20% of this community will be removed (Mattiske 2005). There is an urgent need to fully document the plant variation within this community. None of the communities identified in this survey is currently in a conservation reserve.

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Table 1

Sorted two-way table of quadrats established Jack Hills showing species by community type. Taxa shaded grey within a community are indicator species identified by INDVAL (Dufrene & Legendre 1997) at the 6 group level (* P< 0.05; ** P<0.01; statistical significance tested by randomisation procedures).

	Community Type 1	2	3	4	5	6
SPECIES GROUP A						
* *Abutilon oxycarpum*	•		••• (shaded)			
* *Enneapogon caerulescens*	•••••• (shaded)	•	••			
** *Acacia citrinoviridis*		••	•••••• (shaded)			•••
Monachather paradoxus	••••	•••••••••	••••	•		
** *Neurachne minor*	•	••	••••• (shaded)			
** *Sida chrysocalyx* ms	••	•••••	•••••• (shaded)	•		•
* *Cheilanthes brownii*	•	••••	••• (shaded)			
** *Acacia aneura* cf. var. *aneura*	•••••	••••••••	••		••••• (shaded)	•
** *Dodonaea petiolaris*	•••	•••••••••••••••• (shaded)				•
Ptilotus schwartzii		•••••••••••	•••			••••
** *Ptilotus obovatus* var. *obovatus*	•••••••••• (shaded)	•••••••••••••••••• (shaded)	•••••• (shaded)	•		•••••••• (shaded)
Solanum ashybii/lasiopetalum complex	••••••••	••••••••••••	••••	•	•	••
Sida atrovirens	•••	•••••••••	•			•••••
Acacia rhodophloia	••	••••••••		•	•	•
SPECIES GROUP B						
Corchorus crozophorifolius	•	•••				
Eragrostis lanipes	•	•				
SPECIES GROUP C						
Acacia aneura cf. var. *tenuis*		•••		•	••	•
Eremophila glutinosa	•			•	•	
* *Maireana villosa*		•		• (shaded)		
SPECIES GROUP D						
* *Acacia kempeana*		••		• (shaded)		
Maireana georgei		••				
Acacia tetragonophylla	•••	•				
Eragrostis eriopoda	•	•••••			•	
SPECIES GROUP E						
** *Acacia stowardii*		••		•• (shaded)		•
Sclerolaena eurotioides	••••	•		•	•	
Senna artemisioides subsp. *helmsii*	••			•		
** *Senna glaucifolia*	••			•• (shaded)		
SPECIES GROUP F						
Acacia pruinocarpa	•					•
Sida ectogma	•					•
Acacia ramulosa var. *linophylla*	••••		••		•	
Sida aff. *intricata* (R.Meissner & Y.Caruso 119)	••					
SPECIES GROUP G						
Cymbopogon ambiguus		•	•		•	•
Tribulus suberosus		••		•	•	
Maireana melanocoma		•			•	
Thysanotus speckii		•			•	
* *Eremophila macmillaniana*	••				•••• (shaded)	
Eremophila phyllopoda subsp. *phyllopoda*	•				••	
Maireana triptera	•				•	
Sclerolaena eriacantha	••	•			••	
Senna stricta x artemesioides subsp. *petiloaris* (E.N.S. Jackson 2888)					••	
Senna sp. Meekatharra (E. Bailey 1-26)		•			••	
SPECIES GROUP H						
Acacia aneura cf. var. *microcarpa*	•	•••				••
Aluta aspera subsp. *hesperia*						••
Mirbelia rhagodioides		••				•••
* *Acacia* sp. Jack Hills (R. Meissner & Y. Caruso 4)		•	•			••••• (shaded)
Thryptomene decussata		•••••	•			••••
Eremophila latrobei subsp. *latrobei*	•••	••	••		•	••••
* *Cheilanthes sieberi* subsp. *sieberi*		••	•		•	••••••• (shaded)
* *Thysanotus manglesianus*		•	••			••••••• (shaded)
* *Halgania gustafsenii* var. *gustafsenii*		••••	•			•••••••• (shaded)
** *Hibiscus sturtii* var. *forrestii*		••				••••••••• (shaded)
** *Triodia melvillei*						••••••••• (shaded)
* *Philotheca brucei* subsp. *cinerea*						••••• (shaded)
* *Eremophila jucunda* subsp. *jucunda*		•				••••• (shaded)
* *Grevillea berryana*	•			•		•••••• (shaded)
* *Eremophila exilifolia*						•••• (shaded)
Prostanthera sp. Murchison (G.Byme 239)						•••
Psydrax latifolia						••
Wurmbea inframediana						••

Table 2

Spearman's rank correlation for soil chemistry and physical site parameters. Numbers show indicate strong correlation between variables ($P < 0.05$).

	ECEC	pH	B	Ca	Cd	Co	Cu	Fe	K	Mg	Mn	Mo	Na	Ni	P	Pb	S	Zn	Altitude	Aspect	Slope	CF Abundance	Max size
ECEC																							
pH	0.72																						
B																							
Ca	0.90	0.69																					
Cd																							
Co	0.64	0.66		0.55	0.32																		
Cu	0.31				0.41																		
Fe	0.47			0.55																			
K	0.62	0.32		0.43			0.30	0.37															
Mg	0.88	0.68		0.68		0.74			0.48														
Mn	0.60	0.64		0.53		0.83	0.37			0.63													
Mo			0.56																				
Na	0.62		-0.29	0.45			0.36	0.36	0.62	0.52		-0.31											
Ni	0.50	0.43		0.37		0.79				0.68	0.47												
P						-0.33		0.47	0.58														
Pb						0.28					0.30		0.36		-0.30								
S		-0.42				-0.39	0.36		0.29				0.43	-0.37	0.30								
Zn	0.69	0.48		0.59		0.43		0.43	0.66	0.54	0.45	-0.30	0.40	0.31	0.38								
Altitude		-0.46				-0.35		0.39		-0.36				-0.38			0.59						
Aspect	0.33			0.32																			
Slope								0.52	0.39								0.29	0.33	0.46				
CF Abundance								0.29											0.35		0.52		
Max size								0.48	0.46						0.61		0.30	0.45	0.39		0.66	0.37	
RO_Abundance		-0.29				-0.40		0.42						-0.30	0.52		0.52		0.39				0.42
Runoff	0.34			0.43				0.44													0.48	0.41	
%LeafLitter																			-0.34		-0.31		-0.34
%Bare Ground								0.29											0.40				

Table 3

Plant community mean values for soil chemistry parameters (measured in mg/kg except eCEC and pH). Differences between ranked values tested using Kruskall –Wallis non-parametric analysis of variance. Community 4 was excluded from analysis due to small sample size. Standard error in parentheses. a,b denote significant difference between groups by post hoc test (P < 0.05). (P = probability, n = number of quadrats, ns = not significant).

	Community Type						
	1	2	3	4	5	6	P
eCEC	2.1 (0.2)	1.5 (0.1)	2.0(0.4)	2.0 (0.2)	1.8 (0.2)	1.6 (0.2)	ns
pH	**5.2 (0.1)^{a}**	**4.5 (0.1)^{b}**	**4.6 (0.2)^{ab}**	4.6 (0.1)	**4.9 (0.3)^{ab}**	**4.4 (0.1)^{b}**	**< 0.01**
P	**18.5 (6.8)^{ab}**	**16.7 (1.5)^{b}**	**21.0 (3.6)^{b}**	11.5 (4.5)	**6.2 1.2)^{a}**	**12.1 (2.6)^{ab}**	**< 0.01**
K	160.3 (21.1)	143.2 (10.8)	186.5 (29.3)	200.0 (30.0)	103.6 (10.0)	110.1 (8.4)	ns
Mg	**77.2 (9.7)**	**54.6(4.5)**	**68.2(15.5)**	79.0(19.0)	**96.6(13.5)**	**49.7(8.9)**	**0.03**
Ca	202.6 (20.4)	132.6 (10.0)	185.3 (37.1)	145.0 (15.0)	151.0 (21.0)	177.2 (26.5)	ns
B	0.5 (0.0)	0.6 (0.1)	0.5 (0.0)	0.5 (0.0)	0.5 (0.0)	0.7 (0.1)	ns
Cd	0.01 (0.0)	0.01 (0.0)	0.01 (0.0)	0.01 (0.00)	0.01 (0.00)	0.01 (0.00)	ns
Co	**0.7 0.1)**	**0.3 (0.1)**	**0.3 (0.1)**	1.4 (0.9)	**1.5 (0.5)**	**0.6 (0.2)**	**0.01**
Cu	**0.6 (0.0)**	**0.6 (0.0)**	**0.7 (0.0)**	0.7 (0.2)	**0.5 (0.1)**	**0.6 (0.0)**	**0.05**
Fe	**38.8 (6.1)^{ab}**	**35.7 (2.1)^{a}**	**45.2(4.8)^{ab}**	35.5 (0.5)	**35.6 (2.0)^{ab}**	**46.9 (3.3)^{b}**	**0.04**
Mn	**47.2 (5.0)**	**29.7 (4.2)**	**31.8 (6.5)**	**45.5 (17.5)**	**59.0 (13.6)**	**42.8 (10.0)**	**0.03**
Mo	0.01 (0.00)	0.01 (0.00)	0.01 (0.00)	0.01 (0.00)	0.01 (0.00)	0.01 (0.00)	ns
Na	12.0 (5.6)	5.1 (0.8)	11.7 (4.7)	17.0 (5.0)	5.4 (1.1)	4.4 (0.5)	ns
Ni	**0.3 (0.1)^{ab}**	**0.3 (0.1)^{ab}**	**0.2 (0.1)^{b}**	1.0 (0.3)	**0.8 (0.1)^{a}**	**0.3 (0.1)^{b}**	**0.02**
Pb	0.5 (0.0)	0.4 (0.0)	0.5 (0.0)	0.6 (0.2)	0.5 (0.1)	0.5 (0.0)	ns
S	**7.9 (4.1)^{a}**	**5.8 (0.6)^{ab}**	**10.0 (1.9)^{b}**	9.0 (4.0)	**2.6 (0.7)^{a}**	**6.6 (0.4)^{ab}**	**< 0.01**
Zn	2.6 (0.4)	1.8 (0.2)	2.2 (0.5)	2.3 (0.5)	1.6 (0.3)	1.7 (0.2)	ns
n=	10	18	6	2	5	9	

Table 4

Plant community mean values for physical site parameters; altitude (m above sea level); aspect (16 cardinal directions), slope (degrees), coarse fragment (CF) abundance (0 – no coarse fragments to 6 very abundant coarse fragments), Maximum size of coarse fragments (1 – fine gravely to 7 large boulders), rock outcrop (RO) abundance (0 – no bedrock exposed to 5 – rockland), runoff (0 – no runoff to 5 – very rapid), % leaf litter and bare ground (1 – >70%, 2 – 30–70%, 3 – <10% 0 – <0 % cover). Differences between ranks tested using Kruskall –Wallis non-parametric analysis of variance. Standard error in parentheses. a, b, c indicate significant difference between groups by post hoc test (P < 0.05). (n = number of quadrats, P = probability, ns = not significant). Community 4 excluded from the analysis due to small sample size.

	Community Type						
	1	2	3	4	5	6	P
Altitude	**401 (0.1)^{bc}**	**418 (0.0)^{bc}**	**442 (0.2)^{ac}**	413 (0.0)	**389 (0.0)^{b}**	**548 (0.2)^{a}**	**<0.01**
Aspect	6.1 (3.2)	5.9 (5.2)	5.3 (11.8)	6.0 (12.5)	5.8 (2.3)	6.9 (16.0)	ns
Slope	**7.2 (1.2)**	**10.8 (0.4)**	**12.5 (0.3)**	1.5 (0.0)	**3.6 (1.7)**	**15.0 (1.2)**	**0.02**
CF Abundance	**3.0 (3.0)^{a}**	**4.2 (1.7)^{b}**	**4.0 (2.4)^{ab}**	4.5 (0.5)	**3.6 (1.3)^{ab}**	**4.7 (2.7)^{b}**	**<0.01**
Max. Size	4.0 (0.4)	5.2 (0.2)	5.0 (0.3)	4.5 (0.5)	3.6 (0.2)	5.1 (0.2)	ns
RO Abundance	1.0 (0.5)	1.3 (0.2)	2.8 (0.6)	0.5 (0.5)	0.4 (0.9)	1.4 (0.2)	ns
Runoff	1.9 (0.4)	2.2 (0.3)	2.3 (0.5)	1.0 (0.5)	2.2 (0.4)	2.4 (0.6)	ns
%Leaf Litter	**1.4 (0.5)**	**1.1 (0.2)**	**1.0 (0.2)**	1.0 (0.0)	**1.0 (0.2)**	**1.0 (0.3)**	**0.02**
% Bare Ground	**1.2 (0.2)**	**1.0 (0.1)**	**1.3 (0.0)**	1.0 (0.0)	**1.0 (0.0)**	**1.7 (0.0)**	**<0.01**
n=	10	18	6	2	5	9	

APPENDIX 1

Flora list for Jack Hills, including all taxa from the sampling quadrats and adjacent areas. Nomenclature follows Paczkowska and Chapman (2000), * indicates introduced taxon.

Adiantaceae

Cheilanthes brownii
Cheilanthes sieberi subsp. *sieberi*

Aizoaceae

Gunniopsis aff. *divisa* (R.Meissner & Y.Caruso 125)
Gunniopsis propinqua
Tetragonia cristata
Trianthema glossostigma

Amaranthaceae

Ptilotus aervoides
Ptilotus chamaecladus
Ptilotus exaltatus var. *exaltatus*
Ptilotus gaudichaudii var. *gaudichaudii*
Ptilotus helipteroides
Ptilotus obovatus var. *obovatus*
Ptilotus polystachyus var. *polystachyus*
Ptilotus roei
Ptilotus rotundifolius
Ptilotus schwartzii

Anthericaceae

Thysanotus manglesianus
Thysanotus speckii

Apiaceae

Daucus glochidiatus
Trachymene ceratocarpa
Trachymene ornata
Trachymene pilbarensis
Asclepiadaceae
Marsdenia australis
Asphodelaceae
Bulbine semibarbata

Asteraceae

Actinobole drummondianum
Actinobole oldfieldianum
Actinobole uliginosum
Brachyscome cheilocarpa
Brachyscome ciliocarpa
Brachyscome iberidifolia
Calocephalus sp.
Calocephalus knappii
Calocephalus multiflorus
Calocephalus sp. Pilbara-Desert (M.E. Trudgen 11454)
Calotis hispidula
Calotis multicaulis
Cephalipterum drummondii
Chthonocephalus pseudevax
Chthonocephalus viscosus
Dielitzia tysonii
Erymophyllum ramosum subsp. *ramosum*
Gnephosis arachnoidea
Gnephosis brevifolia
Gnephosis tenuissima
Helipterum craspedioides
Hyalochlamys globifera
Lawrencella davenportii
Myriocephalus rudallii
Podolepis gardneri
Podolepis kendallii
Pogonolepis stricta
Rhodanthe battii
Rhodanthe charsleyae
Rhodanthe chlorocephala subsp. *splendida*
Rhodanthe citrina
Rhodanthe floribunda
Rhodanthe maryonii
Rhodanthe polycephala
Schoenia cassiniana
Streptoglossa liatroides
Taplinia saxatilis

Boraginaceae

Halgania gustafsenii var. *gustafsenii*
Heliotropium heteranthum
Brassicaceae
Lepidium oxytrichum
Menkea villosula
Stenopetalum anfractum
Stenopetalum filifolium

Caesalpiniaceae

Petalostylis labicheoides
Senna artemisioides subsp. *helmsii*
Senna glaucifolia
Senna glutinosa subsp. *x luerssenii*
Senna sp. Meekatharra (E. Bailey 1–26)
Senna stricta x *artemesioides* subsp. *petiolaris* (E.N.S. Jackson 2888)

Campanulaceae

Wahlenbergia tumidifructa

Caryophyllaceae

Polycarpaea corymbosa

Chenopodiaceae

Chenopodium melanocarpum
Dysphania rhadinostachya subsp. *inflata*
Dysphania rhadinostachya subsp. *rhadinostachya*
Maireana carnosa
Maireana georgei
Maireana melanocoma
Maireana triptera
Maireana villosa

Sclerolaena eriacantha
Sclerolaena eurotioides

Colchicaceae

Wurmbea densiflora
Wurmbea inframediana

Convolvulaceae

Convolvulus clementii

Crassulaceae

Crassula colorata var. *acuminata*

Cuscutaceae

* *Cuscuta epithymum*
* *Cuscuta planiflora*

Euphorbiaceae

Euphorbia boophthona
Euphorbia drummondii subsp. *drummondii*
Phyllanthus erwinii

Geraniaceae

Erodium cygnorum

Goodeniaceae

Brunonia australis
Goodenia berardiana
Goodenia havilandii
Goodenia occidentalis
Goodenia tenuiloba
Velleia glabrata
Velleia hispida

Haloragaceae

Haloragis trigonocarpa

Lamiaceae

Lamiaceae sp.
Prostanthera ferricola

Lobeliaceae

Lobelia heterophylla subsp. Pilbara (R. Meissner & Y. Caruso 1)

Malvaceae

Abutilon fraseri
Abutilon oxycarpum
Abutilon sp. (R.Meissner & Y.Caruso 136)
Hibiscus sp. (R.Meissner & Y.Caruso 123)
Hibiscus sturtii var. *forrestii*
Sida aff. *intricata* (R.Meissner & Y.Caruso 119)
Sida atrovirens
Sida chrysocalyx
Sida ectogama

Mimosaceae

Acacia aneura cf. var. *aneura*
Acacia aneura cf. var. *microcarpa*
Acacia aneura cf. var. *tenuis*
Acacia aneura
Acacia citrinoviridis
Acacia sp. Jack Hills (R.Meissner & Y.Caruso 4)
Acacia cuthbertsonii subsp. *cuthbertsonii*
Acacia demissa
Acacia distans
Acacia kempeana
Acacia pruinocarpa
Acacia ramulosa var. *linophylla*
Acacia rhodophloia
Acacia stowardii
Acacia synchronicia
Acacia tetragonophylla

Myoporaceae

Eremophila compacta subsp. *fecunda*
Eremophila exilifolia
Eremophila forrestii subsp. *forrestii*
Eremophila fraseri subsp. *fraseri*
Eremophila fraseri subsp. *parva*
Eremophila glutinosa
Eremophila jucunda subsp. *jucunda*
Eremophila lachnocalyx
Eremophila latrobei subsp. *latrobei*
Eremophila macmillaniana
Eremophila phyllopoda subsp. *phyllopoda*
Eremophila spathulata

Myrtaceae

Aluta aspera subsp. *hesperia*
Calytrix desolata
Homalocalyx echinulatus P3
Thryptomene decussata

Nyctaginaceae

Boerhavia coccinea

Papilionaceae

Glycine sp. (R.Meissner & Y.Caruso 110)
Indigofera australis
Mirbelia rhagodioides
Swainsona leeana
Swainsona rotunda

Plantaginaceae

Plantago aff. *hispida* (R.Meissner & Y.Caruso 112)

Poaceae

Aristida contorta
Cymbopogon ambiguus
Digitaria brownii
Enneapogon caerulescens
Eragrostis dielsii
Eragrostis eriopoda
Eragrostis lanipes
Eragrostis pergracilis
Eriachne aristidea

Eriachne helmsii
Eriachne pulchella subsp. *pulchella*
Monachather paradoxus
Neurachne minor
Paspalidium clementii
* *Rostraria pumila*
Triodia melvillei
Tripogon loliiformis

Polygalaceae

Polygala isingii

Portulacaceae

Calandrinia cf. *creethae*
Calandrinia creethae
Calandrinia disperma
Calandrinia eremaea complex
Calandrinia sp. The Pink Hills (F. Obbens FO19/06)
Calandrinia polyandra
Calandrinia ptychosperma
Calandrinia remota
Calandrinia translucens
Portulaca oleracea

Proteaceae

Grevillea berryana
Hakea lorea subsp. *lorea*
Hakea preissii

Rhamnaceae

Stenanthemum petraeum

Rubiaceae

Psydrax latifolia
Psydrax suaveolens
Synaptantha tillaeacea var. *tillaeacea*

Rutaceae

Philotheca brucei subsp. *cinerea*
Philotheca sericea

Sapindaceae

Dodonaea pachyneura
Dodonaea petiolaris

Solanaceae

Nicotiana occidentalis subsp. *obliqua*
Nicotiana rosulata subsp. *rosulata*
Solanum ashbyae
Solanum lasiophyllum

Stackhousiaceae

Stackhousia muricata

Tiliaceae

Corchorus crozophorifolius

Zygophyllaceae

Tribulus aff. *adelacanthus* (R.Meissner & Y.Caruso 115)
Tribulus suberosus
Tribulus terrestris
Zygophyllum eichleri
Zygophyllum kochii
Zygophyllum simile

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Flora and vegetation of banded iron formations of the Yilgarn Craton: Mount Gibson and surrounding area

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ABSTRACT

A total of 243 taxa, 233 native and 10 weeds, were recorded from study of the flora and plant communities of the Mount Gibson Range and surrounding ironstone ranges on the Ninghan pastoral lease, 60 km southeast of Paynes Find. Seven priority flora, one declared rare flora and one new species were identified during the study. Fifty quadrats were established to cover the geomorphology, floristic variation and geographical variation across the ranges. Data from these quadrats were used to define seven community types. Geography and landscape morphology separated the communities, with four communities found only on the Mount Gibson Range. Of these four, two had restricted distributions within the range. None of the ranges are currently reserved in the conservation estate.

INTRODUCTION

Banded Iron Formation (BIF) ranges within the Yilgarn Craton are highly prospective for iron ore exploration and mining. Previous studies on ironstone and greenstone ranges in the Goldfields have found high plant endemicity and restricted plant communities and it is thought that these patterns may also be found on the ranges in the Yilgarn (Gibson et al. 1997; Gibson & Lyons 1998a,b; Gibson & Lyons 2001a,b; Gibson 2004a,b). The current knowledge of the vegetation and flora that occur on these ranges is poor and based primarily on the structural description of the dominant vegetation rather than the community composition (Beard 1976).

The study area is located approximately 60 km southwest of Paynes Find and covers the extent of Mount Gibson, Yandhanoo Hills and several smaller hills on the Ninghan pastoral lease.

The climate of the area surrounding Mount Gibson is semi-desert mediterranean, with 9 to 11 months of dry weather, mild wet winters and hot dry summers (Beard 1990). Mean annual rainfall recorded at Paynes Find is 282.5 mm, and rainfall is highly variable in the region (180.5 mm 1st decile; 398 mm 9th decile; recorded 1919 to 2004). Rain primarily falls in winter, although some summer rainfall does occur. The highest maximum temperatures occur during summer, with the January as hottest month (mean maximum temperature 37.1 °C and mean 8.9 days above 40 °C). Winters are mild with lowest mean maximum temperatures recorded for July of 18.4 °C. Temperatures occasionally fall below 0 °C in winter (a mean 3.1 days below 0 °C), with a mean minimum of 5.4°C in July.

In terms of geology, the Mount Gibson Range lies within the Murchison Province of the Yilgarn Craton. The geology of the Mount Gibson area is complex and composed of several fold belts. The Retaliation Belt is represented mainly by the Mount Gibson Range and is comprised of banded iron formations and cherts in the lower sedimentary association, bounded by volcanic flows with marker bands of banded ironstone formation. The Yandhanoo Hills and small hills near Warro Well (Figure 1) are part of the Yandhanoo Belt. This belt is composed mainly of metasedimentary rocks of thoroughly recrystallised cherts and banded ironstone (Lipple et al. 1983).

The Mount Gibson Range occurs in the southern part of the Yalgoo IBRA region. This region is an interzone, between southwest bioregions and the Murchison IBRA region (Environment Australia 2000). Broadscale mapping by Beard (1976) shows several vegetation associations. The Mount Gibson Range was mapped as shrublands of *Acacia acuminata* (jam) and *Allocasuarina acutivalvis* on ironstone. Colluvial slopes were mapped as medium woodland of York gum (*Eucalyptus loxophleba*), Salmon gum (*Eucalyptus salmonophloia*) and gimlet (*Eucalyptus salubris*). Surrounding Mount Gibson, the vegetation was mapped as shrubland of bowgada (*Acacia ramulosa*) and *Acacia quadrimarginea* on stony ridges and shrublands of bowgada and jam scrub.

Payne et al. (1998) describe Mount Gibson as part of the Tallering Land System. This broad classification includes banded ironstone ranges from Mount Karara running northwards to Yalgoo. These included several plant communities occurring on the landforms; 20% of the system is composed of ridges and hills, some banded ironstone, with shallow stony red earths with *A. ramulosa* and other acacias over *Thryptomene* and *Philotheca* species. Fifty eight percent of the land system consisted of hillslopes covered in scattered to moderately dense shrublands of

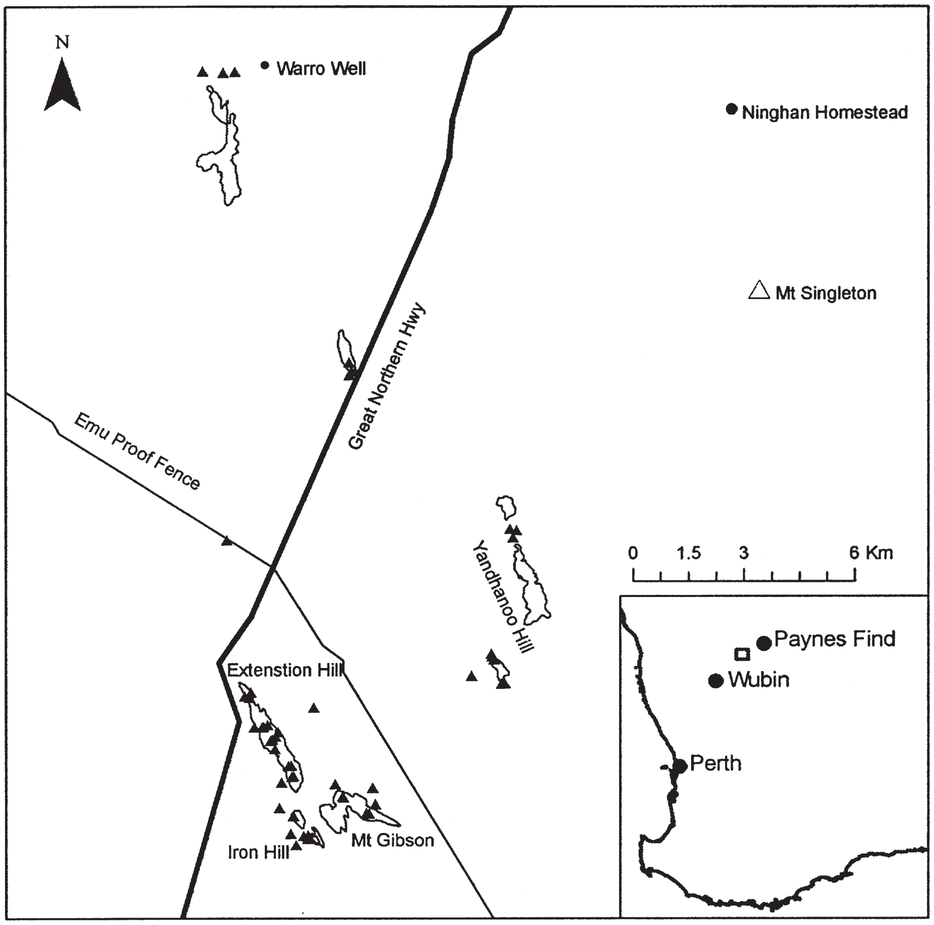

Figure 1. Location of survey and distribution of quadrats (▲) on Mount Gibson and surrounding banded iron formation ranges on Ninghan Station. Contours at 340 m are shown.

A. ramulosa and other *Acacia* spp. over *Eremophila* spp., *Ptilotus obovatus*, *Thryptomene* spp. and *Philotheca* spp. The remaining part of the system covered the stony plains, drainage tracts and stripped surfaces.

The aim of the survey is to identify the plant communities that occur on the ironstone range of Mount Gibson and surrounding areas. This was done through detailed flora lists and community descriptions based upon 50 permanently established quadrats on the range and surrounding area. This survey will be part of a larger regional study of flora and plant communities of banded ironstone formations of Yilgarn Craton.

METHODS

Fifty 20 x 20 m quadrats were established on Mount Gibson and several banded ironstone ranges in the surrounding area. In this report, Mount Gibson Range refers to several smaller hills, Extension Hill, Iron Hill and Mount Gibson (Figure 1). All quadrats were established between September and October 2005. The location of quadrats attempted to cover the major geographical, geomorphologic and floristic variation found on the hills and valleys in the study area. Each quadrat was permanently marked with four steel fence droppers and their positions determined using a GPS unit. All vascular plants within the quadrat were recorded and collected for later identification at the Western Australian Herbarium. Data on topographical position, disturbance, abundance, size and shape of coarse fragments on the surface, the amount of exposed bedrock, cover of leaf litter and bare ground were recorded following McDonald et al. (1990). Additionally, growth form, height and cover were recorded for dominant taxa in each stratum (tallest, mid- and lower).

Twenty soil samples were collected from the upper 10 cm of the soil profile within each quadrat. The soil was bulked and the 2 mm fraction was analysed for B, Ca, Cd, Co, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S and Zn using the Mehlich No. 3 procedure (Mehlich 1984). The extracted samples were then analysed using an Inductively Coupled Plasma - Atomic Emission Spectrometer (ICP-AES). This procedure is an effective and cost efficient alternative to traditional methods for evaluating soil fertility and has been calibrated for Western Australian soils (Walton & Allen 2004). pH was measured in 0.01M $CaCl_2$ at soil to solution ratio of 1:5. Effective cation exchange capacity (eCEC) was calculated from the sum of exchangeable Ca, Mg, Na and K (Rengasamy & Churchman 1999). Exchangeable Ca, Mg, Na and K were obtained by multiplying the values of Ca, Mg, Na and K obtained from ICP-AES by a standard constant.

Quadrats were classified on the basis of similarity in species composition on perennial species only, to be consistent with other analyses of banded ironstone ranges. Life form followed Paczknowska and Chapman (2000), where perennial is defined as a plant whose life span extends over 2 or more growing seasons. The quadrat and species classifications were undertaken using the Bray and Curtis coefficient and Flexible UPGMA (Unweighted pair-group mean average, Belbin 1989). Indicator species and species assemblages characterising each community were determined following Dufrene and Legendre (1997). Quadrats were ordinated using SSH (semi-strong hybrid multidimensional scaling), correlations of environmental variables were determined using the PCC routine in PATN (Belbin 1989) and significance determined by MCAO (monte- carlo attributes in ordination) permutation tests in PATN. PCC is a routine that runs multiple linear regressions on the variables and the ordination coordinates, resulting in a vector for each variable within the ordination plot. The MCAO is a monte-carlo test determining the robustness of the PCC results by randomly assigning values of variables to objects and then running the PCC routine (Belbin 1989).

Statistical relationships between quadrat groups were tested using Kruskall-Wallis non parametric analysis of variance (Siegel 1956), followed by non-parametric post-hoc comparison (Zar 1999). Correlations between soil and physical site parameters were analysed using the Spearman's rank correlation.

Nomenclature generally followed Paczkowska and Chapman (2000).

RESULTS

Flora

A total of 243 taxa, 233 native and 10 weeds, were recorded from the 50 established quadrats and adjacent areas. A total of 56 families as recorded, and dominated by Asteraceae (51 taxa, 4 weeds), Myrtaceae (19), Mimosaceae (18) and Poaceae (16 taxa, 3 weeds).

Rare and Priority Flora

Seven priority species (designated P1, P2, P3) and one declared rare flora (DCF) were found during the survey. All species are poorly collected, with less than 20 collections for each species present in the Western Australian Herbarium.

- *Acacia cerastes* (P1) is a small shrub to 1 m with intricate wiry branches and reduced phyllodes and is known only from Mount Gibson Range and several granite outcrops near Mount Gibson. This was an opportunistic collection from the range. The species is a disturbance opportunist and was recorded growing on an old exploration track.
- *Austrostipa blackii* (P3) is a perennial tufted grass found mainly in the eastern states of Australia. It was recorded from only one site on Yandhanoo Hills growing on a rocky hillcrest under *Acacia umbraculiformis* and *Melaleuca nematophylla* shrubland.
- *Darwinia masonii*, one of two declared rare flora recorded in the survey, is restricted to the Mount Gibson Range. It is a myrtaceous shrub to 2 m with bright red flowers and long styles indicating bird pollination. This species occurred across the entire range, growing on the rocky crests and upper slopes.
- *Dodonaea amplisemina* (P3) is poorly collected shrub to 2 m. It is closely related to *Dododaea pinifolia* but differs with larger fruit and two different leaf forms. This shrub was highly palatable and was severely grazed by feral goats. It was collected only from two sites on Yandhanoo Hills, growing in *A. ramulosa* and *A. umbraculiformis* shrublands.
- *Micromyrtus* sp. Warriedar (S. Patrick 1879A) (P1) is a spindly myrtaceous shrub growing to 2 m with small pale yellow flowers. It is known from only 10 records in the Western Australian Herbarium and collected only from banded ironstone ranges in the Yalgoo IBRA region. This is the first record of this taxon for the Mount Gibson Range. *Micromyrtus* sp. Warriedar (S. Patrick 1879A) was collected mainly from the crests of Mount Gibson only.
- *Persoonia pentasticha* (P2) is a proteaceous shrub to 2 m with pungent 5 ribbed leaves. It has previously been recorded from Mount Gibson Station and has been recorded from other areas of banded ironstone formations.
- *Podotheca uniseta* (P3) is a small annual daisy, closely related to *Podotheca gnaphaloides*, differing by the presence of a single pappus on each achene. It was collected from a single site on Mount Gibson. This is the first record of the species for the range.
- *Rhodanthe collina* (P1) is an annual daisy with small delicate flowers. It has been poorly collected with only 13 records in the WA Herbarium. In this survey, it was found growing on crests and slopes of Yandhanoo Hills and the Great Northern highway, and on the Emu Proof Fence.

New Species

- *Lepidosperma gibsonii* DRF is a new species endemic to Mount Gibson. It was initially collected from Extension Hill, within a proposed mining footprint. The species is found growing across the range, mainly in gullies and sheltered positions (Barrett 2007). This species is closely related to *Lepidosperma ferricola*, which is also an endemic to the Koolyanobbing Range, in the eastern goldfields (Barrett 2007).

Range Extensions

Five species found during the survey, including the priority species *A. blackii*, had significant range extensions (>100 km from previously known collections).

- *Austrostipa hemipogon* is commonly found across the southwest of the State. It is a tufted perennial grass. It was recorded from a single site on Mount Gibson.
- *Crassula tetramera* and *Crassula closiana* are small annual succulent herbs, both less than 5 cm. *Crassula tetramera* is poorly represented in the herbarium, with only 11 collections. It can be easily distinguished from other species in the genera due to the 4-merous flowers and follicles opening by an apical pore. *Crassula closiana* is also distinctive with a long flowering pedicel and follicles. The survey extended their northwest and northeast distribution respectively. Due to their small size, they may have been overlooked.
- *Hemigenia macphersonii* has been poorly collected, with only six specimens in the Western Australian State Herbarium. In this survey, it was collected from a single site on the Mount Gibson Range. It has previously been recorded from other banded ironstone ranges. The survey extended it's southern extent by approximately 100 km.

Taxonomic interest

- *Hibbertia* aff. *rostellata* belongs to an unresolved species complex with *Hibbertia exasperata*, *Hibbertia nutans* and *Hibbertia uncinata*, and referred to as the *Hibbertia exasperata* group (Wheeler 2004). *Hibbertia rostellata* is found mainly in the Avon Wheatlbelt and parts of the Mallee IBRA regions, growing on yellow sands, sand over gravel, and lateritic gravel, although a few specimens have been collected from greenstone ranges in the Goldfields. In contrast, *H.* aff. *rostellata* was collected only from the Mount Gibson Range and mainly from *Allocasuarina acutivalvis* subsp. *prinsepiana* woodlands on rocky crests and midslopes. The Mount Gibson populations are approximately 100 km from the nearest population of *H. rostellata*. The taxonomy of this group needs to be resolved.
- *Hibbertia hypericoides* is a shrub to 1.5 m with bright yellow flowers. It is distributed from the Swan Coastal Plain, north to the Geraldton Sandplains. The population collected at Mount Gibson are nearly 200 km to the east of the nearest collection, which is a significant range extension for the species. In this survey it was collected from Yandhanoo Hills and Mount Gibson Range from rocky outcrops on crests and midslopes. It has previously been collected from Yandhanoo Hills.

Plant communities

A total of 239 taxa were recorded for the 50 established quadrats, with 120 species of perennial taxa. Ninety three taxa occurred in more than one quadrat. Final analysis was conducted using perennial species only. Preliminary analysis showed little difference on community classification when annual species and singletons were removed. Two species, *Rhodanthe polycephala* and *Rhodanthe laevis*, were combined to a species complex for the analysis, due to the difficulty in differentiating between the two species in the field.

Community groups were separated into 7 plant communities, based upon clear patterning in the final dendrogram (Figure 2). The first split in the dendrogram separated Communities 6 and 7 found mainly on Extension Hill, a part of the Mount Gibson Range. The second division separated the remainder of sites on Mount Gibson (Communities 4 and 5) and the colluvial outwashes (Community 3) from sites on Yandhanoo Hills and other hills more distant to Mount Gibson (Communities 1 and 2). These divisions can also be seen in the sorted two-way table of the sites and species classification (Table 1).

<u>Community 1</u> – Woodlands, shrublands and open shrublands of *A. umbraculiformis*, *A. ramulosa* var. *ramulosa* and *Calycopeplus paucifolius* over shrublands of *Eremophila latrobei*, *Philotheca sericea*, *Mirbelia bursarioides* and *Aluta aspera* subsp. *hesperia*. This

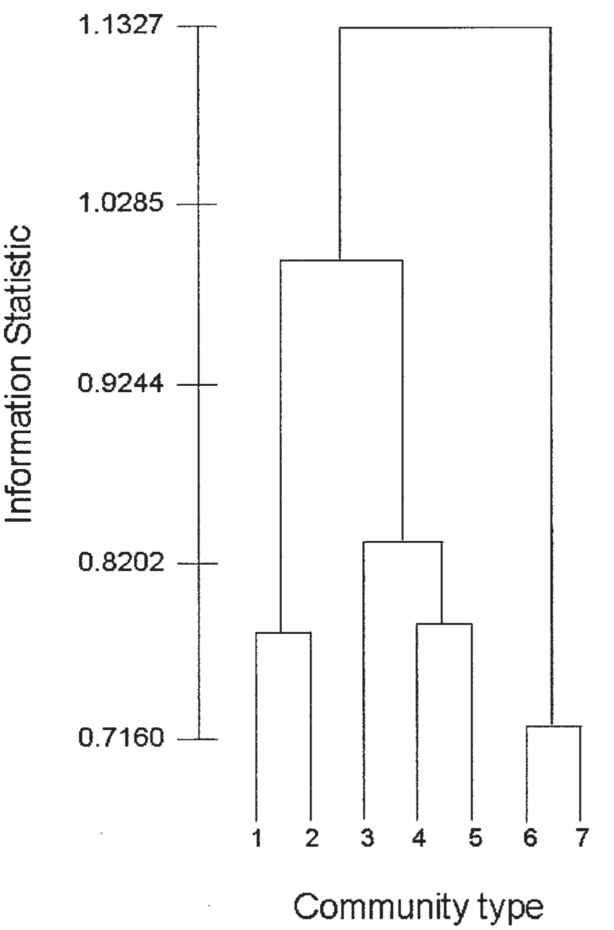

Figure 2. Dendrogram of 7 group level classification of the 50 quadrats established on Mount Gibson and surrounding ranges.

community was found on Yandhanoo Hills and sites adjacent to the Great Northern Highway from crests to lower slopes. The mean species richness was 34.2 ± 0.8 species per quadrat. It was characterised by species from Group E and indicator species *A. umbraculiformis*, *Acacia ramulosa* subsp. *ramulosa*, *E. latrobei* subsp. *latrobei* and *Monachather paradoxus* (Table 1).

Community 2 – Woodlands and shrublands of *Acacia assimilis* subsp. *assimilis* and *A. umbraculiformis* over shrublands of *Eremophila* spp., *Hemigenia* sp. Yalgoo and *M. bursarioides*. This community consisted of all sites near Warro Well, a single site from adjacent to the Emu Proof Fence and a site from Yandhanoo Hills (Figure 1). This community contained the most species poor sites (mean 23.3 ± 0.8 taxa per quadrat) and is characterised by species from Group D and E (Table 1). Indicator species were *A. ramulosa* var. *ramulosa*, *A. aspera* subsp. *hesperia*, *Cheiranthera filifolia* var. *simplicifolia*, *Eremophila forrestii* subsp. *forrestii*, *E. latrobei* subsp. *latrobei*, *H.* sp. Yalgoo (A.M. Ashby 2624), *Micromyrtus clavata* and *M. bursarioides*.

Community 3 – Open *Eucalyptus* woodlands over *Acacia* spp. This community is represented by only 3 quadrats located near Mount Gibson, Yandhanoo Hills and the Great Northern Highway on the colluvial plains. The dominant *Eucalyptus* species was either *Eucalyptus kochii* subsp. *amaryissa* and/or *Eucalyptus loxophleba* subsp. *supralaevis*. This community is characterised by species from Group B and mean species richness of 35.3 ± 0.7 species per quadrat (Table 1). Indicator species were *Acacia obtecta, Acacia tetragonophylla*, *M. paradoxus, Olearia muelleri*, *Ptilotus obovatus* subsp. *obovatus*, *Rhagodia* sp. Watheroo (R.J. Cranfield & P.J. Spencer 8183) and *Senna artemisioides* subsp. *filifolia*.

Community 4 – Mallee woodland and woodlands of *Eucalyptus* spp. (*Eucalyptus horistes*, *E. loxophleba* subsp. *supralaevis* or *E. kochii* subsp. *amaryissia*) over shrublands of *A. acuminata*. This community was only found on the lower slopes of the Mount Gibson Range. The community is characterised by species from Group A and B with a mean species richness of 32.4 ± 0.7 species per quadrat (Table 1). Indicator species were *A. acuminata, Acacia anthochaera*, *Acacia andrewsii*, *Acacia colletioides*, *Allocasuarina acutivalvis* subsp. *prinsepiana*, *Amphipogon caricinus*, *Maireana georgei*, *Melaleuca hamata, Philotheca brucei* subsp. *brucei* and *Scaevola spinescens*.

Community 5 – Open shrublands and shrublands of *Allocasuarina acutivalvis* subsp. *prinsepiana*, *C. paucifolius*, and *A. tetragonophylla* over shrublands of *P. brucei* subsp. *brucei* and *Ptilotus obovatus*. This community consisted primarily of sites on rocky outcrops on upper slopes and hill crests on Mount Gibson Range. It was not found on Extension Hill. This was the most species rich community (mean 38.5 ± 1.2 species per quadrat) and was characterised by taxa from groups E and H (Table 1). Indicator species were *Acacia exocarpoides*, *A. tetragonophylla*, *Cheilanthes adiantoides*, D*arwinia masonii*, *Hakea recurva*, *P. brucei* subsp. *brucei*, *Prostanthera magnifica*, *Prostanthera patens* and *P. obovatus* var. *obovatus*.

Community 6 – Open woodlands, shrublands and sparse shrublands of *A. acutivalvis* subsp. *prinsepiana*, *M. nematophylla*, *A. assimilis* subsp. *assimilis* and *Grevillea obliquistigma* subsp. *obliquistigma* over shrublands of *Hemigenia* sp. Paynes Find and *Leucopogon* sp. Clyde Hill. This community is found mainly on the crests and upper slopes of Extension Hill (Figure 1) with mean species richness of 35.1 ± 0.8 species per quadrat. It was characterised by taxa from species group G with indicator species *A. acutivalvis* subsp. *prinsepiana*, *Cassytha nodiflora, Grevillea obliquistigma* subsp. *obliquistigma, Hemigenia* sp. Paynes Find, *Leucopogon* sp. Clyde Hill, *M. nematophylla and Melaleuca radula* (Table 1).

Community 7 – Open woodlands, woodlands and shrublands of *Allocasuarina acutivalvis* subsp. *prinsepiana*, *Acacia coolgardiensis* subsp. *effusa* over *Aluta apera* subsp. *hesperia*. This community was found only on the lower slopes of Extension Hill and was characterised by taxa from Species Group G and I (Table 1). The sites had a mean species richness of 31.6 ± 1.2 species per quadrat. Indicator species were *A. coolgardiensis* subsp. *effusa, A. acutivalvis* subsp. *prinsepiana*, *A. aspera* subsp. *hesperia*, *A. caricinus* var. *caricinus*, *Baeckea* sp., *Enekbatus stowardii*, *Eucalyptus oldfieldii*, *Melaleuca fabri*, and *Stylidium confluens*.

Physical Correlates

The soil parameters showed significant intercorrelations but there were few significant correlations with site characters (Table 2). Maximum rock size showed significant correlations with all the other physical site characters. Iron showed significant correlations with most of the physical site characters apart from aspect, surface coarse fragment abundance and litter cover (Table 2).

Community 1 showed several significant differences in soil composition to the other communities (Table 3). It had a lower pH than Community 5 and was higher in copper and potassium than Communities 4 and 6. Community 7 was also lower than Community 1 in copper levels but had similar levels of potassium (Table 3). Zinc was different in several communities, with Community 1 having a higher level than Communities 4, 5 and 7.

Community 1, on Yandhanoo Hills and Great Northern Highway, recorded more grazing (caused by feral goats) than the Communities 6 and 7 found on Extension Hill (Table 4), and had a higher percentage cover of leaf litter than Community 7. Community 4 occurred on more gentle slopes than Community 1, which was found on the slopes and crests of Yandhanoo Hills and Great Northern Highway (Table 4).

Community 4 had smaller amount of coarse surface fragments than Community 5 and 7 and little or no rock outcrops compared to Community 5 and 6, the latter found on sites with rock outcrops (Table 4).

The three dimensional ordination (stress = 0.17) clearly separated Communities 6 and 7, found mainly on Extension Hill. These communities are characterised by lower levels of grazing, copper and zinc (Figure 3). The communities more distant from the Mount Gibson Range

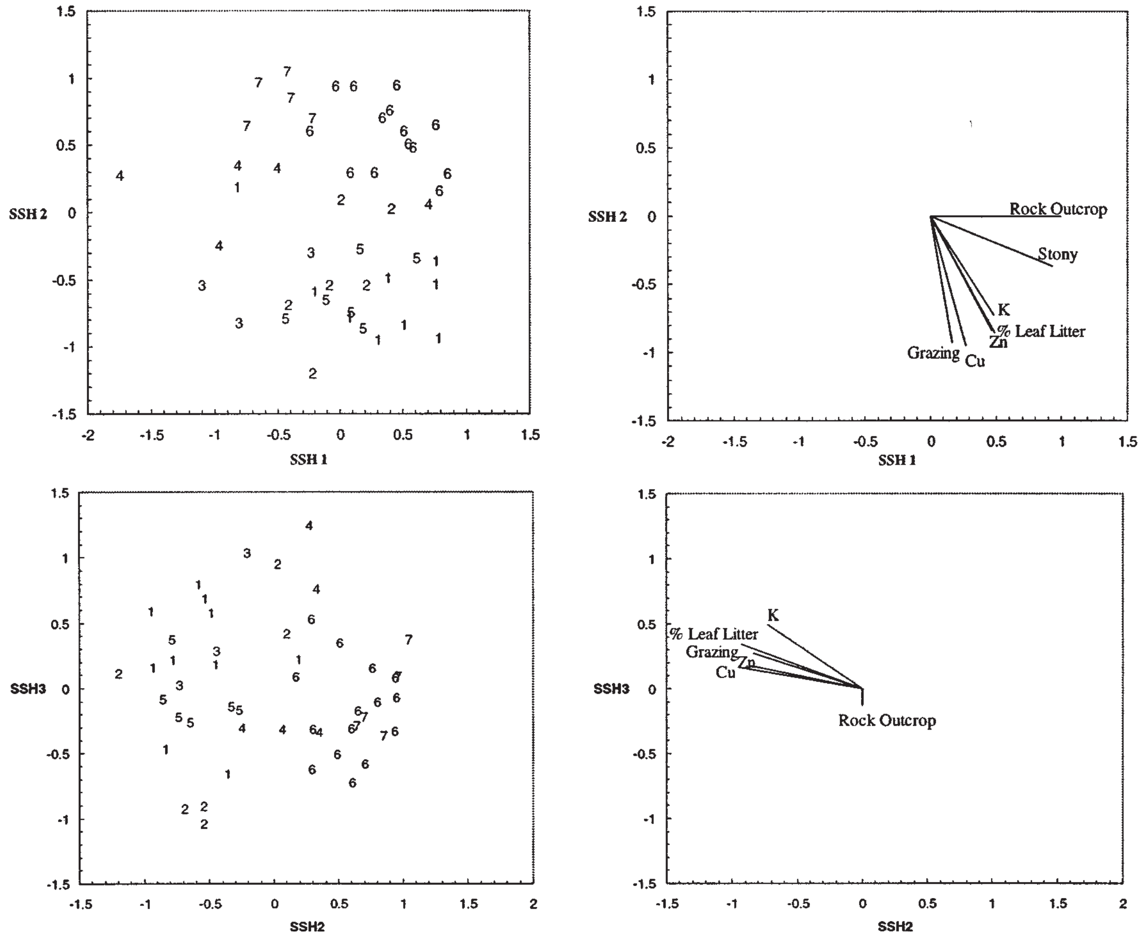

Figure 3. Three dimensional ordination showing Axis 1, 2 and 3 of the 50 quadrats established on Mount Gibson and surrounding ranges showing community type. Lines represent the strength and direction of the best fit linear correlated variables (P<0.05).

(1 and 2) are located in the lower right quadrant and were correlated with higher zinc, copper and grazing. Community 4 (Eucalypt woodlands on lower slopes) was more variable generally lower in surficial rock and coarse fragment cover. Community 5 is located in the lower half of the ordination, with the sites clustered together and correlated with higher surficial rock and coarse fragments. It is found on the upper slopes and crests of Iron Hill and Mount Gibson, high grazing, percentage leaf litter, copper and zinc.

DISCUSSION

Flora

Two hundred and forty three taxa were recorded for Mount Gibson. Two declared rare flora (DRF), seven priority flora and one new species were identified during the survey. The two DRF taxa, *D. masonii* and *L. gibsonii*, are endemic to the Mount Gibson Range. Similar numbers of taxa and priority flora have been recorded for other banded ironstone and green stone ranges on the Yilgarn Craton (see Gibson 2004b). The closest ironstone ranges to this survey are situated to the north and are contained within the Central Tallering landsystem (including Mt. Karara). A concurrent survey of these ranges found 414 taxa, while covering twice the area and number of quadrats (Markey & Dillon, 2008). More comparable is the survey of banded iron ranges of Koolanooka and Perenjori Hills to the west, which found 237 taxa, with six endemic species (Meissner & Caruso, 2008).

L. gibsonii is known only from the Mount Gibson Ranges, growing in gullies and on slopes in shallow soils over ironstone (ATA Environmental 2006a, Barrett 2007). Recent taxonomic work has recognised many new species of *Lepidosperma*, including *L. gibsonii*, which are endemic to banded ironstone ranges on the Yilgran Craton (Barrett 2007).

Mount Gibson occurs within the interzonal Yalgoo bioregion (Thackway & Cresswll 1995), an area with affinities to both Eremaean and Southwest botanical Provinces (Beard 1976). The ranges of several Southwest taxa, *A. hemipogon* and *H. hypericoides*, are at the eastern extent of their range. In contrast, a characteristic Eremaean species complex, *A. aneura*, is at the western most extent of its distribution.

Communities

Geographical location was a strong influence on the classification of the communities. Community 1 is found primarily at Warro Well, Community 2 from Yandhanoo and the Great Northern Highway and Communities 4, 5, 6 and 7 all occur on the Mount Gibson Range. Community 3 is the only shared community, occurring on the colluvial soils between Yandhanoo Hills and Extension Hill and near the hills on Great Northern Highway.

Within Mount Gibson Range, geographical location also influences the community types, with several communities restricted to specific parts of the range. Community 5 is found on Iron Hill and Mount Gibson but not Extension Hill, while Community 7 is only found on the lower slopes of Extension Hill. Community 6 occurs predominantly on Extension Hill, but has several quadrats located on Mount Gibson (Figure 1). There are similarities between the hills on the lower slopes of Mount Gibson Range, with Community 4 found across the range on the lower slopes and colluvial sites.

The geographic patterns are largely consistent with those described in a floristic survey conducted concurrently with this project (ATA Environmental 2006b). That survey provided more detailed classification with twice the number of permanent quadrats established on the crest and upper slopes of the Mount Gibson Range and surrounding area.

Within the Mount Gibson Range, topography separated some of the communities. Community 4 occurred on the lower slopes of Mount Gibson Range, Community 6 was found mainly on the crests and midslopes of Extension Hill, Community 5 occurred on the rocky outcrops of Iron Hill and Mount Gibson, and Community 7 was found only on the lower slopes of Extension Hill. However, Communities 1 and 2 occurred on all positions on the hills ie. crest, midslopes and lower slopes.

Soil fertility was not a strong variable in separating community type, with only a gradient of high to low potassium within the ordination. Community 1 was higher in potassium than Communities 4 and 6. However, total nitrogen was not measured in this survey, and this may reveal an additional relationship.

The Mount Gibson Range has been mapped as the Tallering landsystem (Payne et al. 1998) which include the Blue Hills, Mt. Karara and Windanning ironstone ranges to the north. However, when comparing the communities found on the Central Tallering landsystem (Markey & Dillon, in press), there were no communities in common with Mount Gibson. In particular, many of the dominant taxa on the Central Tallering ranges, such as *Acacia sibina*, were not recorded on Mount Gibson (Markey & Dillon, in press).

This study found several communities restricted to the Mount Gibson Range and no communities found elsewhere on any ironstone ranges outside of this area. The high species turnover within the ranges ie. markedly different plant communities occurring on relatively close ridges within Mount Gibson, has implications for future conservation of the range, especially communities 6 and 7 which are restricted to specific parts of the Mount Gibson Range. None of the ranges is currently in a conservation reserve.

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Table 1

Sorted two-way table of quadrats established on Mount Gibson and surrounding ranges showing species by community type. Taxa shaded grey within a community are indicator species identified by INDVAL >17 (Dufrene & Legendre 1997) at the 7 group level (* indicates p< 0.05; ** p<0.01; statistical significance tested by randomisation procedures).

	Community Type 1	2	3	4	5	6	7
SPECIES GROUP A							
Acacia acuaria				•		•	
Eremophila oldfieldii subsp. *angustifolia*				•	•		
* *Acacia anthochaera*				• •			
* *Senna artemisioides* subsp. *filifolia*			• •	• •	•		
Eucalyptus kochii subsp. *amaryssia*			•	•			
Austrostipa trichophylla	• • • •	•	• •	•			
Santalum acuminatum		•	•	•			•
SPECIES GROUP B							
** *Acacia acuminata* (narrow phyllode variant)				• • • •		• • •	
Sclerolaena fusiformis			•	•			
* *Eucalyptus loxophleba* subsp. *supralaevis*			•	• • •		•	
* *Olearia muelleri*			• •	• • •			
* *Acacia andrewsii*			•	• • •	•		
* *Scaevola spinescens*				• • •	• •		
* *Acacia colletioides*				• •			
* *Maireana georgei*				• •			
* *Melaleuca hamata*				• • •			•
Austrodanthonia caespitosa	•			•			
SPECIES GROUP C							
** *Acacia obtecta*			• •				
Olearia pimeleoides		•	•				
Callitris columellaris			• •	• •	• •		
** *Rhagodia* sp. Watheroo (R.J. Cranfield & P.J. Spencer 8183)			• •			•	
SPECIES GROUP D							
Acacia aneura var.	•	• • •	•				
* *Monachather paradoxus*	• • • • •	•	• •			•	
* *Eremophila forrestii* subsp. *forrestii*		• •					
Ptilotus drummondii	•	• •			•	•	
* *Cheiranthera filifolia* var. *simplicifolia*		• • • •	•	•			
** *Hemigenia* sp. Yalgoo (A.M. Ashby 2624)		• • •					
** *Micromyrtus clavata*	•	• • • •					
Wurmbea densiflora		• • •		•	•	• • • •	
Dichopogon tyleri		•		•			
Dianella revoluta var. *divaricata*	• • •	• •	• •			• • •	•
Thysanotus pyramidalis	•	• •	•			• •	• • •
SPECIES GROUP E							
** *Acacia exocarpoides*	• • •	•		•	• • • • •	•	
Alyxia buxifolia				•	• •		
Philotheca sericea	• • • • • • •	• • • •		•	• • •	• • • • • • • •	•
Solanum lasiophyllum	• • • •		•		• • •		
* *Acacia tetragonophylla*	•	• •	• •	• •	• • • • • •	•	
** *Hakea recurva*	• • •		•		• • • • • •		
* *Ptilotus obovatus* var. *obovatus*	• • • •		• • •	• • •	• • • • • •		
** *Philotheca brucei* subsp. *brucei*		• •		• • • •	• • • • • •	• • •	
Austrostipa elegantissima	• •		• •	• • •	• • • •	• • • • •	
Comesperma integerrimum	• • • •		• •	•	• • •	• • •	•
Eremophila clarkei	• • • • •	•	• •	• • • •	• • • • • •	• • • •	•
Dodonaea inaequifolia				• • •	• • • •	•	•
** *Prostanthera patens*					• • •		
** *Acacia umbraculiformis*	• • • • • •	• •					
Austrostipa scabra	• • • • • • •		•		• • • •		
Sida atrovirens	• • • • •	• •		• •	• • •		
* *Acacia ramulosa* var. *ramulosa*	• • • • • • • •	• • • • • •	• •		• • •		
** *Eremophila latrobei* subsp. *latrobei*	• • • • • • •	• • • • • •			• • •	•	
* *Mirbelia bursarioides*	• • • • •	• • • • •		•	• • • •		
Calycopeplus paucifolius	• • • • • • • •			•	• • • • •	• • • • • • • • • •	• •
SPECIES GROUP F							
Austrostipa blackii	• •						
Dodonaea sp. Ninghan (H. Demarz 5121)	• •						
Cheilanthes sieberi subsp. *sieberi*	• •	•				•	
Solanum ellipticum	• •					•	

Table 1 (cont.)

	Community Type 1	2	3	4	5	6	7
SPECIES GROUP G							
Acacia assimilis subsp. *assimilis*	••• •	•• •	•			•• •••••••••	•• •
Arthropodium dyeri	•• •	• •		••	• •	• •••• •••	
* *Aluta aspera* subsp. *hesperia*	•• ••	•••• •	•	• •	•	•••• ••• • ••	•••••
** *Allocasuarina acutivalvis* subsp. *prinsepiana*	•	•		••••	••• •	•••••••••••••••	•••••
* *Cheilanthes adiantoides*	••••••• •	•••••	•	••••	••••••	••••••••••••• •	••••
Thysanotus manglesianus	•		••	•••••	••••	••• ••••••••••	•••••
* *Grevillea obliquistigma* subsp. *obliquistigma*		•			•	• ••• •• ••••••	•••
* *Hemigenia* sp. Sticky Terete (B.H. Smith 449)						•••• ••••• •	••••
** *Melaleuca nematophylla*	•	•			•• •	•••••••••••••••	••
* *Leucopogon* sp. Clyde Hill (M.A. Burgman 127)		•		•	•	••• ••••• • ••	
Hibbertia hypericoides	• • •••				• ••	•••••••••••	
Xanthosia bungei	•				••	• •• • • • •	
Grevillea paradoxa				•• •	•	• •••••• ••	•
Micromyrtus sp. Warriedar (S. Patrick 1879A)				• ••	•	• ••• • • ••	•
* *Melaleuca radula*						• ••••	
SPECIES GROUP H							
Acacia stowardii					•	•	
Arthropodium curvipes		•			• •	• • •	
Brachychiton gregorii					••	•	
* *Cassytha nodiflora*					•	•• ••• ••	
** *Darwinia masonii*					••••••	• •• • ••	
* *Prostanthera magnifica*					•• •	• •••	
Hibbertia aff. *rostellata* (R.Meissner & Y.Caruso 27)				•	•	• • ••	•
SPECIES GROUP I							
* *Acacia coolgardiensis* subsp. *effusa*	•		•	••		• •	••••
** *Enekbatus stowardii*				••		• •	•••••
** *Melaleuca fabri*							•••••
** *Stylidium confluens*						• ••	••••
** *Amphipogon caricinus* var. *caricinus*				•••		• ••• •	•••••
Drosera macrantha subsp. *macrantha*	••			•		• • • ••	•• •
* *Eucalyptus oldfieldii*						•	••
* *Baeckea* sp. Mt Gibson							••
SPECIES GROUP J							
Melaleuca leiocarpa					•		•
SPECIES GROUP K							
Acacia stereophylla var. *stereophylla*						• •	•
Melaleuca cordata						••	
SPECIES GROUP L							
Hibbertia arcuata		••		•		• •	
Rhyncharrhena linearis		•		•			
SPECIES GROUP M							
Cyanicula amplexans						• •	
Gastrolobium laytonii					•	• •	

Table 2

Spearman's rank correlation of soil chemistry parameter and physical site characters. Cells with numbers present represent significant correlation at P < 0.05.

	eCEC	pH	B	Ca	Cd	Co	Cu	Fe	K	Mg	Mn	Mo	Na	Ni	P	Pb	S	Zn	Aspect	Slope	Surface Rock Abundance	Surface Rock Size	Rock Outcrop Abundance
eCEC																							
pH	0.55																						
B	0.44																						
Ca	0.98	0.60	0.41																				
Cd																							
Co	0.43	0.43	0.46	0.35	0.29																		
Cu	0.29		0.43			0.55																	
Fe	0.47			0.53																			
K	0.41		0.42	0.29		0.53	0.72																
Mg	0.94	0.55	0.40	0.89		0.45		0.41	0.39														
Mn	0.50	0.71	0.35	0.49		0.75	0.44			0.54													
Mo					0.46	0.31	0.33		0.32		0.33												
Na	0.52		0.37	0.40		0.35		0.28	0.70	0.58		0.30											
Ni	0.54		0.44	0.47		0.67	0.45		0.56	0.46	0.36		0.47										
P	0.01	-0.41							0.36				0.38										
Pb							-0.31																
S		-0.78		-0.33		-0.44					-0.58		0.33		0.46								
Zn			0.28			0.41	0.61		0.60				0.37	0.42	0.40								
Aspect							-0.29								-0.31								
Slope								0.32															
Surface Rock Abundance					-0.40																		
Surface Rock Size	0.35			0.37	-0.27			0.41		0.33										0.40			
Rock Outcrop Abundance								0.55					0.31				0.29			0.50		0.67	
Runoff								0.29												0.75		0.31	0.38
%Litter					-0.30		0.34														0.38	0.34	
%Bare								0.36														0.30	

Table 3

Plant community mean values for soil chemistry parameters (measured in mg/kg except eCEC and pH). Differences between ranked values tested using Kruskall –Wallis non-parametric analysis of variance. Standard error in parentheses. a and b represent significant differences between community types at P < 0.05 (n = number of quadrats, P = probability, ns = not significant). Community 3 was excluded from analysis due to low quadrat number.

	Community Type							
	1	2	3	4	5	6	7	P
eCEC	3.3 (0.5)	3.5 (0.3)	3.3 (0.6)	3.9 (1.4)	4.8 (0.7)	3.6 (0.5)	2.5 (0.3)	ns
pH	4.7 (0.1)[a]	5.2 (0.1)[ab]	5.1 (0.2)	5.2 (0.4)[ab]	5.2 (0.0)[b]	4.9 (0.1) [ab]	4.9 (0.1) [ab]	0.02
Ca	393.0 (57.8)	476.736.1	411.779.8	578.0253.3	651.777.7	472.069.5	294.037.2	ns
Mg	89.2 (14.9)	84.8 (8.5)	88.7 (22.2)	81.2 (20.0)	140.8 (32.5)	99.9 (14.3)	76.4 (11.6)	ns
P	9.1 (2.0)	4.7 (0.5)	13.7 (6.2)	5.8 (0.6)	6.3 (1.4)	7.6 (0.9)	5.0 (0.5)	ns
K	198.0 (16.1)[a]	125.7 (8.4)[ab]	163.3 (28.5)	97.0 (10.2)[b]	116.8 (13.0)[ab]	113.8 (8.5)[b]	112.0 (22.5)[ab]	<0.01
B	0.7 (0.1)	0.8 (0.1)	0.7 (0.2)	0.6 (0.1)	0.5 (0.0)	0.6 (0.1)	0.5 (0.0)	ns
Cd	0.01 (0.00)	0.01 (0.00)	0.01 (0.00)	0.01 (0.00)	0.01 (0.00)	0.01 (0.00)	0.01 (0.00)	ns
Co	0.5 (0.2))	0.5 (0.1)	0.9 (0.5)	0.4 (0.2)	0.3 (0.1)	0.2(0.0)	0.3 (0.1)	ns
Cu	2.4 (0.1)[a]	2.2 (0.4)[ab]	2.0 (0.5)	1.2 (0.2)[b]	1.4 (0.1)[ab]	1.2 (0.1)[b]	1.3 (0.1)[b]	<0.01
Fe	51.7 (4.0)	45.2 (3.5)	44.7 (4.8)	48.6 (7.6)	69.8 (5.8)	73.2 (12.4)	43.0 (2.3)	0.02
Mn	92.5 (17.2)	100.2 (10.9)	135.7 (38.2)	68.8 (17.7)	106.7 (14.4)	71.7 (10.9)	81.2 (20.7)	ns
Mo	0.01 (0.00)	0.01 (0.00)	0.01 (0.00)	0.01 (0.00)	0.01 (0.00)	0.01 (0.00)	0.01 (0.00)	ns
Na	35.1 (8.2)	14.8 (1.3)	19.7 (4.8)	12.8 (3.2)	21.3 (5.3)	21.1 (4.7)	23.8 (9.6)	ns
Ni	0.3 (0.1)	0.4 (0.1)	0.3 (0.1)	0.3 (0.1)	0.3 (0.1)	0.2 (0.0)	0.2 (0.1)	ns
Pb	0.7 (0.1)	0.8 (0.1)	0.9 (0.2)	0.8 (0.1)	0.9 (0.1)	0.9 (0.1)	0.8 (0.1)	ns
S	17.6 (3.7)[a]	6.3 (0.7)[b]	10.0 (4.0)	10.6 (1.5)[ab]	8.2 (0.8)[ab]	14.3 (2.5)[a]	12.2 (2.2)[ab]	0.01
Zn	3.3 (0.4)[a]	2.4 (0.4)[ab]	2.8 (0.7)	1.4 (0.2)[b]	1.3 (0.2)[b]	1.7 (0.1)[ab]	1.3 (0.2)[b]	<0.01
n	10	9	3	5	6	15	5	

Table 4

Plant community mean values for physical site parameters; aspect (16 cardinal directions), slope (degrees), coarse fragment (CF) abundance (0 – no coarse fragments to 6 very abundant coarse fragments), grazing (0 –no evidence of grazing and 1 grazed), maximum size of coarse fragments (1 – fine gravely to 7 large boulders), rock outcrop (RO) abundance (0 – no bedrock exposed to 5 – rockland), runoff (0 – no runoff to 5 – very rapid), % leaf litter and bare ground (1 – >70% to 4 – <10%). Differences between ranks tested using Kruskall-Wallis non-parametric analysis of variance. Standard error in parentheses. a, b and c represent significant differences between community types at P < 0.05 (n = number of quadrats, P = probability, ns = not significant).

	Community Type							
	1	2	3	4	5	6	7	P
Aspect	6.9 (1.5)	7.7 (1.9)	3.7 (3.7)	8.4 (2.0)	8.3 (2.7)	7.3 (1.5)	9.8 (2.8)	ns
Slope	10.7 (1.6)[a]	4.2 (0.8)[ab]	1.0 (1.0)	2.8 (0.6)[b]	10.7 (2.0)[ab]	9.3 (1.4)[ab]	12.6 (7.1)[ab]	0.01
Grazing	1.0 (0.0)[a]	1.0 (0.0)[a]	1.0 (0.0)	0.4 (0.2)[ab]	0.7 (0.3)[ab]	0.2 (0.1)[b]	0.0 (0.0)[b]	<0.01
CF Abundance	3.9 (0.2)	4.3 (0.3)	2.0 (0.6)	3.4 (0.4)	3.7 (0.3)	3.7 (0.2)	3.0 (0.5)	ns
Max. Size	4.5 (0.3)[ab]	4.2 (0.3)[ab]	2.7 (0.3)	3.4 (0.4)[b]	5.3 (0.3)[a]	4.1 (0.2)[ab]	2.4 (0.6)[b]	<0.01
RO Abundance	1.6 (0.4)[ab]	0.3(0.2)[ab]	0.0 (0.0)	0.0 (0.0)[b]	2.8 (0.7)[a]	2.3 (0.4)[a]	0.4 (0.4)[ab]	<0.01
Runoff	1.8 (0.2)	1.8 (0.3)	0.0 (0.0)	1.4 (0.2)	2.5 (0.3)	2.4 (0.2)	2.0 (0.3)	ns
%Leaf Litter	3.8 (0.1)[a]	3.5 (0.2)[ab]	2.7 (0.3)	2.4 (0.2)[ab]	3.3 (0.3)[ab]	2.6 (0.3)[ab]	2.0 (0.5)[b]	<0.01
% Bare Ground	1.2 (0.1)	1.2 (0.1)	1.0 (0.0)	1.0 (0.0)	1.3 (0.2)	1.2 (0.1)	1.0 (0.0)	ns
n =	10	9	3	5	6	15	5	

APPENDIX 1

Flora list for Mount Gibson, including all taxa from the sampling quadrats and adjacent areas. Nomenclature follows Paczkowska and Chapman (2000), * indicates introduced taxon.

Adiantaceae

Cheilanthes adiantoides
Cheilanthes sieberi subsp. *sieberi*

Aizoaceae

* *Cleretum papulosum*

Amaranthaceae

Ptilotus drummondii
Ptilotus exaltatus
Ptilotus gaudichaudii var. *parviflorus*
Ptilotus helipteroides
Ptilotus obovatus var. *obovatus*

Anthericaceae

Arthropodium curvipes
Arthropodium dyeri
Caesia sp. Wongan (K.F. Kenneally 8820)
Dichopogon tyleri
Thysanotus manglesianus
Thysanotus pyramidalis
Tricoryne elatior

Apiaceae

Daucus glochidiatus
Hydrocotyle rugulosa
Trachymene cyanopetala
Trachymene ornata
Trachymene pilosa
Xanthosia bungei

Apocynaceae

Alyxia buxifolia

Asclepiadaceae

Rhyncharrhena linearis

Asphodelaceae

Bulbine semibarbata

Asteraceae

Bellida graminea
Blennospora drummondii
Brachyscome cheilocarpa
Brachyscome ciliocarpa
Brachyscome perpusilla
Brachyscome pusilla
Calocephalus multiflorus
Calotis hispidula
Calotis multicaulis
Cephalipterum drummondii
Ceratogyne obionoides
Chthonocephalus pseudevax
Feldstonia nitens
Gilberta tenuifolia
Gilruthia osbornei
Gnephosis tenuissima
Hyalosperma demissum
Hyalosperma glutinosum subsp. *glutinosum*
Hyalosperma glutinosum subsp. *venustum*
* *Hypochaeris glabra*
Isoetopsis graminifolia
Lawrencella davenportii
Lawrencella rosea
Millotia myosotidifolia
Myriocephalus guerinae
Myriocephalus pygmaeus
Olearia humilis
Olearia muelleri
Olearia pimeleoides
Podolepis canescens
Podolepis lessonii
Podotheca gnaphalioides
Podotheca uniseta
Rhodanthe battii
Rhodanthe chlorocephala subsp. *rosea*
Rhodanthe chlorocephala subsp. *splendida*
Rhodanthe citrina
Rhodanthe collina
Rhodanthe laevis
Rhodanthe manglesii
Rhodanthe maryonii
Rhodanthe polycephala
Rhodanthe pygmaea
Rhodanthe spicata
Rhodanthe stricta
Schoenia cassiniana
Schoenia filifolia subsp. *filifolia*
* *Sonchus oleraceus*
Waitzia acuminata var. *acuminata*
* *Urospermum picroides*
* *Ursinia anthemoides*

Brassicaceae

Lepidium oxytrichum
Stenopetalum anfractum
Stenopetalum filifolium

Caesalpiniaceae

Senna artemisioides subsp. *filifolia*
Senna glutinosa subsp. *chatelainiana*
Senna sp. Austin (A. Strid 20210)

Campanulaceae

Wahlenbergia gracilenta
Wahlenbergia tumidifructa

Casuarinaceae

Allocasuarina acutivalvis subsp. *prinsepiana*

Celastraceae

Psammomoya grandiflora

Chenopodiaceae

Chenopodium melanocarpum
Maireana georgei
Maireana marginata
Maireana trichoptera
Rhagodia sp. Watheroo (R.J. Cranfield & P.J. Spencer 8183)
Sclerolaena fusiformis
Sclerolaena gardneri

Colchicaceae

Wurmbea densiflora

Crassulaceae

Crassula closiana
Crassula colorata var. *acuminata*
Crassula colorata var. *colorata*
Crassula extrorsa
Crassula tetramera

Cupressaceae

Callitris columellaris

Cuscutaceae

* *Cuscuta epithymum*

Cyperaceae

Schoenus nanus
Lepidosperma gibsonii

Dasypogonaceae

Chamaexeros macranthera

Dilleniaceae

Hibbertia arcuata
Hibbertia glomerosa var. *glomerosa*
Hibbertia hypericoides
Hibbertia aff. *rostellata* (R.Meissner & Y.Caruso 27)

Droseraceae

Drosera macrantha subsp. *macrantha*

Epacridaceae

Leucopogon sp. Clyde Hill (M.A. Burgman 1207)

Euphorbiaceae

Calycopeplus paucifolius
Euphorbia boophthona
Euphorbia tannensis subsp. *eremophila*
Poranthera microphylla

Geraniaceae

* *Erodium cicutarium*
Erodium cygnorum

Goodeniaceae

Brunonia australis
Goodenia berardiana
Goodenia havilandii
Goodenia mimuloides
Goodenia occidentalis
Goodenia pinifolia
Goodenia pinnatifida
Scaevola spinescens
Velleia cycnopotamica
Velleia hispida
Velleia rosea

Haloragaceae

Gonocarpus nodulosus
Haloragis odontocarpa forma rugosa
Haloragis trigonocarpa

Juncaginaceae

Triglochin sp. B Flora of Australia (P.G. Wilson 4294)

Lamiaceae

Hemigenia macphersonii
Hemigenia sp. Sticky Terete (B.H. Smith 449)
Hemigenia sp. Yalgoo (A.M. Ashby 2624)
Prostanthera magnifica
Prostanthera patens
Prostanthera althoferi subsp. *althoferi*

Lauraceae

Cassytha nodiflora

Lobeliaceae

Lobelia winfridae

Loganiaceae

Phyllangium sulcatum

Loranthaceae

Amyema gibberula var. *tatei*

Malvaceae

Sida atrovirens
Sida chrysocalyx

Mimosaceae

Acacia acuaria
Acacia acuminata (narrow phyllode variant)
Acacia andrewsii
Acacia aneura
Acacia anthochaera
Acacia assimilis subsp. *assimilis*
Acacia cerastes
Acacia colletioides
Acacia coolgardiensis subsp. *effusa*
Acacia exocarpoides
Acacia neurophylla subsp. *erugata*

Acacia obtecta
Acacia ramulosa var. *ramulosa*
Acacia stereophylla var. *sterophylla*
Acacia sibirica
Acacia tetragonophylla
Acacia umbraculiformis

Myoporaceae

Eremophila clarkei
Eremophila forrestii subsp. *forrestii*
Eremophila glutinosa
Eremophila latrobei subsp. *latrobei*
Eremophila oldfieldii subsp. *angustifolia*

Myrtaceae

Aluta aspera subsp. *hesperia*
Baeckea sp.
Darwinia masonii
Enekbatus stowardii
Eucalyptus horistes
Eucalyptus kochii subsp. *amaryssia*
Eucalyptus kochii subsp. *plenissima*
Eucalyptus loxophleba subsp. *supralaevis*
Eucalyptus oldfieldii
Melaleuca atroviridis
Melaleuca cordata
Melaleuca eleuterostachya
Melaleuca fabri
Melaleuca hamata
Melaleuca leiocarpa
Melaleuca nematophylla
Melaleuca radula
Micromyrtus clavata
Micromyrtus sp. Warriedar (S. Patrick 1879A)

Orchidaceae

Cyanicula amplexans
Cyanicula sp.

Papilionaceae

Gastrolobium laytonii
Mirbelia bursarioides

Phormiaceae

Dianella revoluta var. *divaricata*

Pittosporaceae

Cheiranthera filifolia var. *simplicifolia*

Plantaginaceae

Plantago aff. *hispida* (R.Meissner & Y.Caruso 121)

Poaceae

Amphipogon caricinus var. *caricinus*
Aristida contorta
Austrodanthonia caespitosa
Austrostipa blackii
Austrostipa elegantissima
Austrostipa eremophila
Austrostipa hemipogon
Austrostipa nitida
Austrostipa scabra
Austrostipa trichophylla
Bromus arenarius
Lachnagrostis plebeia
Monachather paradoxus
* *Pentaschistis airoides* subsp. *airoides*
* *Elymus* sp.
* *Vulpia muralis*

Polygalaceae

Comesperma integerrimum

Portulacaceae

Calandrinia eremaea complex
Calandrinia sp. Blackberry (D.M. Porter 171)
Calandrinia sp. Bungalbin (G.J. Keighery & N. Gibson 1656)
Calandrinia sp. Truncate capsules (A. Markey & S. Dillon 3474)
Calandrinia translucens

Proteaceae

Grevillea obliquistigma subsp. *obliquistigma*
Grevillea paradoxa
Grevillea pityophylla
Grevillea sp.
Hakea recurva
Persoonia pentasticha
Persoonia sp.
Persoonia sp. Paynes Find (D. Edinger et al. 313)

Rutaceae

Phebalium tuberculosum
Philotheca brucei subsp. *brucei*
Philotheca sericea
Philotheca tomentella

Santalaceae

Santalum acuminatum
Santalum spicatum

Sapindaceae

Dodonaea inaequifolia
Dodonaea sp. Ninghan (H. Demarz 5121)

Solanaceae

Nicotiana rosulata
Solanum ellipticum
Solanum lasiophyllum
Solanum orbiculatum subsp. *orbiculatum*

Sterculiaceae

Brachychiton gregorii
Rulingia luteiflora

Stylidiaceae

Stylidium confluens

Thymelaeaceae

Pimelea avonensis

Urticaceae

Parietaria cardiostegia

Zygophyllaceae

Zygophyllum eremaeum
Zygophyllum ovatum
Zygophyllum tesquorum

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Flora and vegetation of the banded iron formations of the Yilgarn Craton: the central Tallering Land System

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ABSTRACT

A quadrat-based survey was undertaken on the flora and floristic communities of several ironstone ranges and outcrops in the Yalgoo bioregion, covering the central extent of the Tallering Land System. One hundred and three 20 x 20 m quadrats were established over the extent of this region, and covered the topographic profile of these landforms. A total of 414 taxa (species, subspecies, varieties and forms) and four hybrids were identified from these quadrats. Fifteen taxa of conservation significance were found in this survey, five of which had not been previously recorded from the area. Significant range extensions for 21 species are reported in this study. At least nine new taxa were identified, of which several are of conservation significance. Nine regional endemic and near-endemic taxa were found over the study area, with half restricted to the south-west hills.

Eight floristic community types (five main types, two with subtypes) were resolved from classification analysis of floristic data (presence / absence). These community types were strongly associated with topography and soil chemistry. Geographical variation was found among the floristic communities within the region, and some communities were found to be restricted to the south-west of the survey area. These restricted communities were found to occur in the more mesic regions of the survey area, on rocky uplands of BIF, and had notable component of flora from the South West Floristic Region.

The central Tallering Land System is currently unreserved, although three pastoral leases have been purchased by the Western Australian Department of Conservation and Land Management (CALM) (now known as the Department of Environment and Conservation (DEC)) with the intention for future inclusion in the conservation estate. Mining and exploration tenements cover nearly all of the central Tallering Land System. This area has significant conservation values, and proposed mining activities must be assessed and managed to minimise impacts on significant flora and floristic communities.

INTRODUCTION

Previous quadrat-based surveys have examined the flora and floristic communities on a number of ranges in the eastern goldfields. These have provided a regional overview of these ranges, improved current knowledge of their flora and found that individual ranges of both banded iron formation (BIF) and greenstones possess unique communities that differ floristically from other ranges (Gibson 2004a, b; Gibson and Lyons 1998, 2001a, 2001b). Ironstone and greenstone landforms within the northern Murchison geological region currently lack such detailed information, and are currently subject to considerable exploration and mining interests. This current survey aims to examine the flora and floristic communities of a series of small ironstone ranges in the northern Yilgarn region, and is one of a series of surveys being conducted by DEC on ranges of prospectable BIF and associated metasedimentary geologies. These surveys aim to ultimately redress deficiencies in data for these areas, provide a regional context for these communities, and contribute to the conservation and management of biodiversity on BIF ranges.

STUDY SITE

This survey focuses on the vegetation communities associated with several narrow, elongate belts of metamorphic sedimentary rocks that occur within the central Tallering Land System of Payne et al. (1998). These form two main arches that span a distance of c. 52 km east – west and extend c. 55 km in a north-south direction between Perenjori, Paynes Find and Yalgoo (Figure 1). The study area extends over the Karara, Badja, Thundelarra and Warriedar Stations, within the Yalgoo and Perenjori shires. This survey specifically targeted hills and ridges of banded iron formation (BIF) within this area.

The Tallering Land System was first described and mapped by Payne et al. (1998), and refers to the hills and ranges of ironstone, volcanic and metasedimentary geologies which are located between Mt Gibson and Tallering Peak. As the central portion of this land system coincides with the banded iron formations targeted by this survey, and the name 'central Tallering Land System' is adopted by this study as the collective name of these landforms within the study region.

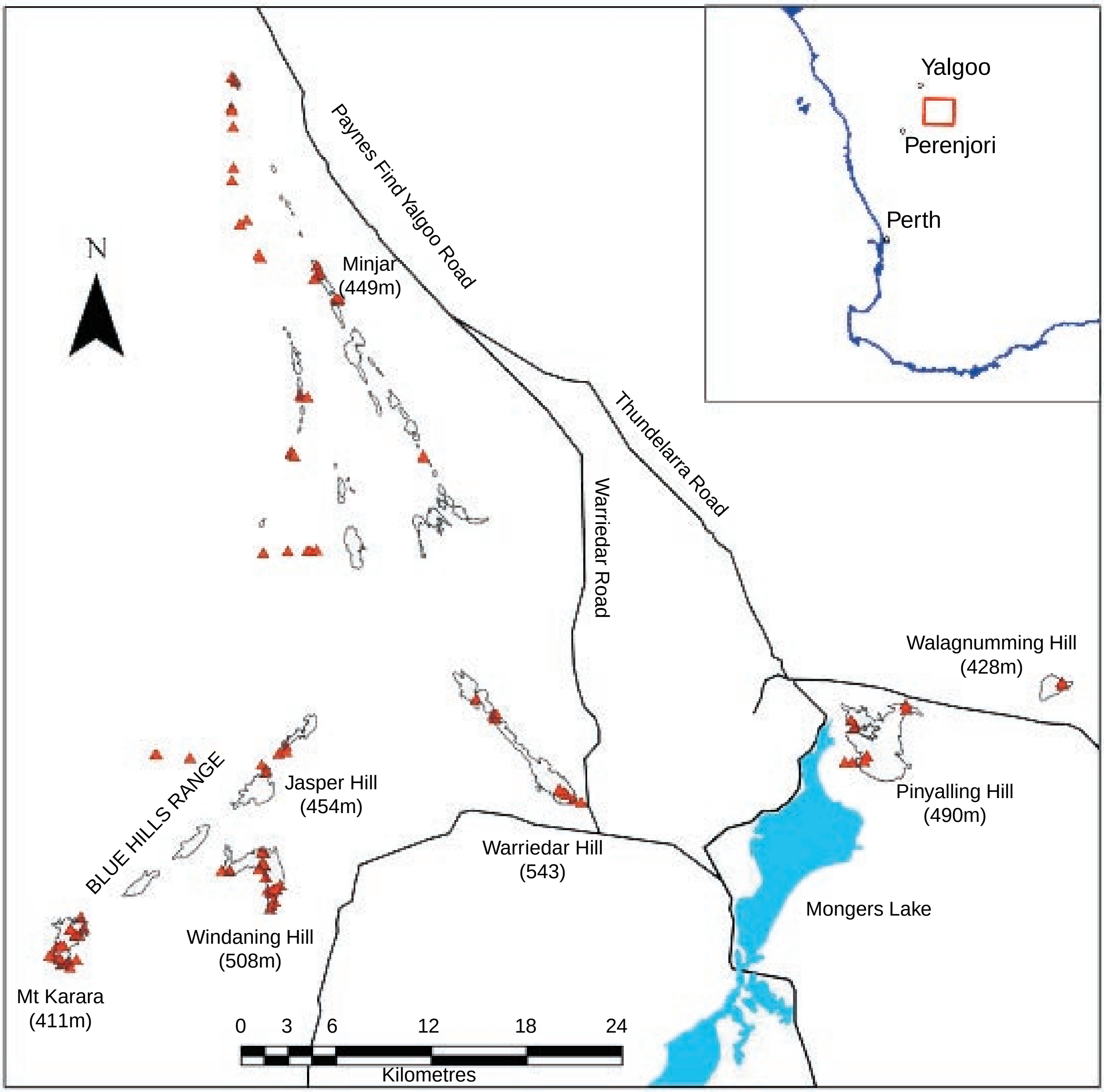

Figure 1. Map showing the location of the survey region and location of the specific ranges, landforms and landmarks which constitute the central Tallering Land System. Locations of the 103 floristic quadrats are marked by triangles (▲).

Land Use History

The lands within the Yalgoo bioregion have been subject to pastoral and mining activity, although it has not been subject to extensive land clearing like the adjacent wheatbelt region. Pastoral leases were first established in the study area in the latter half of the 19th century, commencing with Thundelarra (Pinyalling Spring) and Badja stations in the early 1870's, and with most leases established by the early 1900's (Hennig 1998a). Thundelarra and Badja Stations are currently active. Between 2000 and 2004, the adjoining Karara, Lochada and Warriedar pastoral leases were purchased by the Department of Conservation and Land Management (CALM 2004). The current tenure status of this area is Unallocated Crown Land, and is in the process of tenure review with the intention of this area becoming conservation estate. These former leases have been subsequently de-stocked, wells closed and feral animal eradication programs implemented (CALM 2005).

Gold discoveries in the late 19th century led to the establishment of towns and gold mining activities in the region (Beard 1976a; Hennig 1998a). From the late 1960s until 1974, iron ore mining was conducted at the Blue Hills (Beard 1976b). Within the past decade, there has been dramatic upsurge in mineral exploration and mining activities following increased demand from China. Current mineral exploration activities in the region target rock ores as a source of iron, and both precious (Ag, Au) and industrial metals (Ni, Cr, Mn, Mo, Va, Tg) (Baxter & Lipple 1985; Baxter et al. 1983; Department of Industry and Resources 2007; Lipple et al. 1983; Muhling and Low 1977). There are currently two active mines in the study area at Gossan Hill and Golden Grove, whilst iron ore exploration is in progress on Mt Karara, Windaning Ridge and Blue Hills Range. Most of the central Tallering Land System is covered by mining tenements.

Climate

The study area is bounded by the 300 and 250 mm isohyet and lies within the Semi-Desert Mediterranean bioclimatic region (Beard 1976a, 1990), where the annual evaporation range of 2800 – 3200 mm greatly exceeds the annual rainfall (Leighton 1998). The area has mild winters and hot, dry summers, and a low, moderately variable rainfall that falls mostly in winter, but irregular summer rainfall may occur (Beard 1976a, b; Leighton 1998). Winter rainfall is derived from rain-bearing cold fronts associated with the westerly wind system, and 62% of median annual rainfall is received during the winter season (Leighton 1998). Summer rainfall events are thunderstorms and heavy downpours derived from the depressions that are the remnants of tropical cyclones (Leighton 1998), such that over 120 mm can fall in a day (Australian Bureau of Meteorology 1908–). Rainfall is patchy and irregular in its distribution over the study area. Downpours may not be widespread but can be restricted to small areas, even within or between adjacent stations (Leighton 1998; A. Markey, pers. obs[1]).

As Paynes Find and Yalgoo are the two closest meteorological centres to the study area, weather data from these centres provides some information on the climate of the survey area (Australian Bureau of Meteorology 1908–). There is a rainfall gradient over the region, such that rainfall decreases in a north-easterly direction. Therefore, the mean annual rainfall declines from Paynes Find (282 mm) northwards to 258 mm at Yalgoo (these records commencing from 1896 (Paynes Find) and 1919 (Yalgoo) until 2004). Rainfalls were good in the months preceding this current field survey (Spring 2005), and consequently there was an abundant growth of annuals and good flowering of perennial species within the study season.

For both centres, the average winter (June – August) maximum temperature is 19.1 °C, and the average summer (December – February) daily maximum is 36.3°C. January is the hottest month, with maximum temperatures of 37.1 °C and 37.2 °C in Paynes Find and Yalgoo, respectively. Conversely. the coldest month is July with mean minimum temperatures of 5.4 °C and 6.2 °C, respectively. Temperatures rarely fall below 0 °C, and occur on an average of 3.1 days and 0.6 days during July for Paynes Find and Yalgoo respectively. The predominant growing season is in winter, given that it is the coolest and wettest season (Leighton 1998).

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Geology

The geology of the study region has been described and mapped over four geological sheets; Perenjori 1: 250 000 (SH/50 – 6) (Baxter & Lipple 1985), Yalgoo 1: 250 000 (SH/50-2) (Muhling and Low 1977), Ninghan 1: 250 000 (SH/50-7) (Lipple et al. 1983), Kirkalocka 1: 250 000 (SH/50-3) (Baxter et al. 1983). The Murchison region is an undulating plateau of low relief, with large playa lake systems and erosional escarpments (breakways). Much of this region consists of Cainozoic deposits which overlie the granitoids, infolded belts of metamorphic sedimentary and igneous rocks of the Archaean Yilgarn Craton (Baxter et al. 1983; Johnson 1998; Lipple et al. 1983; Muhling & Low 1977). This subdued landscape is interrupted by hills, ridges and uplands of exposed Archaean granitoid and metamorphic sedimentary bedrock which rise above the surrounding plains.

Within the study area, the altitude ranges from low to high relief (360 – 543 m above sea level). Most hills range from 30 to 180 m in height above the surrounding plains, although a number of significant hills can exceed this (Figure 1). Whilst granitoids form monoliths and pavements, the metamorphic sedimentary and igneous rocks form elongate hills and rugged strike ridges that are linear-arcuate, and north to north-west trending (Johnson 1998; Lipple et al. 1983; Payne & Pringle 1998). These belts of Archean metamorphosed and deformed greenstones consist of mafic to ultramafic volcanics and felsic volcanics, and metasedimentary rocks of shale, siltstone, chert, jaspilite, and banded iron formation (BIF) (Baxter & Lipple 1985; Johnston 1998; Lipple et al. 1983; Muhling & Low 1977). Erosion of these Archean metasediments and volcanics forms a colluvium of sand, silt and angular ironstone, greenstone and quartz fragments, which deposit as talus and scree slopes and outwash fans on the margins of these landforms (Johnson 1998). Soils of these landforms consist of shallow or skeletal (< 50 cm) stony soils on the ridges, rises and hills, and associated with rocks, boulders and outcropping bedrock, which are replaced by shallow stony red earths and red clayey sands and ferruginous gravel on the lower slopes and outwashes (Hennig 1998b).

Three Land Systems have been identified by Payne and Pringle (1998) which refer to landforms of greenstone and banded iron formation in the Paynes Find – Sandstone area. These are the Tallering (prominent ridges and hills of banded iron formation, dolerite and metasedimentary rocks), Watson (metasedimentary rocks), and Gabanintha (volcanics and metasedimentary rocks) Land Systems. Of these Land Systems, the central extent of the Tallering Land System is the geomorphological unit which most specifically corresponds to the strike ridges and hills of banded iron formation examined in this survey. The banded iron formations and other metasedimentary rocks of the central Tallering Land System are associated with the Warriedar Fold Belt.

Vegetation

The study area is located in the Yalgoo subregion, which is nested within the Austin Botanical District of the Eremaean Botanical Province (Beard 1976b, 1990). This subregion of Beard (1976a) corresponds to the IBRA Yalgoo Bioregion (Environment Australia 2000; Thackway & Creswell 1995). Being in close proximity to the north-eastern boarders of the biologically diverse South West Botanical Province (Beard 1990; Hopper & Gioia 2004), the Yalgoo subregion is a transitional zone between the two botanical provinces (Beard 1976a; Environment Australia 2000; Thackway & Creswell 1995). However, there have been few detailed surveys on the vegetation communities within this region which spans this transition from the South West Botanical Province to the arid Eremaean Province. The vegetation maps of the Austin Botanical District were on a scale of 1:1000 000, and communities were defined primarily by physiognomy and dominant taxa (Beard 1976a). The Austin Botanical District is dominated by low mulga (*Acacia aneura*) woodland on the plains and reduced to *Acacia* scrub on hills (Beard 1976a, 1990). The hill vegetation was reported as shrublands dominated by *Acacia aneura*, *Acacia quadrimarginea, Acacia ramulosa* and *Acacia grasbyi* over a mid stratum of *Senna* and *Eremophila* shrubs, with little difference being noted between communities on granitoids and metamorphic sedimentary rocks at this scale (Beard 1976a, 1990).

On a more detailed scale, Beard (1976b) produced a 1:250 000 map of physiognomic vegetation formations of the Perenjori area, which only covers the lower half of this current survey area. On this scale, the extensive outcroppings of Archean metamorphic rocks (including banded iron formations) are associated with two vegetation systems; the Windaning System and Gnow's Nest System. The Windaning System consists of outcrops of Archaean metamorphic rocks which are covered in scrub (*Acacia ramulosa*, *Allocasuarina* sp., *Melaleuca* cf. *uncinata*, *Acacia quadrimarginea* and *Acacia acuminata* (=*A. burkittii*), and scattered eucalypts. The valleys are vegetated with acacia scrub and scattered emergent trees (Beard 1976b). Only the southern extent of the Gnows Nest System (coinciding with the Gnows Nest Range) was mapped, this southern extent being more subdued in topography than the Windaning system (Beard 1976b). Vegetation was described as *Acacia* scrub, dominated by A. *ramulosa* and *A. acuminata* (=*A. burkittii*), with *A. quadrimarginea* on steeper slopes.

Pringle (1998) described the vegetation of the Sandstone – Yalgoo - Paynes Find area on a scale of 1:250 000, defining structural vegetation systems based on perennial taxa. A total of eight upland vegetation communities ('habitats') were identified from across all the land systems, of which three were characteristic of ironstone substrates. These three upland ironstone communities occur within the Tallering Land System (Pringle 1998), as does a fourth, lowland community. These communities are: stony ironstone acacia (SIAS), ironstone ridge mixed shrubland (IRMS) and breakaway mixed shrubland (BRXS) on the hillslopes and crests (uplands), and lateritic sandplain acacia shrubland (LACS) and the lower slopes and outwashes. The SIAS community consists of a dominant stratum of trees of *Acacia* spp., *Casuarina* and / or *Eucalyptus*, over a tall shrub layer of *A. ramulosa*, *A. burkittii*, *A. quadrimarginea*, *A. tetragonophylla* and *Santalum spicatum*, over lower shrub strata of diverse and variables species, including *Eremophila forrestii*, *Scaevola spinescens*, *Ptilotus obovatus*, *Senna artemisioides* subsp. *filifolia*, *Eremophila latrobei*, *Philotheca brucei*, *Solanum lasiophyllum* and *Sida atrovirens* (= *Sida* sp. dark green fruits (S. van Leeuwen 2260), the grass, *Austrostipa elegantissima* and the pteridiophyte, *Cheilanthes austrotenuifolia*. The IRMS community includes *Philotheca sericea* and *Thryptomene decussata* as dominant taxa, is species-rich and has floristic affinities to the South West Botanical Province. This community is restricted to the southwest of the Sandstone-Paynes Find-Yalgoo area (Pringle 1998).

Since Pringle (1998), various small-scale, unpublished surveys have been undertaken on various landforms within the study area, these being undertaken by consultants and restricted to areas within immediate vicinity of proposed mining activities. The most comprehensive of these surveys at the time of this survey described 21 structural vegetation communities for the landforms in the south-western part of the survey area, of which 10 are associated with ironstone landforms (Woodman Environmental Consulting Pty Ltd 2003, 2004a, 2004b, 2004c). These can be generally partitioned into *Eucalyptus* woodlands on lower slopes and outwash plains, and thickets and scrubs on the hills, rises and uplands variously dominated by *Allocasuarina acutivalvis*, *Acacia ramulosa* subsp. *ramulosa*, *Acacia burkittii* (=*A. acuminata*) mixed dominant *Acacia* species over a heath or low scrub of mixed species.

Prior surveys on the central Tallering Land System are based on structural descriptions of vegetation communities, at scales either too broad or too refined for a regional overview within this land system. The aim of the current survey is to provide a regional overview of the flora and vegetation which is sufficient in detail to resolve floristic communities both within and among these landforms within the central Tallering Land System.

METHODS

One hundred and three 20 x 20m permanent quadrats were established on Mt Karara, Jasper Hill, Windaning Hill and its associated ridge (henceforth referred to as Windaning Ridge), Warriedar Hill, Pinyalling Hill, Walagnumming Hill, Minjar Hill and the low strikes of ironstone west and north of Minjar Hill (Figure 1), between September and October 2005. Quadrats were placed on the crests, slopes and peneplains mainly within the middle third of Tallering Land System type of Payne et al. (1998), and were placed strategically to encompass the topographical profile of these landforms and their associated vegetation communities. This methodology has been used to survey other ranges in Western Australia (e.g. Gibson 2004a). Quadrats were established only in the least disturbed vegetation in the area, and burnt, heavily grazed and cleared areas were avoided.

Quadrats were marked with four steel fence droppers and their altitude and position recorded by GPS and photographed at a set distance (usually 5 m) from each corner. The presence and cover of all vascular plant species (angiosperms, gymnosperms and pteridiophytes) were recorded in each quadrat, with material collected for verification at the Western Australian Herbarium. Vegetation structure was described according to McDonald et al. (1998). All data on topographical position, aspect, slope, % litter, % bare ground, % rock cover class of both surface deposits and exposed bedrock, shape of surface rock fragments, soil colour and soil texture were noted according to the standard definitions outlined in McDonald et al. (1998). Percentage surface rock fragment cover class, maximum rock fragment size (MxR) and exposed bedrock outcrop cover were all coded on a semi-quantitative scale. Percentage surface rock fragment cover classes (Frag Rock) were scored on seven point 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 was classed on a six 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). Leaf litter and bare ground were visual estimates of the percentage of ground cover. Topographic position (Tp) in the landscape was coded on a five point scale which was semi-quantitative: outwash (1); lower slope (2); mid slope (3), upper slope or low, isolated ridge (4), crest (5).

For each quadrat a bulked soil sample was collected from the top 10 cm, this being complied from 20 smaller samples collected regularly over the area of the quadrat. The ≤ 2mm fraction of these soils were analysed for a suite of 12 elements at the Chemistry Centre of Western Australia, using inductively coupled plasma atomic emission spectrometry (ICP AES). This involved the simultaneous determination of a suite of elements (P, K, S, Ca, Mg, Na, B, Co, Cu, Fe, Mg and Zn) using the Mehlich No. 3 soil test procedure (Mehlich 1984, Walton and Allen 2004). Effective cation exchange capacity (eCEC) was calculated from the summing of charge equivalents of Ca, Mg, Na and K after their conversion from their respective elemental concentrations (dividing by the constants 200.4, 121.6, 230, and 390 respectively) (D. Allan, pers. comm. [2]; Rayment & Higginson 1992, Soil & Plant Council, 1999). Estimates of climatic variables (mean annual temperature, mean annual rainfall, rainfall coefficient of variation) was obtained from BIOCLIM (Busby 1986).

Classification and ordination analyses were conducted on a data matrix of 164 perennial taxa, with the singleton and annual taxa having being omitted from the data matrix prior to analysis. Resemblance matrixes (Bray Curtis measure of distance) were compared using the '2 Stage' algorithm in Primer (Clark & Gorley 2006) to determine the degree of correlation between datasets following the exclusion of taxa. Preliminary analyses found that singletons (species known from a single quadrat) contained little information. The omission of annuals was justified on the basis that their distribution and abundance over the landscape is a function of rainfall in the preceding months (Mott 1972, 1973). It also allows for comparison of data collected between seasons and years, and is consistent with previous surveys on Western Australian ironstone and greenstone ranges (e.g. Gibson 2004a).

Pattern analysis was conducted using PATN (V3.03) (Belbin 1989). The Bray-Curtis coefficient was used to generate an association matrix for both the classification and ordination analyses. This association matrix consisted of pairwise coefficients of similarities between sites based on floristic data. Agglomerative, hierarchical clustering, using flexible UPGMA (â = -0.1), was used to generate a species and site classification (Sneath and Sokal 1973). A two-way table of the site by species matrix, sorted into groups generated from these site and species classifications. Indicator species analysis was calculated using PC-Ord (McCune & Mefford 1999), using the methods of Dufrêne and Legendre (1997). Indicator values (INDVAL) were used to determine the significant indicator species for each floristic community type, and this statistic were calculated from a combination of the fidelity and constancy of each species to a community type. The INDVAL statistic (%) is maximum (100 %) when all occurrences of a species are restricted to one community type, occurring in all sites that community. INDVAL values were calculated for each species at the eight group level, and a Monte Carlo permutation test (10000 simulations) was used to test for the significance of these indicator species.

Three dimensional semi-strong hybrid multidimensional scaling (SSH MDS) was implemented for the ordination of the sites from the floristic data, using 1000 random starts and 50 iterations (Belbin 1991). Principal Component Correlation (PCC) runs a multiple linear regression of variables on the site ordination (Belbin 1989), and PCC was run on the extrinsic environmental variables on the site ordination from floristic data. The Monte-Carlo procedure (MCAO) was employed in PATN as a bootstrap analysis to evaluate the significance of these correlation coefficients. This was done for each environmental attribute by implementing PCC on the same ordination using randomly assigned values for each environmental variable in the dataset (Belbin 1989). One thousand iterations of this procedure were run. The data was found to be non-normal, highly skewed and heteroscedastic. Therefore, the Kruskal-Wallis non-parametric, one-way analysis of variance and Dunns' posthoc multiple comparisons were used to detect differences among community types for climatic and edaphic variables (Zar 1984).

Nomenclature follows Packowska and Chapman (2000), with the exception of phrase (informal) names which are currently used at Western Australian Herbarium (1998–) to denote taxa that are not yet formerly named.

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Representative specimens of all taxa have been lodged at the Western Australian Herbarium. Geographical distributions of taxa were obtained from online records at the Western Australian Herbarium (1998–).

RESULTS

Flora

A total of 414 taxa (species, subspecies, varieties and forms) and 4 putative hybrids were recorded within or adjacent to quadrats placed on the ironstone hills, ridges and uplands within the region bounded by Mt Karara, Pinyalling Hill and the Minjar Hill area (Appendix 1). Of these 414 taxa, 26 were introduced weeds. Taxa were from 69 families, of which the most speciose were the Asteraceae (69 native taxa, 1 possible hybrid and 4 introduced taxa), Poaceae (23 native and 7 introduced taxa), Mimosaceae (25 taxa), Myrtaceae (24 taxa) Chenopodiaceae (23 taxa and 1 hybrid), Myoporaceae (17 taxa), Goodeniaceae (12), Amaranthaceae (11), Proteaceae (10) and Lamiaceae (8). The most speciose genera were *Acacia* (28), *Eremophila* (17 taxa), *Rhodanthe* (13 taxa), *Ptilotus* (11 taxa) and *Austrostipa* (9 taxa) (Appendix 1). This pattern is common among floras from other ironstone surveys, and among flora within the transition from the South West to the Eremaean Botanical Province (Beard 1976a, 1990; Gibson et al. 2000; Gibson 2004a, b).

Priority taxa

Fifteen taxa of conservation significance were collected in this survey, of which five were new populations (Table 1). These taxa were listed as priority taxa according to the DEC conservation codes for Western Australia (Atkins 2006). As a direct consequence of this survey, three of these priority taxa (*A. karina, A. woodmaniorum* and *Drummondita fulva*) were recently described (Maslin & Buscomb 2007; Meissner & Markey 2007). Several of these priority taxa particularly the perennial shrubs, are largely restricted to outcrops of BIF and associated metasedimentary rocks. These taxa include *Polianthion collinum*, *Calytrix uncinata*, *Micromyrtus trudgenii* and *M. acuta* (Western Australian Herbarium 1998–, Woodman Environmental Consulting Pty Ltd 2007). Other species (*Cryptandra imbricata, Drummondita fulva*) are more catholic in their occurrence on particular substrates.

Acacia woodmaniorum is a recently described species formerly known as *Acacia* sp. Blue Hills Range (R.J. Cranfield 8582), which has taxonomic affinities to *Acacia alata*. It was first collected from the Blue Hills Range in 1992, but was only described by Maslin and Buscomb (2007) after recent collections from both this study and surveys by Woodman Environmental Consulting Pty Ltd (2007). This species appears to be restricted to steep, massive outcrops of BIF on Windaning Hill proper, Windaning Ridge and part of the adjacent Blue Hills Range. However, it does not occur on Mt Karara (Woodman Environmental Consulting Pty Ltd 2007; this study). The most northerly extent of this distribution occurs at Jasper Hill. It is absent from the western (Mt Karara) and the northern half of the study area (north of Jasper Hill and ironstone hills on Badja Station), although apparently suitable habitat has been investigated (C. Godden, pers. comm. [3]; Woodman Environmental Consulting Pty Ltd 2007; this study).

Acacia karina (previously known as *Acacia* sp. Karara (C. Godden 14)) is a member of *Acacia* sect. Juliflorae and bears some resemblance to *Acacia jibberdingensis*, but differs from the latter by lacking a pulvinus. Instead, it appears to be most closely aligned to *A. stanleyi* (Maslin & Buscumb 2007). *Acacia karina* was only recorded on Mt Karara by this current survey, where it is most common (Maslin & Buscumb 2007). Further surveys have located this taxon on the Blue Hills Range and, less frequently, on Windaning Ridge and some nearby, low hills of BIF and granite (Maslin & Buscumb 2007; Woodman Environmental Consulting Pty Ltd 2007). Beyond this area, there is a single collection from Mt Gibson Station (c. 120 km south east of Morowa). However, this taxon was not found during a recent survey of ironstone landforms on Mt Gibson Station (Meissner & Caruso 2008). Recent surveys of BIF in the wider Yalgoo IBRA have failed to find this species beyond its current known range (Markey & Dillon in review, unpublished data).

A variant of *Drummondita microphylla* was collected which had been previously noted by Wilson (1998) to differ from *Drummondita microphylla s.s* in that it possesses minute, red-brown apicula on the leaves and flattened, coriaceous, suborbicular sepals. Populations of this variant are greatly disjunct from *Drummondita microphylla s.s.*, occurring c. 300 km west of the latter species. This variant was not described by Wilson (1998) owing to a lack of flowering material in the Western Australian Herbarium at that time. However, subsequent collections from this and other recent surveys in the Yalgoo IBRA region (Markey & Dillon in review; unpublished data) enabled the formal description of this entity as a new species, *Drummondita fulva* (Meissner & Markey 2007). *Drummondita fulva* appears to be restricted to the survey area, over which it was found to be common on upland sites (particularly within Community type 3, see 'Floristic Communities').

The ranges of four priority species were extended by this survey. The two succulent herbs, *Gunniopsis divisa* and *G. rubra* were located c. 200 km and 100 km away from their respective previously known locations. Both species of *Gunniopsis* were located on colluvial outwash sites within the western half of the study area. At the time of this survey, this was the third record at the Western Australian Herbarium (1998–) for the former taxon (excluding entities that have been recently identified as *Gunniopsis* aff. *divisa* (R. Meissner, pers. comm. [4]).

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Another collection of *Gunniopsis divisa* was made following this survey, located some five km south of the collection from this survey (D. Coultas s.n.), which brings the total to three known locations for this species.

Two of the other priority species found in this survey also occur on BIF hills c. 70 km west of Mt Karara, these being *Austrostipa blackii* and *Millotia dimorpha*. The former taxon is now known from several locations across southwest Western Australia, its range having been extended by previous surveys (Gibson & Lyons 2001a). The latter, *Millotia dimorpha* is a small annual previously only known from hills of Koolanooka (C.A. Gardner 2680B) and adjacent Kadji Kadji station (W.E. Blackall & C.A. Gardner WEB 744). Several decades after these initial collections, it was relocated on the Koolanooka and Perenjori hills in 2005 (Meissner & Caruso 2008). This survey located a new population of this species on the slopes of Mt Karara.

This current survey did not locate eleven priority taxa (*Calandrinia kalanniensis* (P2), *Chamelaucium* sp. Yalgoo (Y. Chadwick 1916) (P1), *Eurymyrtus patrickiae*, *Grevillea globosa* (P3), *Grevillea scabrida* (P3), *Grevillea subtiliflora* (P1), *Melaleuca barlowii (P1), Micromyrtus racemosa var. mucronata*, *Spartothamnella* sp. Helena & Aurora Range (P.G. Armstrong 155–109) (P3), *Stenathemum poicilum* (P2) and *Hydrocotyle* sp. Warriedar (P.G. Wilson 12267) (P1), which known from the area from previous flora surveys of mining tenements in the study area (Gindalbie Pty Ltd 2004; Woodman Environmental Consulting Pty Ltd 2004a, 2007). Most of these taxa have been located by these surveys on the lowlands surrounding the BIF ranges.

Undescribed taxa

Several taxa were identified in this survey which had affinities to known taxa, but were sufficiently morphologically distinct to consider as new entities. Most of these have been subsequently formally described (see above), but five entities require further taxonomic work to resolve their status. Some of these taxa may warrant further consideration for conservation listing as they appear to be restricted to the study area.

- The discovery of an entity with affinities to *Calotis cuneifolia* was surprising in that the latter taxon is common in the Northern Territory, Queensland and New South Wales (Jessop 1981), yet is known from only two locations in Western Australia. These two locations are Perrin Vale station (c. 323 km east from Windaning Ridge) and one 1903 collection in the general vicinity of 'Cue' (c. 235 km north east of Windaning Ridge). This represents a significant disjunction from the eastern Australian populations. Further examination of these two Western Australia accessions and material collected during this survey found this Western Australian entity to be different from the eastern Australian *Calotis cuneifolia s.s.*, in that the former is a diminutive annual which possess a habit more akin to that of *Calotis hispidula* than that of the taller, robust, perennial, herbaceous habit of the latter taxon (Jessop 1981). Therefore, the Western Australian material may represent a closely related taxon (i.e. *Calotis* aff. *cuneifolia* (A. Markey & S. Dillon 3447). In this survey, *Calotis* aff. *cuneifolia* was located on ironstone hill slopes growing in dense patches of leaf litter under mulga shrubland.
- *Lepidosperma* sp. (A. Markey & S. Dillon 3468) is distributed primarily on ironstone substrates on Karara Station, and appears to be endemic to the south west of the study area[5] (Woodman Environmental Consulting Pty Ltd 2007). It has taxonomic affinities to the *L. costale* species complex and the most closely related taxon to it is *Lepidosperma* sp. Koolanooka (K.R. Newbey 9336) (R. Barrett, pers. comm.[4]). This latter taxon is also an ironstone endemic, and appears to be restricted to the banded iron formations of Perenjori and Koolanooka Hills (Meissner & Caruso 2008; R. Barrett, unpublished data[4]). Further taxonomic work is required to both formally describe and clarify relationships among these taxa of *Lepidosperma*.
- Two unusual variants of *Eremophila* were collected from the eastern-most outwash communities on rocky plains, both of which require further work to resolve their taxonomic relationships and distribution. One was an unusual variant of *Eremophila playcalyx* (*E.* cf. *platycalyx* A. Markey & S. Dillon 3337) with greatly enlarged calyces. However, *Eremophila playcalyx* is a highly variable species, and this extreme form may be still within this range of variation**.**
- The second entity, *Eremophila* sp. (A. Markey & S. Dillon 3338), could not be matched to any known species within the collections of the Western Australian Herbarium. It has affinities to *E. georgei* and *E. clarkei* because of sigmoidally shaped and flattened pedicel and serrated leaf margins, however, this entity differs from the former two taxa by having a deeper purple flower colour and narrower, shorter leaves with highly recurved leaf margins that gave the leaves a terete appearance. Furthermore, *E. clarkei* has simple, sometimes dendritic hairs on sepals, whilst this variant has glandular hairs.

Putative Hybrids

Several putative hybrids were identified, their surmised from morphological characters. A putative hybrid of *Cheilanthes* cf. *lasiophyllum x sieberi* (A. Markey & S. Dillon 3048) was collected, and this is the first collection of a putative hybrid within this genus in Western Australia. Hybridisation and polyploidy has been documented among species in North America (Wagner & Gilbert 1957) and Europe (Knobloch et al. 1975), however recent publications only document polyploidy among Australian species (Tindale & Roy 2002). The hybrid, *Senna glutinosa*

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ssp. *chatelainiana* x *charlesiana* (A. Markey & S. Dillon 3413) is another new putative hybrid, although hybrids within *Senna* complex are well documented (Randall & Barlow 1998).

A number of intergrades between taxa were identified in this survey. Intergrades among the subspecies of both *Allocasuarina acutivalvis* and *Eucalpytus leptopoda* are known for the study region, as this coincides with an area where the two subspecies co-occur (M. French, pers. comm.[6]; Wilson & Johnson 1989). Similarly, integrades of *Maireana planifolia* x *villosa* are known from areas where the parental species co-occur (Wilson 1984). Some of these intermediate forms may represent distinct taxa (P. Wilson, pers. comm.[7]).

In the case of *Prostanthera althoferi* ssp. *althoferi* x *serica* (intergrade), this intergrade has the greatest affinity to *P. campbellii*, *P. sericea* and *P. althoferi* ssp. *althoferi*, although the terete, villous and relatively wide (2 mm) leaves place this as distinct from these three taxa (*c.f.* Conn 1988). One putative parental taxon (*Prostanthera sericea*) is not known from the Yalgoo subregion, although a similar species (*Prostanthera campbellii*) is more widespread and possibly involved. A range of intermediate forms between these three species have been collected from over a wide area over the northern and eastern goldfields.

Endemic Taxa

Nine endemic and near endemic taxa were identified within the study area, (a regional endemic being defined as restricted to an area within a 100 km radius, and near endemics being defined having most populations located within a 100 km radius with one – two outlying, disjunct populations) these being; *Millotia dimorpha*, *Lepidosperma* sp. (Markey & Dillon 3468), *Acacia karina*, *Acacia woodmaniorum*, *Micromyrtus trudgenii*, *Micromyrtus acuta*, *Wurmbea* sp. Paynes Find, *Caladenia petrensis, Polianthion collinum* and *Drummondita fulva*. Seven of these nine taxa are listed as priority taxa (Table 1), and three taxa appear to be mostly or wholey restricted to the south-western corner of the survey area (*Acacia karina*, *Acacia woodmaniorum*, *Lepidosperma* sp. (Markey & Dillon 3468). Information to date would suggest that *Acacia woodmaniorum* and *Lepidosperma* sp. (A. Markey & S. Dillon 3468) are endemic to Jasper Hill, Mt Karara and Windaning Ridge (Woodman Environmental Consulting Pty Ltd 2007).

Range extensions

Range extensions of over 100 km were found for a total of 21 species, 17 of which are not listed as threatened. There were eleven species collected which represent a range extension of c. 100 – 200 km from closest, previously known collection at the Western Australian Herbarium (1998–). A number of these were notable in that these were new records for these species in the Yalgoo subregion, including: *Austrodanthonia* sp. Goomalling (A.G. Gunness et al. OAKP 10/63), *Davesia hakeoides* subsp. *subnuda, Hydrocotyle callicarpa, Trachymene pilosa, Podolepis gardneri, Einadia nutans* subsp. *eremaea, Maireana marginata*, *Centrolepis aristata, Crassula closiana* and *Pleurosorus rutifolius.* The nearest known location of *Cheilanthes brownii* was 200 km north of the survey area, with the majority of collections from the far northern regions of Western Australia. Both *Cheilanthes brownii* and *Cheilanthes adiantoides* have been poorly collected from the Murchison Region, which may reflect poor collection and confusion with *Cheilanthes austrotenuifolia* and *C. sieberi* subsp. *sieberi* rather than actual scarcity. Greater range extensions of c. 250 – 400 km beyond the currently known range were recorded for *Calotis* aff *cuneifolia*, *Crassula tetramera, Sclerolaena microcarpa, Senecio gregorii, Stylidium perpusillum* and *Sida ectogama*.

Floristic Communities

Prior to analysis, fifteen taxa had to be amalgamated into seven species complexes for floristic analyses as there was some difficulty in differentiating between closely related taxa owing to quality of flowering material (e.g. the *Velleia cycnopotamica / rosea* complex), the presence of intergrades (e.g. *Eucalyptus leptopoda* subsp. *arctata* and *Eucalyptus leptopoda* subsp. *elevata*) or when varieties were closely related and were more informative when combined at a higher taxonomic level (e.g. the three forms of *Haloragis odontocarpa*). The *Acacia aneura* species complex was resolved to morphotypes which approximate the varieties described by Pedley (2001), as the mulga complex (*Acacia aneura* and allied species) is currently being reviewed by Miller et al. (2002).

Three hundred and ninety taxa were recorded from 103 quadrats within the survey area, of which 180 were annual taxa while 46 perennial taxa were recorded from only one quadrat. Preliminary analyses found that singletons and annuals had little overall effect on community classification, apart from enhancing the separation of outwash sites from hillslopes. These taxa were omitted, leaving 164 taxa in the dataset (42 % of total taxa). '2-Stage' comparison (Clark & Gorley 2006) of resemblance matrices found 89% correlation between the data matrix with all taxa (singletons and annuals) and the perennial dataset used in final analyses. For the 103 quadrats, the average species richness per quadrat was 48.8 ± 10.5 taxa per quadrat, and ranged from 26 to 79 taxa per quadrat. For the final dataset, there was an average of 23.3 ± 4.9 shared perennial taxa per quadrats (range 9 – 37 taxa per quadrat).

The floristic classification of the 103 quadrats resulted in their ordering into eight community types and subtypes, which is illustrated by a summary dendrogram in Figure 2. Five main community types were recognised, with three of these communities (1, 4 and 5) further divided into

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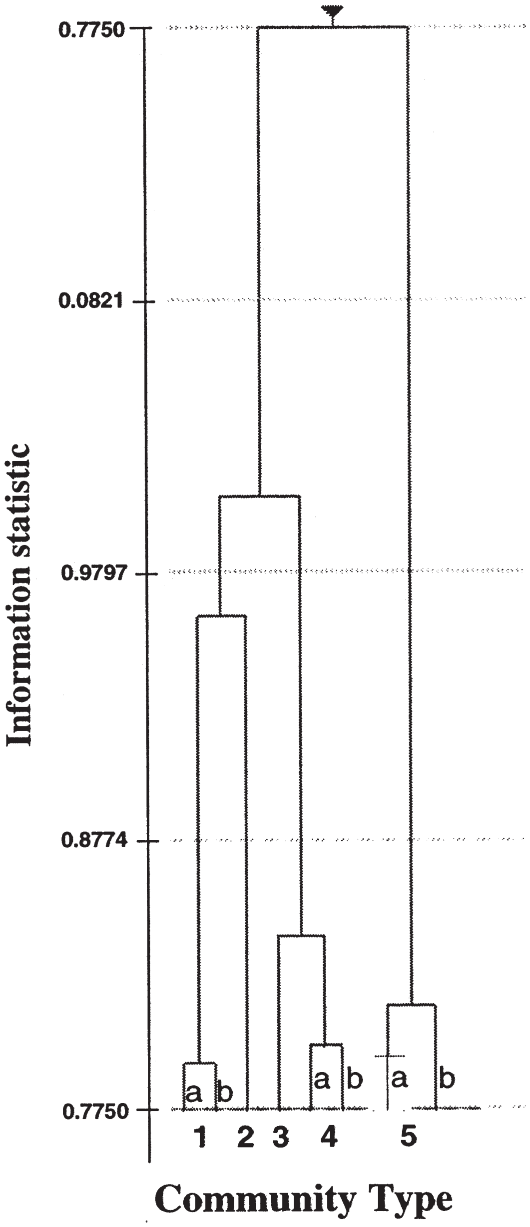

Figure 2. Summary dendrogram of floristic community types of the Central Tallering Land System, resolved from classification analysis of a presence / absence data matrix of 164 perennial taxa from 103 quadrats. The dendrogram is resolved to the five group level, with subtypes resolved in Community types 1, 4 and 5.

distinctive subtypes (Figure 2). Therefore, the floristic communities have been resolved at two levels, these being the five and eight group levels. The classification also resolved the 164 species into twelve Species Groups (Appendix 2). These decisions on selecting levels within the site and species dendrograms were based on dendrogram topographies, the two way table (Appendix 2) and field observations. INDVAL statistics are presented in Table 2, and statistically significant indicator taxa (as determined from the Monte Carlo routine at the eight group level) are also marked in Appendix 2.

The primary division separates floristic communities on lower slopes, footslopes, colluvial outwashes and plains (type 5) from those on hillslopes, crests and upland plateaux (types 1, 2, 3 and 4). Hence, the first major distinction was between the lowland tall open *Acacia* shrublands and *Eucalyptus* woodlands from the shrublands and thickets on the hillslopes and uplands. This division is also discernable on the sorted two-way table ordered by the site and species classification (Appendix 2), and is particularly evident in Species groups G, J and L.

Below this primary level of divergence, four floristic communities were identified for the crests, slopes and foothills on the ironstones of the Tallering Land System. The second major division separated Community types 1 and 2 from Community types 3 and 4, which coincides with the segregation of the southern and western sites with richer loamy soils from the eastern and northern sites in drier situations (outcrops) and on more skeletal soils. This division is associated with Species Group H, and, to a lesser extent, group G (Appendix 2).

Community type 1 was a relatively wide-ranging community found from Mt Karara to the northern and eastern limits of the study area. It consists of both the lower slope *Acacia* shrublands with emergent *Eucalyptus* woodlands and upper hillslope and crest shrublands. This community is subdivided according to floristic differences associated with topographical position.

Community type 1a occurs on ironstone substrates that were low in the landscape (at an average altitude of 361 m), either on the lower slopes of hills, small massive outcrops of banded ironstone formation or low rises in the upland peneplains. It is distributed from Mt Karara to the strikes of BIF north of Minjar Hill and east to the footslopes of Warriedar Hill, but was absent from the extreme south-east extent of the study area. Community type 1a is differentiated from Community type 1b by being relatively species poor (Appendix 2), and lacking good representation of the ubiquitous Species Group G. The majority of species from Species Groups H and I are well represented. There is an average of 38.9 ± 2.6 total taxa per quadrat, of which there is a correspondingly poor number of annuals (19.5 ± 5.3 taxa / quadrat). Common and significant indicator species (Table 2) include *Acacia coolgardiensis* subsp. *latior* and *Acacia sibiana* in the dominant stratum, over the shorter shrubs, *Aluta aspera* subsp. *hesperia*, *Eremophila forrestii* subsp. *forrestii*, *Philotheca desertii* subsp. *desertii* and *Hemigenia* sp. Cue (K.F. Kenneally 47A). *Eremophila latrobei* subsp. *latrobei* and the rockfern, *Cheilanthes adiantoides* are characteristic understorey species for both this community, and Community types 1b and 2. Being a lowland community, this community included emergent trees such as *Callitris columellaris*, *Eucalyptus ewartiana*, *E. leptopoda*, and open tall shrublands of *Acacia* (*A. aneura*, *A. ramulosa* var. *ramulosa* and *A. coolgardiensis* subsp. *latior*).

Community type 1b is the most common and widespread community type, and consists of the typical, speciose shrublands which occur on the shallow, loamy soils of hillslopes and isolated ridges throughout the survey area. This community type typically consists of *Acacia* (*A.

sibiana, *A. ramulosa* var. *ramulosa*) and *Allocasuarina* dominated shrublands and thickets over a rich shrub understorey, and often with emergent trees of *Eucalyptus* and *Melaleuca leiocarpa*. Community type 1b was found to usually occur on gently sloping hillslopes that were moderately high in landscape (average altitude 399 ± 5 m. However, it was found at all levels along the topographical profile as this vegetation unit was repeated on foothills of outcropping BIF. There is good representation from Species Groups G, H and, in particular, group I, which distinguish this group from Community Type 1a. Characteristic and common species include *Eremophila latrobei* subsp. *latrobei*, *Mirbelia bursarioides*, *Philotheca sericea*, *Eremophila clarkei*, *Prostanthera magnifica* and *Cheilanthes adiantoides* (Table 2, Appendix 1).

Community type 2 is found relatively high in the landscape, on moderate – very steep, rocky inclines and facing a range of aspects. This community is restricted in its distribution, being located only on the slopes of Mt Karara and the far western slopes on Windaning Ridge (near the old Mungada minesite). Whilst most typical of upper slopes, this community type is also repeated low in the landscape on low ridges of exposed ironstone on lower slopes and foothills. It consists of a range of shrublands and thickets over an understorey rich in shrubs, and as such was moderately species rich (average total 50.9 ± 7.3 taxa / quadrat). Annuals were particularly abundant in this community type in the, averaging 27.6 ± 5.3 annual taxa per quadrat (Table 3). Significant indicator species include the tall shrubs *Allocasuarina acutivalvis*, *Melaleuca nematophylla, Grevillea paradoxa and Gastrolobium laytonii* and the low shrubs *Aluta aspera* subsp. *hesperia*, and *Xanthosia bungei* (Table 2). Of particular note is the presence of the sedge, *Lepidosperma* sp. (A. Markey and S. Dillon 3468), which was restricted to this community type on Mt Karara. Taxa in species Group F and a subset of Species Groups D both are characteristic of Community type 2, with many of the taxa in the former group being largely restricted to this community on the slopes of Mt Karara and Windaning Ridge (e.g. *Mirbelia microphylla*, *Eucalyptus petraea* and *Calothamnus gilesii*, *Grevillea paradoxa* and *Persoonia hexagona* and *Acacia karina*.

Community type 3 consists of sparse shrublands on the crests and moderately steep slopes of low escarpments, ridges and outcrops of BIF. Sites are typically rocky and situated moderately high in the landscape (at an average altitude of 406 m). This community is located predominantly in the northern and eastern parts of the survey area, particularly on the low ridges on Badja Station in addition to the top plateau of Windaning Ridge. The underlying geology consists of both banded iron formation and paler, weathered sedimentary siltstones and cherts. It is a moderately species rich community, with an average of 48.3 ± 10.3 taxa per quadrat, albeit relatively low in annuals (21.2 + 5.4 taxa per quadrat, Table 3). Characteristic species include those which grow in fissures of exposed pavements of BIF such as *Stylidium longibracteatum*, *Micromyrtus trudgenii* and *Calytrix uncinata* (Table 2). Also of note is *Acacia aulacophylla*, which replaces *Acacia assimilis* subsp. *assimilis* as a dominant shrub in the northern extent of the study site. Other notable and significant indicator species include *Eremophila glutinosa*, *Melaleuca hamata* (rarely encountered, with both occurrences in this community type), *Austrodanthonia caespitosa*, *Mirbelia bursarioides*, *Cheiranthera filifolia* var. *simplicifolia*, *Drummondita fulva*, *Prostanthera patens* and *Thryptomene costata* (Table 2, Appendix 2). Many of these taxa are in either Species Groups G or E which, together with Group I, constitute the main species groups associated with this community type. An absence of taxa from Group D distinguishes Community type 3 from type 4.

Community type 4 occurs on rocky ridges and tors usually in the east and north of the study area. As with Community type 1, the division of this community into subtypes also corresponds with topography.

Community type 4a consists of open stands of *Callitris collumelaris* and sparse shrublands located at the highest points in the landscape on steep, rocky or boulder-strewn ridges, cliffs and tors with shallow, loamy soils (Table 3). This community was found on the east-facing steep cliffs of Windaning Ridge, rocky upper slopes of Pinyalling Hill, two foothill sites on Mt Karara and on the metasedimentary rocks (psammitic and peltic – semi peltic) of Warriedar Hill (*cf.* Lipple et al. 1983). It is a very species rich community (54.8 ± 9.4 taxa per quadrat), with much of this richness being contributed by annuals (Table 3). Typical and consistent species in this community type are in Species Groups G and I, whilst taxa from Species Group H are conspicuously absent. Species group C is particular to sites on Warriedar Hill, which may possibly reflect the underlying geology. Notable and significant indicator species include those characteristic of rocky terrain, namely the shrubs *Calycopeplus paucifloru*s, *Dodonaea petiolaris* and *Dodonaea viscosa*, the rockferns, *Cheilanthes sieberi* subsp. *sieberi, Cheilanthes lasiophyllum and Pleurosorus rutifolius* and the herbaceous *Isotoma petraea* (Table 2, Appendix 2). The latter three species were infrequent but faithful to this community type.

Community type 4b appears to be restricted to the eastern regions of the survey area, on the slopes of Pinyalling, Walagnumming, Warriedar and Chulaar Hills. Although still rocky, this community occurs on gentle – moderate slopes with less exposed bedrock and more collvium than Community type 4a. Structurally, the vegetation consists of tall shrublands of *Acacia ramulosa* var. *ramulosa* or *Acacia aneura* with a sparse shrub understorey. This community type was located over the topographical profile of hills, from lower slopes to crests. It is relatively more species depauperate than type 4a and lacks representation from across Groups A to F (Table 3, Appendix 2). However, there is still good representation in groups G and I. Characteristic indicator species include *Acacia aneura* var. cf. *major* and *Acacia umbraculiformis* in the dominant stratum over the low shrubs and herbaceous perennials, *Phyllanthus erwinii*, *Ptilotus drummondii* var. *drummondii*, *Sida* sp. Golden calyces glabrous fruit (H.N. Foote 32), and *Solanum ellipticum* (Table 2).

As previously mentioned, **Community type 5** was the group of sites found to have the highest dissimilarity to other sites in the dataset. This community was further resolved into two subtypes, as is shown in the sorted two-way table (Appendix 2). Community type 5a typically consists of shrublands on rocky terrain and exposed low tors of bedrock on footslopes and peneplains, whilst Community type 5b is associated with flatter terrain, a sparser covering of surface gravels and no exposed bedrock.

Community type 5a consists of open *Eucalyptus* woodlands and sparse *Eremophila* or *Acacia* shrublands over sparse, low chenopod shrubs. Being located in the depositional part of the landscape, this community receives colluvium from the adjacent uplands. The substrate consists of readily eroding siltstone, cherts, and other sedimentary rocks which have been exposed from under layers of more resistant BIF. This is a species rich community (53.1 ± 17.2 taxa per quadrat), and is relatively richer in annual taxa (29.0 ± 14.8 taxa per quadrat) than Community type 5b (Table 3). There is consistent representation from species group L, and the significant indicator species include *Acacia erinacea*, *Enchylaena lanata / tomentosa*, *Eremophila oldfieldii* subsp. *oldfieldii*, *E. oppositifolia* subsp. *angustifolia*, *Senna* sp. Austin, *Maireana carnosa*, and a number of species of *Sclerolaena* (Table 2). This community was encountered on two distinctive footslope sites from Mt Karara and at various locations over Badja station.

Community type 5b is comprised of lowland open *Eucalyptus* woodlands and *Acacia ramulosa* var. *ramulosa* shrublands over sparse shrubs of *Senna*, *Ptilotus obovatus* var. *obovatus*, *Scaevola spinescens* and chenopods. These occur on gently sloping – flat lower slopes and outwash plains, on deeper red earths. Whilst occurring in the north and west of the study area, the community is absent from eastern sites, possibly being replaced by the eastern stony shrublands within Community type 5a (see above). The significant indicator species include *Eucalyptus kochii* subsp. *amaryssia*, *Maireana planifolia* x *villosa*, *Olearia humilis*, and the two characteristic species of *Senna*, *S. charlesiana* and *S. artemisioides* subsp. *filifolia* (Table 2). This community differs from type 5a by the more consist presence of taxa from Species group I, distinctive taxa from Species Groups H and J fewer taxa from Species Group L (Appendix 2).

Other communities not in classification

A distinctive structural vegetation community was observed in this survey that has been described previously in flora surveys in the area around Windaning Ridge (Bennett Environmental Consulting Pty Ltd 2003, Woodman Environmental Consulting 2004a). These low dense shrublands and heaths occur on the lower slopes and upland plateaux, and appear to occur on shallow gravels over a sheet of bedrock which prevents the establishment of taller shrubs. Only one or two species of myrtaceous shrub were dominant; such as *Micromyrtus acuta*, *Thryptomene costata* and *Aluta aspera* subsp. *hesperia*. Otherwise, these patches of vegetation were relatively depauperate (c. 12 perennial species per quadrat), and are considered to be a subset of the surrounding vegetation within a structural mosaic of vegetation on the lower slopes and undulating uplands. These patches of vegetation were not fully sampled in this survey because of this low species richness. However, such low heaths and dense shrublands around ironstone belts harbour species of conservation significance (e.g. *Micromyrtus acuta*).

Environmental Correlates

Univariate Analyses

The elements cadmium, molybdenum and boron were omitted from analysis owing to levels being below the limit of instrument detection in over half of the soil samples. The remaining soil elemental concentrations, soil pH and effective cation exchange capacity (eCEC) were compared for intercorrelation, and correlation with site physical and climatic variables, using the non-parametric Spearman rank correlation coefficient (Table 3). Soil pH, eCEC and elemental concentrations (except lead) were intercorrelated, the highest correlation being among eCEC, calcium and magnesium. Most soil elements were not correlated with physical parameters, although iron and phosphorus were positively correlated with topography. As expected, climate variables were all highly intercorrelated, and there was a significant correlation between these and both latitude and altitude. With the exception of surface fragment abundance, there was also a high degree of intercorrelation among the physical parameters (eg: slope, topographic position, rock size and cover) (Table 4).

The soils for the survey area were found to be acidic (pH ≤ 5.1), which has been reported for shallow, stony soils within the larger Sandstone – Paynes Find area (Hennig 1998b). Differences in soil parameters were expected to correlate with floristic community and topographical position. Non-parametric analysis of variance found significant differences in values for all soil variables among the eight floristic community types (Table 3). Soil parameter values were the lowest for Community type 1a and, to a lesser extent, Community types 1b and 4b. Conversely, high values were found in various soil parameters for Community types 3, 4a, 5a and 5b. Therefore, the soils from sites classified as Community type 1a were the most acidic, had the lowest eCEC and low concentrations of exchangeable cations and minerals. These values correspond to leached, skeletal red earths over weathered, exposed bedrock high in the landscape. Low pH may be associated with both products of ironstone weathering and low levels of basic cations (*cf.* Gray & Murphy 2002). Soils from Community types 5a and 2 were trending to being relatively less acidic, and soils within Community type 5a and 5b were high in minerals such Na, Ca, Mg, Ni and S. These high-mineral, less acidic soils can be largely attributed to topographic position, where these sites are enriched by colluvium, leachates and clay (Gray & Murphy 2002). Soils from

Community types 2 and 4a had high eCEC levels and relatively high levels of various elements, notably Ca, K, Mg, P, Fe and Zn (Table 3). Such high levels in these rocky, upland sites may related to *in situ* soil development from weathering of the parental rock (*cf.* Gray & Murphy 2002). It was observed that upland rocky sites did accumulate rich loams in rock crevices that trapped organic material and moisture, and high numbers of annuals were associated with such microsites for Community types 2 and 4a (Table 3).

From a comparison of physical site parameters among the community types, there were significant differences among groups for altitude, slope, topographical position and various estimates of exposed bedrock, loose rock and leaf litter cover (Table 3). On average, Community type 4a occurs on sites with the steepest gradient, highest altitudes, large surface rocks and high cover of exposed bedrock. Community types 2 and 3 also are associated with rocky, high topographical positions and altitudes, but occur on less steep slopes, at lower topographical positions and with reduced amounts of exposed bedrock (Table 3). Community types 1b and 4b occur at lower altitudes and are associated with moderate gradients and less exposed bedrock. Community types 5a and 1a occur at the lowest altitudes, and 1a, 5a and 5b occupy the lowest topographical positions with a reduced gradient. Sites within these latter community types (particularly 1a and 5b) have significantly smaller surface rocks and a lower percentage cover of exposed bedrock (Table 3).

There were differences in climatic variables among the community types, although the differences in average annual temperatures were low (< 1° C) and may not be biologically meaningful (Table 3). There were significant differences in latitude and longitude among the community types (Table 3), and this may partially relate to climate, as geographical location and climate are intercorrelated (Table 4). Community Type 2 is the most geographically restricted community, being associated with the south-western part of the region where the climate is significantly cooler and wetter (Table 3). Community Type 1a and 3 are located predominantly in northern sites associated with higher temperatures but average rainfall, whilst Community Type 4b is occurs in the north-east of the study area with the lowest average rainfall. The remaining communities (1b, 4a, 5a and 5b) are located over the extent of the study area where temperatures and rainfall are within the middle range of estimates, except for Community Type 4a which has the lowest average rainfall estimates among the communities (Table 3). Within Community Type 5a, two distinctive sites on the eastern stony plains are associated with a relatively more arid climate.

SSH MDS Ordination

Semi strong hybrid multidimensional scaling (SSH MDS) of the site floristic data was used to illustrate graphically compositional differences among the sites that had been classified into their respective floristic community types (Figure 3). The stress level (0.22) indicates that there was some difficulty in reducing the data to three dimensions. Sites from Community types 5a and 5b have the greatest separation from the other community types in the ordination, and five sites within Community type 5a are particularly distinct from the main spread of the ordination. It is noted that two sites from the eastern stony plains around Pinyalling Hill are relatively dissimilar in floristic composition to other, more western sites within Community type 5a (Figure 3b), which was also observed in the entire site classification dendrogram (results not shown). Further sampling of these eastern stony plains may determine if these eastern areas support a distinct floristic community.

Principal component correlation (PCC) found significant correlations between the majority of environmental variables and the ordination (Figure 3). There are two major trends across the ordination which are generally orthogonal to one another; one that is associated with a gradient of soil chemistry, and a second general trend associated with site physical parameters (especially topographical position, slope and substrate). Among these site physical parameters, topography is the least correlated with the other variables. The association of the trends across the ordination and with community types reiterates most of the findings from the univariate comparisons. As indicated by their co-linearity, groups of soil variables are highly correlated (Figure 3, Table 4). One suite of correlated soil parameters (Co, Cu, eCEC, Ca, Mg, Na, Ni, S and K) aligns with Community Types 5a and 5b, which are sites of high overall soil mineral content. Sites from these communities, particularly Community Type 5b, also coincide with a region associated with low topographic position. Sites trending to the lower end of the nutrient gradient and also higher leaf litter levels belong to Community types 1a, 1b and 2. Only Community Type 4a aligns closely with the high end of the gradient for slope and rockiness, whilst Community type 3 is associated with this region to a lesser degree. Another trio of nutrients (Fe, Zn and P) are co-linear with both slope and maximum rock fragment size. Together, these environmental parameters are positively correlated with sites from Community types 3, 4a and 4b. Community Type 2 aligns with the high extremes of the rainfall gradient, whilst Community types 4a and 4b are at the drier extreme. This stronger association of Community type 2 with a rainfall and latitudinal gradient could explain why Community Type 2 was not closely associated the gradient of physical parameters, as would have been expected from the univariate analyses.

DISCUSSION

Flora

Recent surveys of BIF and greenstone ranges of the Yilgarn Craton are finding these arid landforms to be floristically richer than previously considered (Gibson et al. 2007). This survey of several ranges within the Central Tallering land System recorded 414 taxa in a season which was

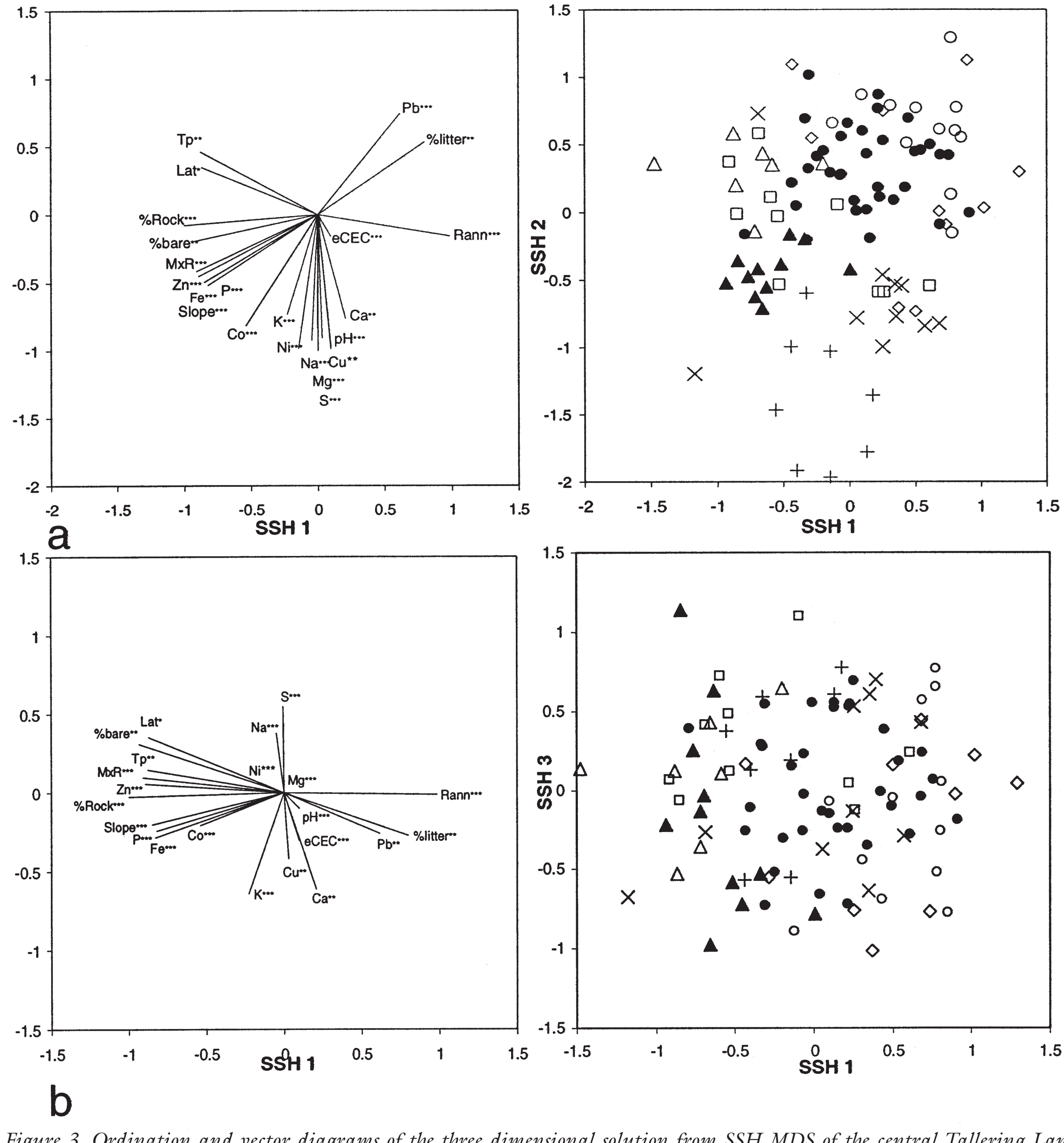

Figure 3. Ordination and vector diagrams of the three dimensional solution from SSH MDS of the central Tallering Land System floristic dataset. Quadrats (sites) are labelled by community type (1a ○, 1b ●, 2 ◇, 3 □, 4a ▲, 4b Δ, 5a +, 5b ×). Vectors indicating best linear fit of the variables are drawn in positive direction. Only vectors with a significant correlation (from MCAO) are illustrated, with the level of significance for each parameter indicated by asterisks (= $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$). See methods for explanation of codes for environmental parameters. a: Ordination axes 1 versus 2, b: Ordination axes 1 versus 3.*

notable for its abundance of annuals following good rainfall in the preceding months. Within Mt Karara, Windaning Ridge and Jasper Hill alone, 335 taxa are documented. A similar survey in the nearby Koolanooka and Perenjori hills (70 km west of Mt Karara) recorded 238 taxa (Meissner & Caruso 2008) and 235 taxa were recorded from BIF ranges in the Gullewa region (55 km northwest of Mt Karara). (Markey & Dillon in review). Quadrat based surveys in the eastern goldfields report numbers of taxa ranging from 238 taxa in the Mt Manning Range (Gibson 2004b) to 345 taxa in the southern Forrestiana greenstone belt (Gibson 2004a). Moving from the interzones to the interior of the Eremaean province, species counts from similar, quadrat-based surveys are lower for BIF ranges in the northern goldfields. In the Murchison IBRA, this number ranges from 173 to 244 taxa (Markey & Dillon 2008, Meissner et al. in review). These relatively high species counts for the Central Tallering Land System are elevated, in part, by high counts of winter annuals, but they also suggest that these BIF landforms within the Central Tallering Land System are particularly speciose, especially around Mt Karara, Windaning Hill and the Blue Hills Range.

As would be expected for the interzonal nature of the Yalgoo bioregion (Beard 1976a; Environment Australia 2000; Thackway & Cresswell 1995), the total flora of the study region has affinities to both the speciose and mesic South West and arid Eremaean Botanical Provinces / Floristic Regions described by Beard (1976a, 1990) and Hopper and Gioia (2004). A high proportion of the taxa recorded within the study area are at the southern or western limits of their distribution (e.g. *Ptilotus aervoides*, *Gnephosis arachnoidea* and *Senna glaucifolia*), others are at their northern limits (e.g. *Ptilotus drummondii* var. *drummondii*, *Alyxia buxifolia* and *Centrolepis aristata*) and another subset of the flora are characteristic of this interzonal region bordering the two provinces (e.g. *Erymophyllum glossanthus*, *Bellida graminea* and *Chamaexeros macrantha*). These range extensions and new records for the Yalgoo bioregion are a consequence of increased collecting efforts. These findings also continue a trend for the discovery of species in the transitional regions of the Eremaean that were previously considered to be endemic to the South West Botanical Province / Floristic Region (Hopper & Gioia 2004).

The flora and floristic communities of the central Tallering Land System are dominated by wide-ranging taxa, with relatively few endemic or disjunctly distributed taxa. Of the nine endemic and near endemic taxa identified, five of these are restricted to the southwest corner. Other surveys have found from none to five endemic taxa on greenstone and BIF ranges in the northern and eastern goldfields (Gibson et al. 2007). Within the wider region of the northern Yilgarn, the central Tallering Land System, especially the Mt Karara – Windaning area, is comparatively rich in endemic and near endemic taxa.

Trends in endemism and species diversity on BIF ranges across the Central Tallering land system are on a small scale relative to the wider region, but mirror those documented for other BIF ranges and granite outcrops in the Yilgarn Craton, and in the overall southern Western Australian flora (Beard 1976a, 1990; Gibson et al. 2007; Hopper et al. 1997; Hopper & Gioia 2004). A combination of fluctuations in climate and a trend for increasing aridity during the Tertiary, stochastic events (dispersal, survival and extinctions) and evolutionary processes have been postulated to account for the high species diversity and endemism in the South West Floristic Region, in which ancient rock outcrops and ranges act as isolated refugia and sites of speciation (Hopper et al. 1997, Hopper & Gioia 2004). This hypothesis has been applied to account for patterns of species distribution and endemism observed in the interzonal regions of the Eremaean (Gibson & Lyons 1998; Gibson et al. 2007).

Floristic Communities:

Beard (1976b) mapped the Mt Karara, Windaning Ridge and the southern portion of the Gnows Nest Range at a scale of 1:250 000, resolving these into two vegetation systems (the Windaning and Gnows Nest Systems). This study supports the distinctiveness of the Windaning System, but further resolves eight distinct floristic communities within and among these two systems, and within the larger context of the central Tallering Land System. While some communities were found to be relatively widespread over the study area, there was evidence to suggest a regional differentiation of communities across the study area which is aligned along an east-west and north-south gradient. This coincides with a serial replacement of species over the extent of the area (e.g. *Persoonia hexagona* is replaced by *Persoonia manotricha* in the north east of the area). Most notably, Community type 1 (a & b) are replaced by Community type 4 (a & b) over a north-eastern gradient. There is also a transition within Community type 5, where the lowland *Eucalpytus* woodlands of Community type 5b are replaced in the far eastern extent of the study area by a variant of Community type 5a, which may be an under-sampled and possibly different community type. These *Acacia* shrublands on the eastern stony plains were sampled around Pinyalling and Walagnumming Hills, and may occur from the base of Walagnumming Hill to further north around the vicinity of Fields Find and the Bullajungadean Hills.

Although only c. 55 km apart, the slopes and crests of Mt Karara, Pinyalling and Warriedar Hills habour relatively dissimilar communities. Of note is Community type 2, which was located only on the slopes of Mt Karara and western face of Windaning Ridge and, with more sampling, may be located on ironstone ridges between Mt Karara and Windaning Ridge. Even within this community there were differences in particular species and species groups between Mt Karara and Windaning Hill (e.g. *Persoonia hexagona* was only located on Mt Karara, whilst *Acacia woodmaniorum* was not located on Mt Karara). Such geographical variation (east – west) within this community type has been confirmed by subsequent surveys (Woodman Environmental Consulting Pty Ltd 2007).

The findings of this study reiterate those from other studies (e.g. Gibson 2004 a, b; Gibson & Lyons 1998, Markey & Dillon 2008), that there are differences in floristic composition of the communities among the greenstone and BIF ranges of the Yilgarn Craton. Therefore, BIF ranges tend to harbour unique or geographically restricted communities (Gibson et al. 2007). The nearest ironstone ranges west of the study area are the Koolanooka Hills, some 70 km west of Mt Karara, which share with the latter range some restricted taxa such as *Millotia dimorpha*. However, when the perennial flora of both ranges is combined and compared, there is nearly 30 % difference in species (30 of 98 taxa) (data from Meissner and Caruso (2008)). Furthermore, the communities described for the Koolanooka Hills, from classification analysis of floristic data, were unlike any described in this study for the central Tallering Land System (Meissner & Caruso 2008). Of particular note is the more widespread occurrence of *Eucalyptus* in the communities and over the entire topographic profile of the Koolanooka Hills. This genus is gradually restricted to the lower slopes and, eventually, only to outwash sites over a north-east gradient within the central Tallering Land System. *Acacia* and, in particular, *Acacia aneura*, dominates the vegetation communities of the central Tallering Land System while it is notably absent from Koolanooka. This concurs with Beard's (1976a, b) documentation of the transition from *Eucalyptus* to *Acacia* dominated communities across the Yalgoo region and description of the Murchison region as 'mulga country'.

Environmental correlates

The primary division in the classification segregates the communities of *Eucalyptus* woodlands and open *Acacia* shrublands on lowland – outwash sites from those on the rocky, steeper terrain higher on the landform. This major distinction between upland and lowland communities has been noted in other studies within the greater Yalgoo – Murchison region (Beard 1976a, b; Markey & Dillon in review; Pringle 1998). Topographic position is strongly associated with other environmental attributes, such as slope, rock outcrop cover, fragment abundance, bedrock exposure and soil chemical composition, water retention and soil development (Cole 1973; Gibson 2004a, b; Gibson & Lyons 2001b; Hennig 1998b; this study). Therefore, the greatest floristic differences coincide with extremes in topographic and environmental gradients. The Central Tallering lowland communities are situated on a deeper soil profile of stony red earths, red clayey sands and ironstone gravels deposited at the base of the landforms, which has been enriched by leachates and receives colluvium from the hillsides (Hennig 1998b). This compares with communities that have developed on the steeper slopes on exposed, weathered bedrock covered in shallow – skeletal stony soils that have formed *in situ*. These soils are derived from the parent rock (Cole 1973; Gray & Murphy 2002), and the relatively higher levels of iron and phosphorus in upland soils reflects this process of soil development from massive BIF.

Although there was a small gradient of increasing soil pH with decreasing topographic position in the landscape, soils were generally acidic throughout the survey area. The tendency for lower slope outwash sites to have relatively less acidic soils probably relates to the higher concentrations of cations and higher eCEC, which buffers against acidity (Gray & Murphy 2002), whilst skeletal soils are being derived directly from heavily weathered rocks. Other studies have reported more basic soils (pH > 8.0) in outwash locations which have been derived from the weathering of mafic rocks and calcretes. In turn, these sites support quite distinct vegetation communities (e.g. Gibson & Lyons 1998, 2001b). Such sites are not reported for this survey because areas of mafic and ultramafic rocks of the Warriedar Fold Belt were not sampled, these areas being excluded from the Tallering Land System of Payne et al. (1998). Such geologies do occur in the eastern part of the area (Lipple et al. 1983), and the vegetation communities of these would be interesting to compare with the ironstone communities.

The rapid changes in topography over the BIF ranges produce a variety of diverse habitats and microhabitats over a relatively short distance within the landform, which support a number of different floristic community types. These communities are composed of generalist taxa that are both widely dispersed over the landform and surrounds (e.g. *Acacia aneura*, *Solanum lasiophyllum*), and characteristic taxa with a more limited distribution and greater specificity for particular microhabitats. This sequence of communities over the topographic catena (the 'catenary sequence' *sensu* Beard (1976a, 1990)), has been found in similar surveys on ironstone and greenstone ranges in the northern and eastern goldfields (Gibson 2004a, b; Gibson & Lyons 1998, 2001a, b; Meissner & Caruso 2008, Markey & Dillon 2008) and BIF landforms in the arid Pilbara (van Etten & Fox 2004) and in Brazil (Jacobi et al. 2007).

The turnover of communities among BIF ranges is a trend also noted for granite communities (Hopper et al. 1997), and has been attributed to a number of possible, interrelated causes. Geographical position and its associated climate may have also some bearing on some of these communities, and account for their restriction to particular parts of the region. The latitudinal and longitudinal transition in floristic communities across the central Tallering Land System and within the wider Yalgoo – Murchison region coincides with a climatic gradient of increasing aridity (Beard 1976a, b). Differences in floristic composition among ranges may also be associated with differences in the physical characteristics of each landform, such as soil chemistry, geological substrate or topography. Furthermore, these ranges are isolated by expanses of low plains, and opportunities for an exchange of species among them may be limited. In addition to these possible factors, differences in floristic composition may be a consequence of climatic and evolutionary history over the Tertiary and Quaternary. Increasing aridity and climatic instability over these periods has been hypothesised to account for patterns in speciation, endemism and biogeography in the South West Floristic Region (Hopper & Goia 2004) and among granite outcrops in this region (Hopper et al. 1997). This fluctuating aridity could have worked in combination with limited dispersal between ranges, stochastic events of immigration or local extinction, *in situ* speciation events, and range-specific habitats and substrates to account for biogeographic patterns currently observed in BIF ranges of southern Western Australia (Hopper et al. 1997, Hopper & Goia 2004). Like granite outcrops (Hopper et al. 1997), BIF ranges in the northern Yilgarn are biodiversity hotspots, and refugia for endemic or uncommon taxa and floristic communities (Gibson et al. 2007).

Conservation

A number of taxa endemic and near-endemic to the ironstones ranges of the Central Tallering Land System are recommended to have their conservation status reviewed, given their restricted distribution and a potential threat from mineral exploration and mining. In particular, it is recommended that the conservation status of *Millotia* *dimorpha* is revised from P1 to declared rare flora (DRF) given that all known populations are under threat from mining proposals. Both *Acacia woodmaniorum* and *Acacia karina* were recently listed at priority 2 conservation status (Maslin & Buscomb 2007), and should be considerd for a higher priority or declared rare flora (DRF) listing (B. Maslin, pers. comm.[8]). Although not restricted to the study region, *Calotis* aff. *cuneifolia* is recommend for priority listing (P3) as it is only known from three highly disjunct locations, one of which occurs over several exploration or mining tenements. *Lepidosperma* sp. (A. Markey & S. Dillon 3468) requires further taxonomic work before it can be considered for priority listing, but it is likely that it will be awarded high conservation status (R. Barrett, pers. comm.[9]).

The study area has been subject to over a century of pastoralism, and this would be expected to have had some impact on vegetation condition. However, the study region was found to be relatively weed free and in reasonably good condition, as was found previously by Payne et al. (1998). This is to be expected for hilly terrain, which is not under the same sheep grazing pressure as the lowland plains and paddocks supplied with bores. Annual grasses and weedy herbaceous annuals were common in most quadrats, the most common annual being *Pentaschistis airoides*, which was present in 58% of quadrats. Goats were recognised as a serious problem in the Sandstone – Yalgoo region (Payne et al. 1998). This situation has not changed. Goat browsing is evident in all areas visited, and was noted to be so intense in some area that sampling was abandoned (i.e. Walagnumming Hill). Large flocks (≥ 20 animals) were observed in areas within weeks following ground-based culls, which suggest a requirement for regional control programs.

BIF landforms are highly prospectable for minerals, and mining would present greatest immediate threat to their unique and endemic floristic communities and flora. Although BIF ranges constitute a relatively small area of the Yilgarn Craton, they are specifically targeted by mining and very few of these ranges are reserved or have been proposed for protection within the conservation estate. The high turnover of species and communities both within and among these ranges makes the adequate reservation of such floristic diversity particularly challenging. To date, none of the central Tallering Land System occurs on conservation reserve, although the pastoral leases of three stations within the study area (Karara, Lochada and Warriedar) were purchased by CALM (now DEC) for the purposes of inclusion in the reserves system. These stations are currently Unallocated Crown Land undergoing tenure review. Most of these ex-pastoral stations are covered by exploration or mining tenements, and mineral exploration has already commenced on the hematite and magnetite deposits (i.e.: Mt Karara, Jasper Hill and Windaning Ridge). Tenements for various minerals also exist on all of the ironstone and greenstone ranges on adjoining pastoral leases on Thundelarra and Badja Stations, and indeed cover most of the central Tallering Land System. Proposed exploration and mining activities need to be carefully assessed and managed to minimise their impacts on geographically restricted floristic community types and on endemic, priority and poorly known taxa which have been identified for this region.

Note: Following the acceptance of this manuscript for publication/during the preparation of this manuscript for publication, Calotis aff cuneifolia has been given the phrase name Calotis sp. Perrinvale Station (R.J. Cranfield 7096), and listed as having Priority 3 conservation status.

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Table 1

Taxa of conservation significance collected within the Central Tallering Land System. Priority conservation status is according to Atkins (2006), and population status refers to whether the population was unknown or known prior to this study. Endemic taxa are defined as those restricted to hills within 100 km radius. IBRA Regions are denoted as: Yal = Yalgoo, Mur = Murchison, AW = Avon Wheatbelt, GS = Geraldton Sandplain (Thackway & Cresswell 1995, Environment Australia 2000). Asterisks indicate that the distribution is centred on Yalgoo IBRA.

Family	Taxon	Priority status	Population status	Distribution
Aizoaceae	*Gunniopsis divisa*	P1	new population	Yal, Mur
Aizoaceae	*Gunniopsis rubra*	P3	new population	Coo, Mur, Yal, AW
Asteraceae	*Millotia dimorpha*	P1	new population	Endemic
Asteraceae	*Rhodanthe collina*	P1	previously known	Yal, AW*
Celastraceae	*Psammomoya implexa*	P3	previously known	YA, AW
Mimosaceae	*Acacia karina*	P2	new population	Endemic
Mimosaceae	*Acacia woodmaniorum*	P2	previously known	Endemic
Myrtaceae	*Calytrix uncinata*	P3	previously known	Yal, Mur
Myrtaceae	*Micromyrtus trudgenii*	P1	previously known	Endemic
Myrtaceae	*Micromyrtus acuta*	P1	previously known	Endemic
Poaceae	*Austrostipa blackii*	P3	new population	Widespread
Proteaceae	*Persoonia pentasticha*	P2	previously known	Yal, GS, AW
Rhamnaceae	*Cryptandra imbricata*	P3	previously known	Mur, Yal, AW*
Rhamnaceae	*Polianthion collinum*	P3	previously known	Endemic
Rutaceae	*Drummondita fulva*	P3	previously known	Endemic

Table 2

Significant indicator taxa of the eight group classification of BIF landforms within the central Tallering Land System. Indicator values (%) are shown only for taxa which were found to be significant at $p \leq 0.05$ from a Monte Carlo permutation test (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$). The highest INDVAL statistics per taxon are highlighted.

	Floristic Community Type							
Species	**1a**	**1b**	**2**	**3**	**4a**	**4b**	**5a**	**5b**
Acacia coolgardiensis subsp *latior* *	22	1	14	0	0	0	0	1
Acacia sibina **	30	4	6	0	1	0	0	3
Aluta aspera subsp. *hesperia* **	30	17	2	0	0	4	0	0
Cheilanthes adiantoides **	18	18	18	11	4	3	2	6
Dianella revoluta var. *divaricata* **	28	3	0	0	0	2	0	7
Eremophila forrestii subsp. *forrestii* *	24	1	0	0	0	6	4	3
Hemigenia sp. Cue *	20	3	10	0	0	0	0	0
Philotheca deserti subsp. *deserti* **	26	0	2	0	0	0	0	0
Thysanotus pyramidalis *	21	5	0	0	0	0	2	1
Eremophila latrobei subsp. *latrobei* **	19	21	1	14	9	11	0	2
Philotheca sericea **	1	20	6	18	12	17	0	0
Prostanthera magnifica **	1	40	4	0	0	2	0	0
Acacia karina *	1	2	19	0	0	0	0	0
Acacia assimilis subsp. *assimilis* *	12	7	23	0	0	1	2	6
Allocasuarina acutivalvis **	5	5	46	4	0	0	0	0
Calothamnus gilesii *	0	0	20	0	0	0	0	0
Cyanicula amplexans **	0	2	33	0	0	0	0	0
Eucalyptus petraea *	0	0	20	0	0	0	0	0
Gastrolobium laytonii **	0	0	31	0	2	0	0	0
Grevillea paradoxa **	0	0	47	0	0	0	0	0
Hypoxis glabella var. *glabella* *	0	0	20	0	0	0	0	0
Lepidosperma sp. (Markey & Dillon 3468) **	0	0	40	0	0	0	0	0
Leucopogon sp. Clyde Hill *	7	3	17	1	0	0	0	0
Melaleuca nematophylla **	1	6	47	3	0	0	0	0
Melaleuca radula *	0	0	23	3	0	0	0	0
Mirbelia microphylla *	0	0	20	0	0	0	0	0
Persoonia hexagona **	0	0	31	0	2	0	0	0
Thysanotus manglesianus **	13	12	25	0	2	0	0	1
Xanthosia bungei **	0	4	58	2	2	0	0	0
Acacia aulacophylla **	0	1	0	38	10	4	3	0
Arthropodium dyeri *	3	10	15	20	3	2	6	2
Astroloma serratifolium *	0	1	10	18	1	0	0	0
Austrodanthonia caespitosa **	0	1	0	24	6	1	19	0
Calytrix uncinata **	0	0	0	30	0	0	3	0
Cheiranthera filifolia var. *simplicifolia* **	2	4	0	44	0	1	3	1
Drummondita fulva **	1	8	0	37	0	0	0	0
Eremophila glutinosa **	0	1	0	24	3	2	2	0
Melaleuca hamata *	0	0	0	20	0	0	0	0
Micromyrtus trudgenii *	0	6	0	22	19	1	0	0
Mirbelia bursarioides **	0	27	0	32	5	7	0	0
Philotheca brucei subsp. *brucei* **	3	8	8	23	5	8	0	8
Prostanthera patens **	0	5	0	37	10	0	0	0
Stylidium longibracteatum **	0	0	0	50	1	0	2	0
Thryptomene costata **	1	3	0	24	0	8	0	0
Austrostipa trichophylla *	0	1	0	0	22	14	6	7
Calycopeplus paucifolius **	1	8	17	0	25	0	0	0
Cheilanthes lasiophylla *	0	0	0	0	18	0	0	0
Cheilanthes sieberi subsp. *sieberi* **	0	1	0	0	40	16	3	0
Dodonaea petiolaris *	0	0	0	17	20	6	0	1

Table 2 (cont.)

Species				**Floristic Community Type**				
	1a	**1b**	**2**	**3**	**4a**	**4b**	**5a**	**5b**
Dodonaea viscosa **	0	0	5	0	40	0	0	0
Isotoma petraea *	0	0	0	0	18	0	0	0
Acacia aneura var. cf. *major* **	7	9	4	2	1	29	1	0
Acacia umbraculiformis **	1	2	0	5	7	39	0	0
Acacia ramulosa var. *ramulosa* **	10	11	0	6	3	23	3	15
Monachather paradoxus *	18	10	1	2	2	19	0	10
Phyllanthus erwinii **	0	0	0	0	0	26	0	0
Ptilotus drummondii var. *drummondii* **	1	3	2	14	0	29	1	4
Sida sp. Golden calyces glabrous fruit**	0	1	2	0	8	60	0	0
Solanum ellipticum **	0	0	0	2	13	31	1	1
Solanum lasiophyllum *	0	2	4	2	8	21	3	4
Thryptomene decussata *	0	3	0	6	9	22	0	0
Acacia erinacea **	0	0	0	0	0	0	50	0
Austrostipa elegantissima *	1	2	0	5	19	1	22	14
Austrostipa nitida **	0	0	0	0	1	0	42	0
Enchylaena lanata **	0	0	0	1	5	5	47	1
Eremophila oldfieldii subsp. *oldfieldii* **	0	0	0	2	0	0	42	0
Eremophila oppositifolia subsp. *angustifolia* **	0	0	0	1	0	0	36	1
Exocarpos aphyllus **	0	0	0	0	1	0	25	2
Frankenia setosa **	0	0	0	0	0	0	25	0
Maireana carnosa **	0	0	0	0	0	0	64	1
Maireana thesioides **	0	0	0	1	0	0	37	9
Rhagodia drummondii **	0	0	0	0	0	0	32	29
Scaevola spinescens **	0	0	0	8	0	0	47	23
Sclerolaena densiflora *	0	0	0	2	1	0	25	0
Sclerolaena diacantha **	0	0	0	0	0	0	30	2
Sclerolaena fusiformis **	0	0	0	0	0	0	42	2
Sclerolaena gardneri **	0	0	0	0	0	0	30	2
Senna sp. Austin **	1	0	1	0	0	0	48	3
Cryptandra imbricata *	0	0	0	0	0	0	0	20
Eucalyptus kochii subsp. *amaryssia* **	0	0	2	0	0	0	0	32
Maireana villosa x *planifolia* **	0	0	0	0	0	0	0	40
Maireana georgei *	1	0	0	0	0	0	16	19
Olearia humilis **	2	6	0	3	0	0	1	33
Ptilotus obovatus var. *obovatus* **	0	0	1	6	25	5	10	25
Senna artemisioides subsp. *filifolia* **	0	0	0	2	0	0	0	32
Senna charlesiana **	0	1	1	7	1	0	1	27
Number of quadrats	12	35	10	10	11	7	8	10

Table 3

Summary statistics (average ± s.e.) of environmental variables for floristic community types of the Central Tallering Land System. Differences were determined using Kruskal – Wallis non-parametric analysis of variance. (* indicates $p < 0.05$, ** indicates $p < 0.01$, *** indicates $p < 0.001$), with Dunn's posthoc test (LSD $p < 0.05$). Despite significant results for AOV, posthoc tests were insignificant for S. Parameter codes are explained in the methods section. Units for parameters; eCEC = cmol(+)/kg, minerals = mg/kg, annual temperature (Tann) = °C and annual rainfall (Rann) = mm. Abbreviations: Rock Frag = surface rock fragment cover, Rock Max Size = maximum surface rock size category.

	Community type							
Variable	**1a**	**1b**	**2**	**3**	**4a**	**4b**	**5a**	**5b**
Soil Parameters								
eCEC ***	0.91 ± 0.14 [a]	1.91 ± 0.12 [ab]	5.67 ± 1.35 [c]	2.41 ± 0.27 [bc]	3.26 ± 0.36 [c]	1.95 ± 0.19 [ab]	5.20 ± 1.11 [cb]	3.45 ± 0.94 [bc]
pH ***	4.26 ± 0.03 [a]	4.57 ± 0.05 [bc]	4.93 ± 0.12 [c]	4.36 ± 0.09 [ab]	4.63 ± 0.15 [abc]	4.56 ± 0.13 [abc]	5.10 ± 0.23 [c]	4.98 ± 0.21 [bc]
Ca ***	98.2 ± 17.4 [a]	223.0 ± 16.8 [ab]	807.0 ± 217 [c]	246.0 ± 35.3 [abc]	389.1 ± 60.3 [bc]	237.1 ± 28.4 [abc]	376.0 ± 106 [bc]	464.0 ± 166 [bc]
K ***	71.2 ± 8.4 [a]	114.4 ± 6.0 [abc]	145 ± 17.8 [bc]	102.3 ± 9.4 [ab]	164.5 ± 13.3 [c]	118.0 ± 9.2 [abc]	127.8 ± 11.5 [bc]	137.5 ± 13.8 [bc]
Mg ***	23.2 ± 3.3 [a]	52.8 ± 3.0 [ab]	138.4 ± 26.7 [c]	76.3 ± 9.4 [bc]	94.0 ± 8.7 [bc]	50.0 ± 7.1 [ab]	235.9 ± 57.3 [c]	78.4 ± 12.8 [bc]
P ***	4.8 ± 0.4 [a]	6.6 ± 0.5 [a]	19.3 ± 9.5 [ab]	12.0 ± 4.3 [ab]	68.3 ± 15.3 [b]	13.9 ± 3.8 [ab]	6.9 ± 0.8 [a]	6.9 ± 0.7 [a]
Co ***	0.05 ± 0.01 [a]	0.19 ± 0.07 [ab]	0.12 ± 0.02 [bc]	0.12 ± 0.04 [a]	0.14 ± 0.03 [abc]	0.40 ± 0.33 [ab]	0.95 ± 0.40 [bc]	0.32 ± 0.05 [c]
Cu **	0.83 ± 0.0 [a]	1.11 ± 0.07 [ab]	1.03 ± 0.11 [ab]	0.74 ± 0.06 [a]	1.13 ± 0.12 [ab]	0.96 ± 0.10 [ab]	1.16 ± 0.21 [ab]	1.33 ± 0.16 [b]
Fe ***	35.2 ± 4.0 [ab]	42.8 ± 3.0 [ab]	80.6 ± 20.5 [bc]	87.5 ± 14.7 [c]	162.8 ± 28.9 [c]	59.4 ± 9.2 [bc]	53.0 ± 9.1[bc]	31.6 ± 2.0 [a]
Mn **	24.1 ± 5.4 [ab]	47.2 ± 4.4 [ab]	48.1 ± 6.4 [ab]	21.2 ± 6.0 [a]	46.1 ± 12.3 [ab]	43.4 ± 15.8 [ab]	58.1 ± 22.2 [ab]	64.0 ± 10.3 [b]
Na ***	10.6 ± 3.3 [a]	16.7 ± 1.7 [ab]	30.7 ± 5.6 [bc]	67.4 ± 31.4 [bc]	27.3 ± 3.5 [bc]	11.4 ± 1.5 [ab]	243.5 ± 64.8 [c]	30.7 ± 8.4 [abc]
Ni ***	0.12 ± 0.02 [a]	0.22 ± 0.03 [a]	0.18 ± 0.0 [a]	0.24 ± 0.03 [ab]	0.25 ± 0.03 [ab]	0.20 ± 0.05 [a]	0.88 ± 0.15 [b]	0.24 ± 0.04 [ab]
Pb **	0.69 ± 0.04 [ab]	0.75 ± 0.03 [b]	0.81 ± 0.06 [b]	0.60 ± 0.06[ab]	0.45 ± 0.07 [a]	0.66 ± 0.06 [ab]	0.68 ± 0.10[ab]	0.68 ± 0.06 [ab]
S *	17.6 ± 1.6	14.1 ± 0.7	13.3 ± 1.9	22.4 ± 6.9	14.6 ± 1.3	13.0 ± 1.5	41.3 ± 11.7	11.7 ± 1.4
Zn **	1.95 ± 0.20 [a]	2.79 ± 0.23 [ab]	2.21 ± 0.32 [a]	3.28 ± 0.56 [ab]	4.68 ± 0.55 [b]	3.30 ± 0.56 [ab]	4.96 ± 1.21 [ab]	2.39 ± 0.22 [ab]
Climate estimates								
Tann ***	20.1 ± 0.0 [c]	19.9 ± 0.0 [abc]	19.6 ± 0.0 [a]	20.0 ± 0.1 [bc]	19.6 ± 0.1 [a]	20.1 ± 0.0 [c]	20.1 ± 0.1 [bc]	20.0 ± 0.1 [abc]
Rann ***	284 ± 3 [ab]	290 ± 2 [ab]	305 ± 1 [c]	284 ± 4 [ab]	293 ± 4 [bc]	267 ± 5 [a]	280 ± 6 [ab]	292 ± 4 [abc]
Rcv***	55.5 ± 0.5 [a]	56.3 ± 0.3 [ab]	57.9 ± 0.2 [b]	54.9 ± 0.4 [a]	57.4 ± 0.2 [ab]	55.9 ± 0.6 [ab]	55.9 ± 0.6[ab]	56.2 ± 0.5 [ab]
Site Parameters								
Latitude ***	-28.957 ±0.053 [b]	-29.051 ±0.021 [ab]	-29.168 ±0.007 [a]	-28.900 ±0.054 [b]	-29.126 ±0.012 [ab]	-28.971 ± 0.059 [b]	-28.986 ± 0.059 [ab]	-29.039 ± 0.052 [ab]
Longitude***	116.907 ±0.023 [ab]	116.948 ±0.023 [ab]	116.815 ±0.019 [a]	116.934 ± 0.014 [ab]	116.993 ± 0.054 [b]	117.198 ±0.084 [b]	116.983 ± 0.074 [ab]	116.886 ± 0.020 [ab]
Altitude ***	360 ± 4 [a]	399 ± 5 [ab]	428 ± 12 [b]	406 ± 11 [ab]	443 ± 18 [b]	374 ± 18 [ab]	363 ± 13 [a]	379 ± 9 [ab]
Slope ***	3.5 ± 0.6 [ab]	7.5 ± 0.9 [ab]	12.5 ± 2.7 [b]	10.8 ± 2.2 [ab]	23.0 ± 2.6 [b]	10.6 ± 2.6 [ab]	9.4 ± 3.3 [ab]	3.1 ± 1.0 [a]
Topography ***	2.2 ± 0.3 [ab]	3.4 ± 0.2 [abc]	3.8 ± 0.4 [bc]	4.6 ± 0.2 [c]	4.0 ± 0.3 [bc]	3.5 ± 0.5 [abc]	2.5 ± 0.6 [ab]	1.3 ± 0.1 [a]
MxR size ***	3.2 ± 0.2 [a]	4.2 ± 0.2 [abc]	5.1 ± 0.2 [cd]	5.0 ± 0.2 [cd]	5.6 ± 0.2 [d]	4.9 ± 0.4 [bcd]	4.5 ± 0.5 [abcd]	3.3 ± 0.2 [ab]
Fragment ***	4.3 ± 0.3 [ab]	4.8 ± 0.1 [bc]	4.4 ± 0.2 [ab]	5.4 ± 0.2 [c]	4.8 ± 0.2 [bc]	5.0 ± 0.0 [bc]	5.4 ± 0.2 [bc]	3.7 ± 0.2 [a]
Outcrop ***	0.2 ± 02 [a]	1.5 ± 0.3 [ab]	3.1 ± 0.4 [bc]	3.3 ± 0.4 [bc]	4.1 ± 0.3 [c]	2.6 ± 0.6 [abc]	1.2 ± 0.6 [ab]	0.1 ± 0.1 [a]
% Litter ***	21.6 ± 3.7 [bc]	20.5 ± 2.4 [bc]	43.0 ± 7.6 [c]	9.1 ± 3.7 [ab]	3.9 ± 0.8 [a]	17.4 ± 5.6 [abc]	3.4 ± 1.1 [a]	32.0 ± 5.6 [c]
%Bare ***	71.8 ± 4.1 [ab]	70.6 ± 2.1 [a]	68.0 ± 4.1 [a]	80.0 ± 2.1 [ab]	80.4 ± 2.1 [ab]	80.7 ± 4.7 [ab]	85.0 ± 2.8 [ab]	79.0 ± 5.8 [b]
Species Richness								
All Taxa[1]	38.9 ± 2.6	49.4 ± 1.7	50.9 ± 2.3	48.3 ± 3.3	54.8 ± 2.8	47.4 ± 3.3	53.1 ± 6.1	47.9 ± 2.2
Annuals [1]	19.5 ± 1.5	25.1 ± 1.3	27.6 ± 1.7	21.2 ± 1.7	30.1 ± 2.0	26.1 ± 3.6	29.0 ± 5.2	23.9 ± 2.8
Perennials [1]	19.4 ± 1.4	24.3 ± 0.7	23.3 ± 1.3	27.1 ± 2.3	24.7 ± 1.3	21.3 ± 1.5	24.1 ± 1.3	24.0 ± 1.5
N. quadrats	12	35	10	10	11	7	8	10

[1:] including singleton taxa

Table 4: Spearman Rank Correlation coefficients for environmental variables from 103 quadrats on the Central Tallering Land System. Only correlations significant at $p < 0.01$ are shown. Full details on parameter codes are given in the methods section.

	Tann	Rann	Rcv	ECEC	pH	Ca	Co	Cu	Fe	K	Mg	Mn	Na	Ni	P	Pb	S	Zn	Slope	Tp	%Leaf	%Bare	MxR	Fragment a	Outcrop ab	Altitude	Latitude
Climate Estimates																											
Tann																											
Rann	-0.854																										
Rcv	-0.724	0.618																									
Soil Parameters																											
ECEC	-0.497	0.406	0.393																								
pH	-0.419	0.347	0.454	0.661																							
Ca	-0.610	0.501	0.454	0.910	0.696																						
Co	-0.271	.	0.439	0.632	0.792	0.555																					
Cu	-0.349	0.255	0.273	0.442	0.588	0.488	0.632																				
Fe	.	.	.	0.449	.	0.399	.	.																			
K	-0.511	0.324	0.493	0.712	0.554	0.681	0.641	0.615	0.344																		
Mg	-0.431	0.347	0.388	0.930	0.615	0.753	0.618	0.373	0.440	0.669																	
Mn	-0.457	0.363	0.539	0.426	0.782	0.560	0.711	0.692	.	0.563	0.362																
Na	.	.	.	0.604	.	0.368	0.304	.	0.364	0.434	0.703	.															
Ni	.	.	.	0.613	0.352	0.448	0.548	0.418	0.372	0.574	0.696	0.352	0.520														
P	-0.250	.	.	0.469	.	0.451	.	.	0.728	0.432	0.420	.	0.278	0.287													
Pb	.	0.282	0.264	.	.	.	.	.	-0.325	.	.	.	.	.	-0.272												
S	.	.	-0.252	.	-0.603	-0.319	-0.474	-0.424	.	-0.278	.	-0.619	0.389	.	.	.											
Zn	.	.	.	0.318	.	0.251	0.217	.	0.413	0.370	0.340	.	0.291	0.306	0.476	.	.										
Physical Site Parameters																											
Slope	-0.313	.	.	0.424	.	0.369	.	.	0.622	0.429	0.397	.	0.241	0.231	0.599	.	.	0.330									
Tp	.	.	.		.	.	-0.363	-0.315	0.599	.	.	-0.293	.	.	0.415	-0.230	0.245	.	0.341								
%Leaf	.	.	.		.	.	.	.	-0.265	.	-0.254	.	-0.321	-0.256	-0.258	0.241	-0.259	-0.340	-0.290	.							
%Bare	0.335	-0.348	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.						
MxR	.	.	.	0.407	.	0.371	.	.	0.776	0.285	0.365	.	0.266	.	0.611	-0.296	.	0.460	0.697	0.601	-0.259	.					
Frag Rock	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0.276	.	.	-0.378	.	.				
Outcrop	.	.	.	0.331	.	0.329	.	.	0.783	.	0.287	.	.	.	0.624	-0.259	.	0.370	0.524	0.732	.	.	0.763	.			
Altitude	-0.743	0.492	0.239	0.363	.	0.457	.	.	0.319	0.320	0.282	.	.	.	0.364	.	.	.	0.422	0.468	.	-0.315	0.433	.	0.396		
Latitude	0.804	-0.831	-0.902	-0.401	-0.454	-0.490	-0.405	-0.352	.	-0.465	-0.382	-0.563	.	-0.235	.	-0.341	0.284	.	.	.	.	0.237	.	.	.	-0.268	
Longitude	0.361	-0.694	-0.374	.	.	.	.	.	.	.	.	.	.	.	.	-0.41	.	.	.	.	.	235	.	.	.	0.518	.

APPENDIX 1

Flora List for BIF ranges of the central Tallering Land System (Pinyalling Hill, Walagnumming Hill, Mt Karara, Windaning Hill and associated Windaning ridge, Minjar Hill and unnamed BIF on Badja Station). Nomenclature follows Packowska and Chapman (2000), introduced weeds by "*" and both phrase (informal) names and taxa of uncertain taxonomic status (i.e.: *confer* or *affinis*) are followed by a collection number.

Adiantaceae

Cheilanthes cf. *lasiophylla* x *sieberi* (A. Markey & S. Dillon 3048)
Cheilanthes adiantoides
Cheilanthes brownii
Cheilanthes lasiophylla
Cheilanthes sieberi subsp. *sieberi*

Aizoaceae

* *Cleretum papulosum* subsp. *papulosum*
Gunniopsis divisa
Gunniopsis rubra
* *Mesembryanthemum nodiflorum*
Tetragonia diptera
Tetragonia eremaea
Tetragonia moorei

Amaranthaceae

Ptilotus aervoides
Ptilotus divaricatus var. *divaricatus*
Ptilotus drummondii var. *drummondii*
Ptilotus exaltatus
Ptilotus gaudichaudii var. *gaudichaudii*
Ptilotus gaudichaudii var. *parviflorus*
Ptilotus helipteroides
Ptilotus macrocephalus
Ptilotus obovatus var. *obovatus*
Ptilotus polystachyus var. *polystachyus*
Ptilotus sp. Northampton (R. Davis 10952)

Anthericaceae

Arthropodium curvipes
Arthropodium dyeri
Caesia sp. Wongan (K.F. Keneally 8820)
Thysanotus manglesianus
Thysanotus pyramidalis
Thysanotus rectantherus

Apiaceae

Daucus glochidiatus
Hydrocotyle callicarpa
Hydrocotyle pilifera var. *glabrata*
Hydrocotyle rugulosa
Trachymene cyanopetala
Trachymene ornata
Trachymene pilosa
Xanthosia bungei

Apocynaceae

Alyxia buxifolia

Asclepiadaceae

Marsdenia australis
Rhyncharrhena linearis
Asphodelaceae
Bulbine semibarbata

Aspleniaceae

Pleurosorus rutifolius

Asteraceae

Actinobole uliginosum
Angianthus tomentosus
* *Arctotheca calendula*
Bellida graminea
Blennospora drummondii
Brachyscome cheilocarpa
Brachyscome ciliaris
Brachyscome ciliocarpa
Brachyscome perpusilla
Calocephalus aff. *multiflorus* (A. Markey & S. Dillon 3464)
Calocephalus multiflorus
Calotis aff. *cuneifolia* (A. Markey & S. Dillon 3447)
Calotis hispidula
Calotis multicaulis
Cephalipterum drummondii
Ceratogyne obionoides
Chthonocephalus pseudevax
Dielitzia tysonii
Erymophyllum glossanthus
Erymophyllum tenellum
Feldstonia nitens
Gilberta tenuifolia
Gilruthia osbornei
Gnephosis arachnoidea
Gnephosis brevifolia
Gnephosis tenuissima
Helipterum craspedioides
Hyalosperma demissum
Hyalosperma glutinosum subsp. *glutinosum*
Hyalosperma glutinosum subsp. *venustum*
Hyalosperma zacchaeus
* *Hypochaeris glabra*
Isoetopsis graminifolia
Lawrencella davenportii
Lawrencella rosea
Lemooria burkittii
Millotia dimorpha
Millotia myosotidifolia
Myriocephalus guerinae
Myriocephalus oldfieldii
Myriocephalus pygmaeus

Myriocephalus rudallii
Olearia humilis
Olearia muelleri
Olearia pimeleoides
Podolepis canescens
Podolepis capillaris
Podolepis gardneri
Podolepis lessonii
Podotheca gnaphalioides
Pogonolepis stricta
Rhodanthe battii
Rhodanthe chlorocephala subsp. *rosea*
Rhodanthe chlorocephala subsp. *splendida*
Rhodanthe citrina
Rhodanthe collina
Rhodanthe humboldtiana
Rhodanthe laevis
Rhodanthe manglesii
Rhodanthe maryonii
Rhodanthe polycephala
Rhodanthe propinqua
Rhodanthe pygmaea
Rhodanthe spicata
Schoenia cassiniana
Senecio glossanthus
Senecio gregorii
Senecio pinnatifolius
* *Sonchus oleraceus*
Trichanthodium skirrophorum
* *Urospermum picroides*
* *Ursinia anthemoides*
Waitzia acuminata var. *acuminata*
Waitzia nitida

Boraginaceae

Cynoglossum sp Inland Ranges (C.A Gardner 12684)
Omphalolappula concava

Boryaceae

Borya sphaerocephala

Brassicaceae

* *Brassica tournefortii*
Lepidium oxytrichum
* *Sisymbrium erysimoides*
Stenopetalum aff. *sphaerocarpum* (A. Markey & S. Dillon 3414)
Stenopetalum anfractum
Stenopetalum filifolium
Stenopetalum pedicellare
Stenopetalum sphaerocarpum

Caesalpiniaceae

Senna artemisioides subsp. *filifolia*
Senna charlesiana
Senna glaucifolia
Senna glutinosa subsp. *chatelainiana* x *charlesiana* (A. Markey & S. Dillon 3413)
Senna glutinosa subsp. *chatelainiana*
Senna sp. Austin (A. Strid 20210)

Campanulaceae

Wahlenbergia gracilenta
Wahlenbergia preissii
Wahlenbergia tumidifructa
Caryophyllaceae
* *Silene nocturna*
* *Spergula pentandra*

Casuarinaceae

Allocasuarina acutivalvis subsp. *prinsepiana*
Allocasuarina acutivalvis subsp. *acutivalvis* intergrade subsp. *prinsepiana*
Allocasuarina dielsiana

Celastraceae

Psammomoya implexa

Centrolepidaceae

Centrolepis aristata

Chenopodiaceae

Atriplex bunburyana
Atriplex semilunaris
Chenopodium curvispicatum
Chenopodium melanocarpum forma *melanocarpum*
Chenopodium saxatile
Dysphania glomulifera subsp. *eremaea*
Einadia nutans subsp. *eremaea*
Enchylaena lanata
Enchylaena tomentosa var. *tomentosa*
Maireana carnosa
Maireana convexa
Maireana georgei
Maireana marginata
Maireana planifolia
Maireana planifolia x *villosa* (intergrade) (A. Markey & S. Dillon 3482)
Maireana planifolia x *villosa* (intergrade) (A. Markey & S. Dillon 3479)
Maireana thesioides
Maireana trichoptera
Rhagodia drummondii
Rhagodia eremaea
Sclerolaena densiflora
Sclerolaena diacantha
Sclerolaena fusiformis
Sclerolaena gardneri
Sclerolaena microcarpa

Colchicaceae

Wurmbea sp. Paynes Find (C.J. French 1237)

Convolvulaceae

Porana sericea

Crassulaceae

Crassula closiana
Crassula colorata var. *acuminata*
Crassula colorata var. *colorata*
Crassula extrorsa
Crassula tetramera

Cupressaceae

Callitris columellaris

Cuscutaceae

* *Cuscuta epithymum*

Cyperaceae

Isolepis congrua
Lepidosperma sp. (A. Markey & S. Dillon 3468)
Schoenus nanus

Dasypogonaceae

Chamaexeros macranthera
Xerolirion divaricata

Dilleniaceae

Hibbertia arcuata
Hibbertia glomerosa var. *glomerosa*
Hibbertia stenophylla

Droseraceae

Drosera macrantha subsp. *macrantha*

Epacridaceae

Astroloma serratifolium
Leucopogon sp. Clyde Hill (M.A. Burgman 1207)

Euphorbiaceae

Calycopeplus paucifolius
Euphorbia boophthona
Euphorbia drummondii subsp. *drummondii*
Euphorbia tannensis subsp. *eremophila*
Phyllanthus erwinii
Poranthera microphylla
Stachystemon intricatus

Frankeniaceae

Frankenia setosa

Geraniaceae

* *Erodium aureum*
* *Erodium cicutarium*
Erodium cygnorum

Goodeniaceae

Brunonia australis
Goodenia berardiana
Goodenia havilandii
Goodenia occidentalis
Goodenia pinnatifida
Goodenia pusilliflora
Goodenia tenuiloba
Scaevola spinescens
Velleia cycnopotamica
Velleia hispida
Velleia rosea
Velleia sp. (A. Markey & S. Dillon 3463)

Haloragaceae

Gonocarpus nodulosus
Haloragis odontocarpa f. *octoforma*
Haloragis odontocarpa f. *pterocarpa*
Haloragis odontocarpa f. *rugosa*
Haloragis trigonocarpa
Myriophyllum decussatum

Hypoxidaceae

Hypoxis glabella var. *glabella*

Juncaginaceae

Triglochin sp. B Flora of Australia (P.G. Wilson 4294)

Lamiaceae

Hemigenia sp. Cue (K.F. Kenneally 47A)
Hemigenia sp. Yalgoo (A.M. Ashby 2624)
Hemigenia sp. Yuna (A.C. Burns 95)
Prostanthera althoferi subsp. *althoferi*
Prostanthera althoferi ssp. *althoferi* x *serica* (intergrade)
Prostanthera magnifica
Prostanthera patens
Spartothamnella teucriiflora

Lobeliaceae

Isotoma petraea
Lobelia heterophylla
Lobelia rhytidosperma
Lobelia cleistogamoides
Lobelia winfridae

Loganiaceae

Phyllangium sulcatum

Loranthaceae

Amyema gibberula var. *tatei*
Amyema preissii
Lysiana casuarinae

Malvaceae

Abutilon cryptopetalum
Abutilon oxycarpum
Sida sp. Excedentifolia (J.L. Egan 1925)
Sida sp. Golden calyces glabrous fruit (H.N. Foote 32)
Sida sp. dark green fruits (S. van Leeuwen 2260)
Sida ectogama

Mimosaceae

Acacia acuaria

Acacia aff. *coolgardiensis* subsp. *latior* (A. Markey & S. Dillon 3477)
Acacia andrewsii
Acacia aneura var cf. *aneura*
Acacia aneura var. cf. *argentia*
Acacia aneura var. cf. *tenuis*
Acacia anthochaera
Acacia assimilis subsp. *assimilis*
Acacia aulacophylla
Acacia burkittii
Acacia cf. *kalgoorliensis* (A. Markey & S. Dillon 3478)
Acacia colletioides
Acacia coolgardiensis subsp. *effusa*
Acacia coolgardiensis subsp. *latior*
Acacia craspedocarpa
Acacia erinacea
Acacia exocarpoides
Acacia grasbyi
Acacia karina
Acacia longispinea
Acacia minyura
Acacia ramulosa var. *linophylla*
Acacia ramulosa var. *ramulosa*
Acacia rigens
Acacia sibina
Acacia woodmaniorum
Acacia umbraculiformis
Acacia tetragonophylla

Myoporaceae

Eremophila clarkei
Eremophila decipiens subsp. *decipiens*
Eremophila eriocalyx
Eremophila forrestii subsp. *forrestii*
Eremophila galeata
Eremophila georgei
Eremophila glutinosa
Eremophila granitica
Eremophila latrobei subsp. *latrobei*
Eremophila oldfieldii subsp. *oldfieldii*
Eremophila oppositifolia subsp. *angustifolia*
Eremophila pantonii
Eremophila cf. *platycalyx* (A. Markey & S. Dillon 3337)
Eremophila platycalyx subsp. *platycalyx*
Eremophila serrulata
Eremophila sp. (A. Markey & S. Dillon 3338)

Myrtaceae

Aluta aspera subsp. *hesperia*
Calothamnus gilesii
Calytrix uncinata
Eucalyptus ewartiana
Eucalyptus gypsophila
Eucalyptus kochii subsp. *amaryssia*
Eucalyptus leptopoda subsp. *arctata*
Eucalyptus leptopoda subsp. *elevata*
Eucalyptus loxophleba subsp. *supralaevis*
Eucalyptus petraea
Homalocalyx thryptomenoides
Malleostemon tuberculatus
Melaleuca cordata
Melaleuca hamata
Melaleuca leiocarpa
Melaleuca nematophylla
Melaleuca radula
Micromyrtus acuta
Micromyrtus clavata
Micromyrtus sulphurea
Micromyrtus trudgenii
Thryptomene costata
Thryptomene decussata
Verticordia interioris

Orchidaceae

Cyanicula amplexans
Caladenia petrenis
Pterostylis sp. inland (A.C. Beauglehole 11880)
Pterostylis sp. scooped sepals (G. Brockman GBB386)
Pterostylis spathulata

Oxalidaceae

Oxalis perennans

Papilionaceae

Daviesia hakeoides subsp. *subnuda*
Gastrolobium laytonii
* *Medicago minima*
Mirbelia bursarioides
Mirbelia microphylla

Phormiaceae

Dianella revoluta var. *divaricata*

Pittosporaceae

Bursaria occidentalis
Cheiranthera filifolia var. *simplicifolia*
Pittosporum angustifolium

Plantaginaceae

Plantago aff. *hispida* (A. Markey & S. Dillon 3440)

Poaceae

Amphipogon caricinus var. *caricinus*
Aristida contorta
Austrodanthonia caespitosa
Austrodanthonia sp. Goomalling (A.G. Gunness et al. OAKP 10/63)
Austrostipa blackii
Austrostipa elegantissima
Austrostipa eremophila
Austrostipa hemipogon
Austrostipa nitida
Austrostipa scabra
Austrostipa trichophylla
Bromus arenarius
Cymbopogon ambiguus
* *Ehrharta longiflora*

* *Elymus scaber*
Enneapogon caerulescens
Eragrostis dielsii
Eragrostis pergracilis
Eriachne pulchella subsp. *pulchella*
Lachnagrostis plebeia
* *Lamarckia aurea*
Monachather paradoxus
Paspalidium basicladum
* *Pentaschistis airoides*
* *Rostraria pumila*
Thyridolepis mitchelliana
Thyridolepis multiculmis
Tripogon loliiformis
* *Vulpia muralis*
* *Vulpia myuros* var. *myuros*

Polygalaceae

Comesperma integerrimum
Comesperma volubile

Polygonaceae

* *Emex australis*

Portulacaceae

Calandrinia sp. Truncate capsules (A. Markey & S. Dillon 3474)
Calandrinia aff. *eremaea* (A. Markey & S. Dillon 3472)
Calandrinia calyptrata
Calandrinia creethae
Calandrinia eremaea
Calandrinia sp. The Pink Hills (F. Obbens FO 19/06)
Calandrinia sp. Blackberry (D.M. Porter 171)

Primulaceae

* *Anagallis arvensis*

Proteaceae

Grevillea extorris
Grevillea obliquistigma subsp. *obliquistigma*
Grevillea paradoxa
Hakea invaginata
Hakea preissii
Hakea recurva subsp. *arida*
Hakea recurva subsp. cf. *recurva*
Persoonia hexagona
Persoonia pentasticha
Persoonia manotricha

Ranunculaceae

Ranunculus sessiliflorus var. *sessiliflorus*

Rhamnaceae

Cryptandra imbricata
Polianthion collinum

Rubiaceae

* *Galium aparine*
Psydrax latifolia
Psydrax suaveolens
Synaptantha tillaeacea var. *tillaeacea*\

Rutaceae

Drummondita fulva
Philotheca brucei subsp. *brucei*
Philotheca deserti subsp. *deserti*
Philotheca sericea

Santalaceae

Exocarpos aphyllus
Santalum acuminatum
Santalum spicatum

Sapindaceae

Dodonaea adenophora
Dodonaea inaequifolia
Dodonaea lobulata
Dodonaea petiolaris
Dodonaea rigida
Dodonaea viscosa subsp. *mucronata*
Dodonaea viscosa subsp. *spatulata*

Solanaceae

Nicotiana rosulata subsp. *rosulata*
Solanum ellipticum
Solanum lasiophyllum
Solanum nummularium

Stackhousiaceae

Stackhousia muricata

Sterculiaceae

Brachychiton gregorii
Keraudrenia velutina subsp. *velutina*

Stylidiaceae

Levenhookia leptantha
Stylidium longibracteatum
Stylidium perpusillum
Stylidium warriedarense

Thymelaeaceae

Pimelea avonensis
Pimelea microcephala subsp. *microcephala*

Urticaceae

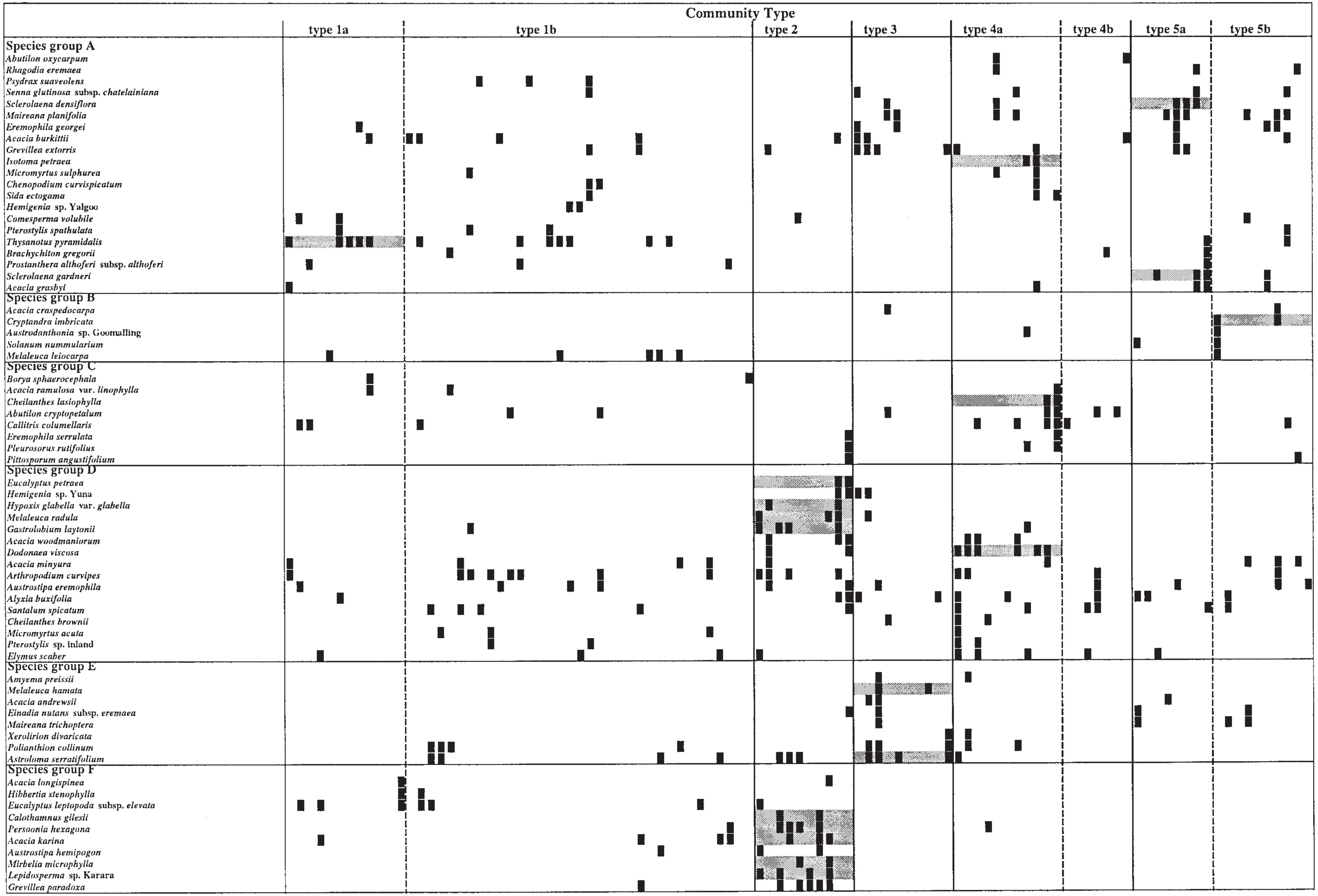
Parietaria cardiostegia

Zygophyllaceae

Zygophyllum eremaeum
Zygophyllum ovatum

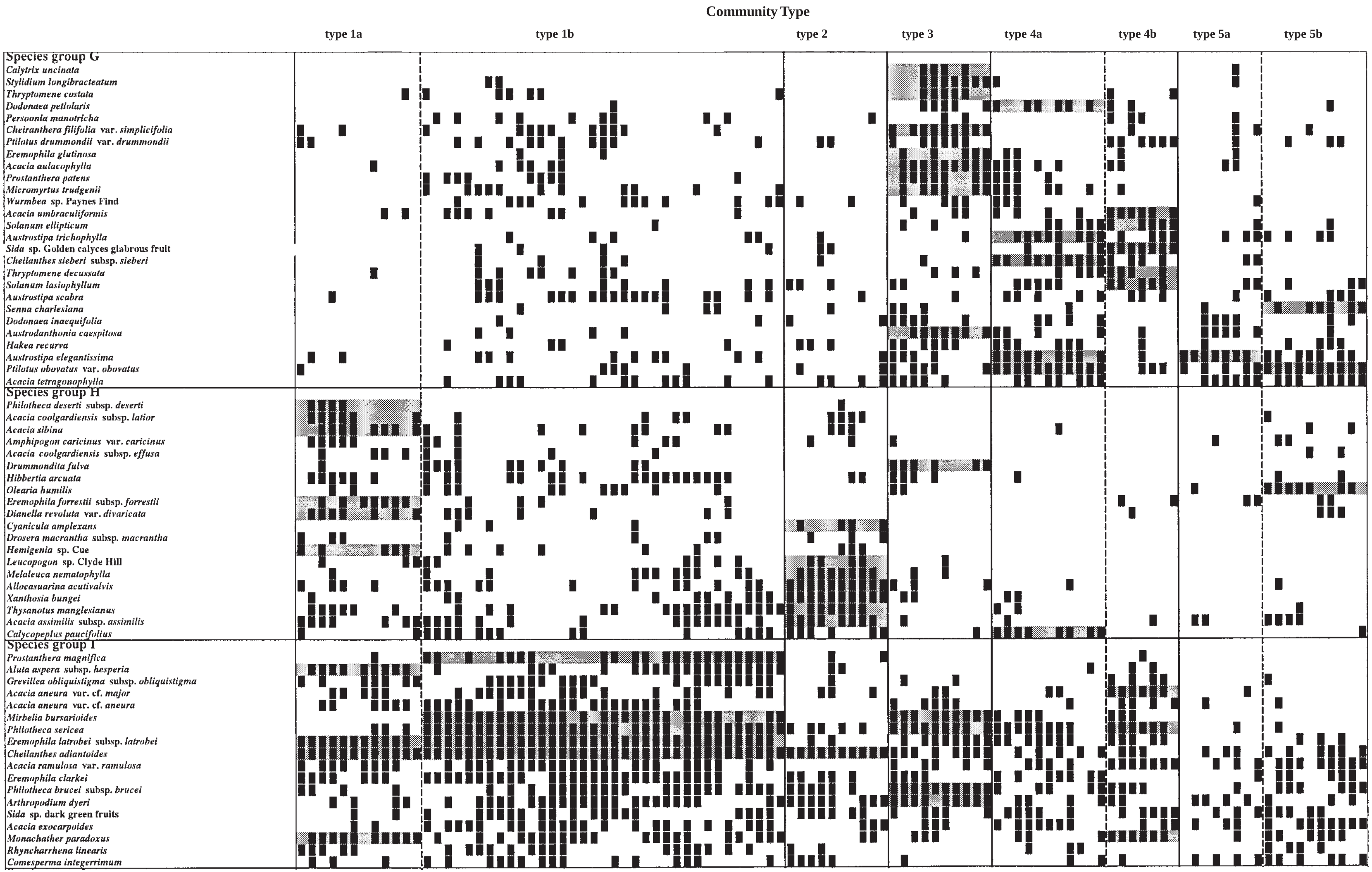
APPENDIX 2

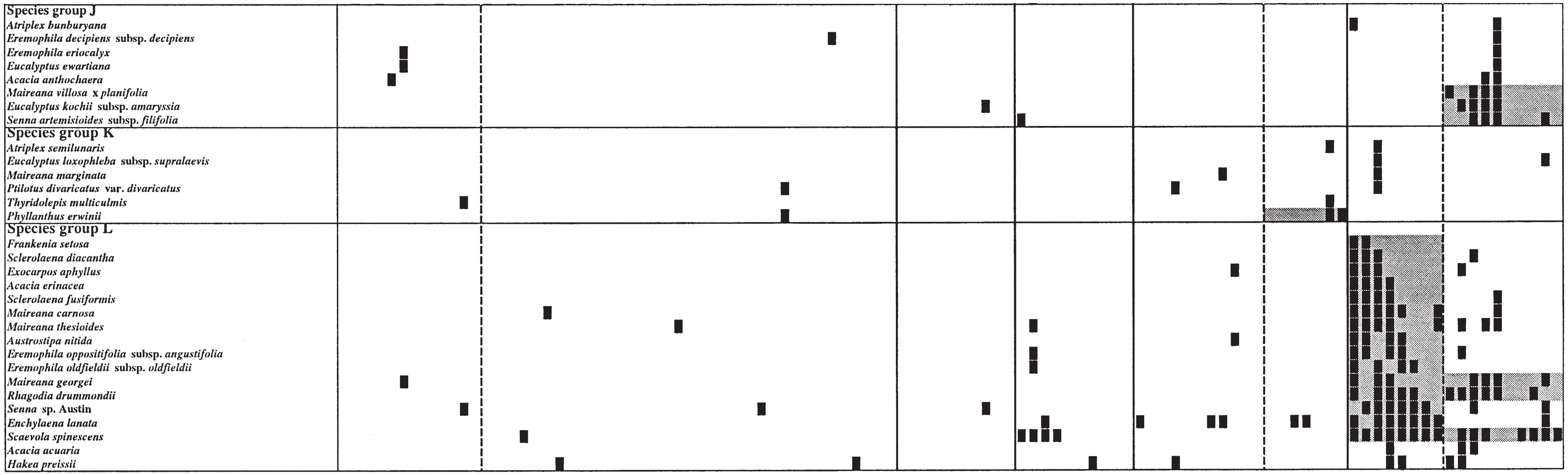
Two way table of site and perennial taxa used in classification and ordination analysis, sorted by quadrat and taxon classification. Species occurences per quadrat are indicated by a square. Species with significant INDVAL statistics are indicated by shading in the respective community type where these values were highest (see Table 2).



APPENDIX 2

(cont.)




Species group J
Atriplex bunburyana
Eremophila decipiens subsp. decipiens
Eremophila eriocalyx
Eucalyptus ewartiana
Acacia anthochaera
Maireana villosa x planifolia
Eucalyptus kochii subsp. amaryssia
Senna artemisioides subsp. filifolia
Species group K
Atriplex semilunaris
Eucalyptus loxophleba subsp. supralaevis
Maireana marginata
Ptilotus divaricatus var. divaricatus
Thyridolepis multiculmis
Phyllanthus erwinii
Species group L
Frankenia setosa
Sclerolaena diacantha
Exocarpos aphyllus
Acacia erinacea
Sclerolaena fusiformis
Maireana carnosa
Maireana thesioides
Austrostipa nitida
Eremophila oppositifolia subsp. angustifolia
Eremophila oldfieldii subsp. oldfieldii
Maireana georgei
Rhagodia drummondii
Senna sp. Austin
Enchylaena lanata
Scaevola spinescens
Acacia acuaria
Hakea preissii

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Flora and Vegetation of the banded iron formations of the Yilgarn Craton: the Weld Range

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ABSTRACT

A survey of the flora and floristic communities of the Weld Range, in the Murchison region of Western Australia, was undertaken using classification and ordination analysis of quadrat data. A total of 239 taxa (species, subspecies and varieties) and five hybrids of vascular plants were collected and identified from within the survey area. Of these, 229 taxa were native and 10 species were introduced. Eight priority species were located in this survey, six of these being new records for the Weld Range. Although no species endemic to the Weld Range were located in this survey, new populations of three priority listed taxa were identified which represent significant range extensions for these taxa of conservation significance.

Eight floristic community types (six types, two of these subdivided into two subtypes each) were identified and described for the Weld Range, with the primary division in the classification separating a dolerite-associated floristic community from those on banded iron formation. Floristic communities occurring on BIF were found to be associated with topographic relief, underlying geology and soil chemistry. There did not appear to be any restricted communities within the landform, but some communities may be geographically restricted to the Weld Range. Because these communities on the Weld Range are so closely associated with topography and substrate, they are vulnerable to impact from mineral exploration and open cast mining. At present, no areas of the Weld Range are within conservation estate. It is recommended that the distribution of these communities is further surveyed to ensure informed management, given the extent of proposed activities on the Weld Range.

INTRODUCTION

The Weld Range greenstone belt is a series of parallel ridges extending a length of c. 50 km, c. 3 km wide and approximately 55 km south west of Meekatharra. This range is one of several belts of metamorphic sediments and metavolcanics in the immediate area which provide some topographic relief within the surrounding subdued landscape, and represent the northern extent of the greenstone belts on the Yilgarn Craton. These ranges have had a long history of exploitation. However, it is the current expansion in mineral exploration and proposed iron ore mining that may have the greatest impact on these landforms. Although the vegetation of the general area has been mapped on a board scale (Beard 1976) and has been addressed in two regional surveys (Curry et al. 1994; Speck 1963), a detailed knowledge of the flora and vegetation communities specific to the Weld Range is lacking. This study aims to redress this deficiency. Furthermore, this study is one of c. 25 surveys being conducted by the Western Australian Department of Conservation (DEC, formerly known as the Department of Conservation and Land Management (CALM)) that are documenting the flora and floristic communities on BIF ranges in the Northern Yilgarn (Gibson et al. 2007). These surveys will ultimately place the flora and floristic communities of the Weld Range within a wider regional context, and assist in the conservation and management of unique taxa and communities.

Study Locality

The Weld Range consists of a series of parallel linear ridges of banded iron formation (BIF), interbedded within greenstones (primarily ultramafic and mafic metavolcanics), which are situated c. 60 km north-west of Cue and c. 85 km south-west of Meekatharra, in the Murchison Region of Western Australia. This range has a north-east trending stratigraphy, with several north-trending faults (Elias 1982). The Weld Range is c. 55 km long, and extends over a latitudinal range of 26.76–27.03 º S, and longitudinal range of 117.43–117.90 º E, consequently including parts of the Madoonga, Glen, Beebyn and Annean pastoral leases and the Wilgie Mia Aboriginal Reserve. Much of the area was vacant crown land until 1900, after which there was a rapid expansion of pastoral leases into the region over the following three decades (Curry et al. 1994). These pastoral leases are still active and primarily run sheep. Gold mining first became established in the Meekatharra district in the late 19th century, with gold and iron exploration occurring on the Weld Range in the early 20th century. However, the oldest mineral excavations on the Weld Range occurred at the site of Wilgie Mia ochre deposit, which had been mined for over 1000 years (Elias 1982). The lands around this site are currently within the Wilgie Mia Aboriginal Reserve, which is part of a Wajarri Yamatji native title claim by the Yamatji Land and Sea Council

Climate

The study area is bounded by the 190–240 mm isohyets and lies within the desert or arid zone bioclimatic region (Beard 1976, 1990; Curry et al. 1994). The climate of the region has typically hot, dry summers and mild winters. Rainfall is unreliable and bimodal, falling in either the summer or winter months (Beard 1976). Winter rainfall is derived from southerly rain-bearing cold fronts, whilst summer rainfall is derived from both thunderstorms and the infrequent and erratic passage of northerly depressions which are the remnants of tropical cyclones (Curry et al. 1994). The study site lies in an area of high evaporation rate, and the trend is for annual rainfall to decline in a north-easterly direction over the general Murchison region (Beard 1976; Curry et al. 1994).

The nearest meteorological centres to the Weld Range are Cue and Meekatharra, where the annual rainfall for both centres is 231 mm (Australian Bureau of Meteorology 1908 –). The highest recorded daily rainfall for Cue (119 mm) has fallen within the summer months. In contrast to these extreme deluges, the average monthly summer rainfall (November–April) for Cue is 20.0 mm, whilst the average winter monthly rainfall (May–October) is 18.5 mm (Australian Bureau of Meteorology 1908–). Using Cue as the nearest metrological station for temperature data, the mean maximum January temperature is 37.8° C, with an average summer temperature (December–February) of 36.9° C, and the average temperature exceeds 30° C during the months from November to March. The coldest temperatures are experienced during the winter months (June–August), when the average maximum temperature is 28.7° C.

Geology

The Weld Range is located within the Murchison geological province, within the Yilgarn Craton Superprovince (Blake & Kilgour 1998). As with much of the area of the Yilgarn Craton, the landscape associated with the Weld Range is subdued and consists of gently undulating plateaux of low relief (which Mabbutt (1963) refers to as 'the Murchison Plains') which are interrupted by hills, ranges and ridges. The Weld Range itself reaches elevations from 20 to > 200 m, with its highest peak at 739 m (Gnanagooragoo Peak). It is approximately 55 km long and between 3 and 4.5 km wide. The geology of the larger area around the Weld Range has been described and mapped over two geological sheets, Cue 1:250 000 (SG/50-15) and Belele 1:250 000 (SG50-11) (Elias 1982; Watkins et al. 1987). This landform is one of several greenstone belts in the province which are set in the Archaean granitoids and gneisses, all of which constitute the Yilgarn Craton. These metamorphic greenstone belts contain mafic and felsic volcanics, mafic, ultramafic and felsic intrusives, into which banded iron formation is interbedded (Elias 1982). Erosion of these Archaean and overlying Proterozoic rocks has occurred since the Tertiary to produce the sediments which overlie much of the surrounding plains. Laterization of these during the Oligocene - Miocene, and further erosion during the Quaternary has removed much of the lateritic duricrust and further exposed the greenstones and granitoids (Elias 1982; Watkins et al. 1987).

The Weld Range greenstone belt has been a topographic feature since before the Tertiary (Elias 1982). This greenstone belt is predominantly dolerite in which is bedded red (hematite), black (magnetite) and white (silica) banded iron-formation and jaspilite (Elias 1982; Watkins et al. 1987). It is this erosion-resistant banded iron-formation along the length of the strike which forms the parallel, steep ridges of the range. Erosion products from the exposed bedrock and laterites form colluvium which accumulates on scree slopes, on the margins of outcrops, and in alluvial fans which decline to gently sloping sheetwash plains (Elias 1982). Significant iron ore reserves occur on both the Weld Range and adjacent Jack Hills (c. 100 km north of Weld Range), which have formed from mineralization of banded iron-formation during the tertiary laterization (Elias 1982).

The soils of the Weld Range vary from shallow to skeletal stony soils and stony loams (lithosols) on the rocky slopes of the hills and ridges, grading to stony red earths and red earths on lower slopes and outwashes (Litchfield 1963). These soils are associated with the exposed, steep, weathering bedrock and soils derived from weathered parent rock include calcareous soils from mafic rocks (Litchfield 1963). Soils of the Weld Range and of the general region are typically infertile and acidic, with increments in pH and fertility occurring in local, depositional parts of the landscape and in calcareous soils (Curry et al. 1994; Litchfield 1963).

Flora

The Weld Range is located within the centre of the Upper-Murchison sub-region, in the Austin Botanical District of the Eremaean Botanical Province of Beard (1976, 1990), the Austin district later being adopted by Thackway & Cresswell (1995) and renamed the Murchison Interim Biogeographic Region (Environment Australia 2000). This district is dominated by mulga low woodland on the plains, whilst *Acacia grasbyi*, *Acacia ramulosa*, *Acacia aneura* and *Acacia tetragonophylla* appear on resistant outcrops. The Jack Hills and Weld Range are the main ranges of the Upper Murchison sub-region and, in his regional survey of the Murchison (1:1000 000), Beard (1976) mapped the Weld Range and Jack Hills as the same structural formation. On the Weld range, Beard (1976) noted that there were two dominant *Acacia* species on the BIF ridges (*Acacia aneura* and *Acacia quadrimarginea*), over *Eremophila latrobei*, *Eremophila oppositifolia*, *Scaevola spinescens*, *Ptilotus obovatus*, *Olearia stuartii* and *Lepidium* sp., which graded to *Acacia aneura* and *Acacia ramulosa* var. *linophylla* on the lower slopes.

On a finer scale than Beard (1976), a further two studies addressed the vegetation communities of the Weld Range as part of a larger regional survey of rangelands. Speck (1963) described vegetation communities and Mabbutt et al. (1963) described land systems in a regional survey of the Wiluna–Meekatharra area. In these studies, two land systems were described for the Weld Range, the Weld land system (on the Weld Range and Jack Hills) and the Gabanintha land system (on the far eastern extent of the Weld Range). Later, Curry et al. (1994) used these same land systems of Mabbutt et al. (1963) in their regional survey of rangelands within the Murchison River Catchment. The advance on Speck's (1963) communities was the use of multivariate analysis of floristic and physical data to resolve communities within the greater area.

Speck (1963) reported five communities on the main Weld land system which corresponded to different positions over the topographic profile, and three of these were restricted to the shallow stony soils on hill crests and slopes. The *Acacia sibirica*–*Eremophila fraseri* community was a distinctive community limited to rocky ridges in the Weld System. Two other communities were more widespread among hills in the region, these being a sparse *Acacia aneura* community (stunted *Acacia aneura* over *Ptilotus obovatus*, *Solanum ellipticum* and *Senna* spp.), and the *Acacia aneura*–*Eremophila macmillaniana* community (*E. macmillaniana* and sparse shrubs with a variable *A. aneura* overstorey). The *Acacia aneura*–*Acacia ramulosa* var. *linophylla* community occurred on the lower slopes and outwashes, and consisted of a tall shrubland over *Eremophila forrestii*, *Eremophila latrobei*, *Eremophila exilifolia*, *Calytrix* sp., *Ptilotus obovatus*, *Dodonaea* spp. and *Senna* spp. over sparse perennial grasses. On the alluvial and colluvial outwashes and footslopes was a sparse shrubland of *Acacia aneura*–*Acacia tetragonophylla* over *Eremophila fraseri*, *Solanum ellipticum* and *Ptilotus obovatus*, small chenopods (*Sclerolaena*) and short annual grasses.

Curry et al. (1994) revisited the Weld land system of Mabbutt et al. (1963) and retained their three altitudinal zones on the landform. Unlike Speck (1963), they did not resolve the vegetation on hill crest and slopes to be any more than a single vegetation community unit. The ranges, peaks and summits were dominated by a Rocky Hill Mixed Shrubland vegetation type, which consisted of *Acacia* aff. *citrinoviridis* and / or *A. aneura* shrublands, and commonly included *Acacia pruinocarpa, Acacia quadrimarginea, Acacia grasbyi* and *Acacia ramulosa*; over mid shrubs of the same *Acacia* species and *Thryptomene decussata*, *Eremophila georgei*, *Eremophila glutinosa, Eremophila latrobei, Eremophila linearis* and *Dodonaea viscosa* over a variety of low shrubs and perennial grasses. The footslopes and interfluves supported a Stony Mulga Mixed Shrubland vegetation type, which was essentially scattered mixed *Acacia* shrubland dominated by the same species as occurring upslope, over mid shrubs of *Eremophila freelingii*, *Eremophila macmillaniana*, *Eremophila cuneifolia* and low shrubs such as *Senna sturtii*, *Ptilotus* spp. and perennial grasses. The valley floors supported the Creekline Shrubland vegetation type, which consisted of tall *Acacia ramulosa* shrublands (with *Acacia aneura* and *Acacia pruinocarpa*) and trees on sandy floors over sparse shrubs. Curry et al. (1994) did not distinguish the communities of the Weld Range to be floristically distinct from those on the Jack Hills or other hilly landforms within the region. The aim of the present survey is to resolve floristic communities within the Weld Range at a finer scale than has been attained by these regional surveys.

METHODS

Fifty two 20 x 20 m quadrats were established over the survey area, during the spring season in late August 2005. Sites were only established where road access was adequate, and much of the Weld Range was inaccessible due to heavy rains and poor track conditions. Sites were also not established within the Wilgie Mia Aboriginal Reserve. Plots were placed on the crests, slopes and outwashes associated with the Weld land system of Curry et al. (1994), and were placed strategically to encompass the topographical profile of the ranges and the general range of variation of geological landforms and associated floristic communities in the area. A similar method has been used to survey greenstone and BIF ranges in the eastern goldfields (Gibson 2004; Gibson & Lyons 2001).

Quadrats were marked with four steel fence droppers, their position and altitude (alt) recorded by GPS and photographed at a set distance (0–5m) near each corner. The presence and cover of all vascular plant species (angiosperms, gymnosperms and pteridiophytes) were recorded in each plot, with specimens collected for verification at the Western Australian Herbarium. Representative specimens of all taxa were lodged at the Western Australian Herbarium, and geographical distributions were obtained from online records at the Western Australian Herbarium (1998–). Vegetation structure was described according to McDonald et al. (1998). All data on topographical position, aspect, slope, % litter, % bare ground, % rock cover class of both surface deposits and exposed bedrock, shape of surface rock fragments, soil colour and soil texture were noted according to the definitions of McDonald et al. (1998). Percentage surface rock fragment cover class (Rock Frag), maximum rock fragment size (MxR) and exposed bedrock outcrop (%Rock) cover were all coded on a semi-quantitative scale. Percentage surface rock fragment cover classes were scored on seven point scale; 0 % cover (0); < 2 % cover (1); 2–10%, (2); 10–20% (3); 20–50% (4); 50–90% (5); > 90% (6). Maximum rock size was classed on a six 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). Leaf litter and bare ground were visual estimates of the percentage of ground cover. Topographic position (Tp) in the landscape was coded on a five point scale which was semi-quantitative: outwash (1); lower slope (2); mid slope (3); upper slope or low ridge (4); crest (5).

For each plot a bulked soil sample was collected, this being compiled from 20 smaller samples collected regularly over the area of the plot. Soils were analysed for a suite of 12 elements at the Chemistry Centre of Western Australia, using inductively coupled plasma atomic emission spectrometry (ICP AES). This involved the simultaneous determination of a suite of elements (P, K, S, Ca, Mg, Na, B, Co, Cu, Fe, Mg and Zn) using the Mehlich No. 3 soil test procedure (Melich 1984, Walton and Allen 2004). Soil pH was determined in an aqueous 0.01M $CaCl_2$ solution, and effective cation exchange capacity (eCEC) was calculated from the summation of exchangeable bases (Ca, Mg, Na and K) after their conversion from concentrations to charge equivalents by dividing by 200.4, 121.6, 230, and 390 respectively (Rayment & Higginson 1992, Soil and Plant Council, 1999, D. Allen, pers. comm.[1]). Estimates of climatic variables (mean annual temperature (Tann), mean annual rainfall (Rann) and rainfall coefficient of variation (Rcv) were obtained from BIOCLIM (Busby 1986).

Pattern analysis was conducted on a presence / absence data matrix of 89 perennial taxa, the singleton and annual taxa having being omitted from the data matrix prior to analysis. Singletons (taxa that appeared in a single plot) were omitted as preliminary analyses found that these contained little information. Annuals (including facultative, short term perennials) were excluded as their distribution and abundance are a function of the previous season's rainfall, and are expected to exhibit high inter-annual variation (Beard 1990; Mott 1972, 1973). The omission of annuals and singletons allows for these results to be comparable with other data collected from other seasons and years, and is consistent with previous surveys on other greenstone and BIF communities (Gibson 2004; Gibson & Lyons 1998, 2001). Resemblance matrices, using the Bray-Curtis measure of association, were compared using the 2 Stage algorithm in Primer (Clark & Gorley 2006) to confirm that there was little information being lost from the dataset by the omission of these taxa.

Pattern analysis was conducted using PATN (V3.03) (Belbin 1989). The Bray-Curtis coefficient was used for the association matrix for sites and species classification and the semi-strong hybrid (SSH) multidimensional scaling for ordination of sites (Belbin 1991). Agglomerative, hierarchical clustering was used to generate a species and site classification, using flexible UPGMA ($\hat{a}$ = -0.1) (Sneath & Sokal 1973). A sorted two-way table was generated that was ordered by these site and species classifications. The number of site and species groups were arbitarily decided at the six and eight group levels respectively, with subgroups described within two of the site groups. These decisions were based on field observations and structure observed within the sorted two way table. Three dimensional semi-strong hybrid (SSH) multidimensional scaling was implemented for the ordination of the presence / absence quadrat data, using 1000 random starts and 50 iterations.

Principal Component Correlation (PCC) runs multiple linear regression of extrinsic variables on the three dimensional ordination (Belbin 1989). The environmental variables were not standardized or transformed before PCC analysis as the Monte-Carlo procedure (MCAO) was employed in PATN as a bootstrap analysis to evaluate the significance of these correlation coefficients. This was done by implementing PCC on the same ordination using a simulated dataset of randomized values for each environmental variable (Belbin 1989). The Kruskal-Wallis non-parametric analysis of variance was used to determine differences in environmental parameters among floristic community groups, followed by Dunn's posthoc multiple comparisons test when required to identify dissimilar groups (Zar 1984). Indicator species analysis was calculated using PC-Ord (McCune and Mefford 1999), using the methods of Dufrêne and Legendre (1997). Indicators values (INDVAL) were used to determine the significant indicator species for each floristic community type at the eight group level, the statistical significance each indicator species values being determined using 1000 replicates of a MCAO site randomization procedure. Indicator species are defined as the most characteristic species of each floristic community type, and the INDVAL measures for each species at a particular level in the classification is calculated from its specificity and fidelity to a community type (Dufrêne & Legendre 1997).

RESULTS

Flora

At total of 244 taxa (species, subspecies, varieties and hybrids) from 50 families of vascular plants were record within or adjacent to the 52 quadrats. Fifteen of these taxa were undescribed or informally named entities, four were novel entities with affinities to known species, five taxa were postulated to be hybrids and 10 species were introduced (Appendix 1). Introduced species consisted of annual grasses and weedy herbs; the most common introduced species being the annual grass, *Rostraria pumila*, which was present in 19% of quadrats. At the time of the survey, good rainfalls had promoted the excellent growth of annuals, which accounted for 52% of recorded taxa. The best represented families in this survey are the Asteraceae (44 native and 2 introduced taxa), Poaceae (19 native, 2 introduced and one putative hybrid), Mimosaceae (13 taxa), Chenopodiaceae (10 taxa and one putative hybrid), Myoporaceae (12 taxa), Amaranthaceae (11 taxa) and Goodeniaceae (10 taxa). The five main genera are *Acacia* (13 taxa), *Eremophila* (12 taxa), *Ptilotus* (10 taxa), *Rhodanthe* (8 taxa) and Senna (7 taxa). These common families and genera are typical of the floras of the Austin Botanical District of the Eremaean province (Beard 1976, 1990).

Priority taxa

Eight taxa of conservation significance were collected in

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this survey (Table 1), all of which were found on rocky substrates associated with the uplands of the Weld Range greenstone belt. Six of these priority taxa had not been previously collected from or near the Weld Range, and therefore represent new populations. The collection of *Stenanthemum patens* was a significant range extension for the species, which was previously known from two other BIF and greenstone hills near Leonora, over 400 km southeast of the Weld Range (Rye 2001). There are four previously known locations of *Phyllanthus baeckeoides*, three being collected in the eastern Goldfields > 400 km southeast of the Weld Range and the closest previously known population located some 170 km north-west on Windimurra Station, Mt Magnet (H. Pringle 3973). The Weld Range is a new location for *Sauropus* sp. Woolgorong (M. Officer S.N. 10/8/94), which is 200 km west from the only other known population on Woolgorong Station. As with a population of *Prostanthera petrophila*, these populations on Woolgorong Station occur on the deep sands and associated scrub of Wanderrie sand country. Although *P. petrophila* is known from other rocky habitats, this is the first reported occurrence of *Sauropus* sp. Woolgorong on rocky banded iron formation and dolerite substrates.

For two other priority taxa, their collection from the Weld Range represented new populations, albeit with less extreme range extensions. *Dodonaea amplisemina* is known from banded iron formation substrates as far south as the Paynes Find region and north of Meekatharra (Shepherd et al. 2007). The nearest known location is the Cue townsite, 70 km south of the Weld Range. Similarly, *Prostanthera petrophila* has been previously collected from near the Cue town centre (E. Wittwer W 1265) but has not been previously known from the Weld Range. This species is currently known from only five locations, all restricted to a moderately small area within the Murchison and Yalgoo IBRA regions. *Acacia speckii* and *Micromyrtus placoides* are more widely distributed in the Murchison region than the previously discussed priority species, and have also been previously recorded from the Weld Range. All three of these latter species were found along the length of the Weld Range.

Prostanthera ferricola (formerly known as Prostanthera sp. Murchison (G. Byrne 239) was first collected near Meekatharra in 2003, and subsequent collections from various BIF ranges in the north Yilgarn have proved enough material to have this entity described as a new species (Conn & Shepherd 2007). *Prostanthera ferricola* has not been allied to any other taxa, but is morphologically similar to both *P. centralis* and *P. magnifica* (Section Prostanthera; Conn 1988) (Conn & Shepherd 2007). It is disjunct in its distribution from *P. magnifica*, which occurs in the Avon and Yalgoo IBRA regions immediately south west of *P. ferricola*, and *P. centralis,* which ranges from far eastern WA into the Northern Territory (Conn 1988; Western Australian Herbarium 1998 –). This entity is currently only known from six populations located within in the Gascoyne and Murchison IBRA regions. In all locations, this species was recorded as growing on rocky soils associated with BIF or quartz outcrops. This entity has been recently listed as having Priority Three conservation status (DEC conservation codes for Western Australia, Atkins (2006)), based on its limited geographical distribution and low number of known populations. Four of these six known populations occur on highly prospectable BIF ranges that are covered by mining tenements.

There are seven other priority taxa recorded for the Weld Range by the Western Australian Herbarium (1998 –) which were not located in this survey, these being *Beyeria* sp. Murchison (B. Jeanes s.n. 7/7/2005) (P2), Baeckea sp. Melita Station (H. Pringle 2738) (P3), *Grevillea inconspicua* (P4), *Grevillea stenostachya* (P3), *Grevillea pauciflora* (P3), *Ptilotus beardii* (P3) and *Calytrix verruculosa* (P1). The results from this current study bring the total number of priority taxa known to occur on the Weld Range to fifteen.

Flora of Interest

A number of entities were collected from the Weld Range which are currently undescribed and remain as taxa of interest (Appendix 1). Among these is *Acacia* sp. Weld Range (A. Markey & S. Dillon 2994) which was found to be widely distributed across the Weld Range. This taxon is poorly collected, with only nine records having been lodged in the Western Australian Herbarium at the time of this survey. Prior to this survey, there was only one collection of *Acacia* sp. Weld Range (A. Markey & S. Dillon 2994) from the Weld Range. *Acacia* sp. Weld Range (A. Markey & S. Dillon 2994) is a wide – phyllode variant allied to the *Acacia xanthocarpa* species complex (B. Maslin, pers. comm.[2]) Given that this taxon has yellow, hairy pods which are superficially similar to *Acacia citrinoviridis*, this is probably the taxon that was referred to as "*Acacia* aff. *citrinoviridis*" by Curry et al. (1994) and noted by them as the dominant taxon for both the Jack Hills and Weld Range. Recent collections confirm that *Acacia citrinoviridis s.s.* does occur on the Jack Hills (Meissner & Caruso 2008). *Acacia* sp. Weld Range (A. Markey & S. Dillon 2994) can be distinguished from this latter species, red leaf margins which become yellow with age (red margins do not develop on *A. citrinoviridis*), relatively broader phyllodes, spreading hairs on long receptacles, short peduncles, and patent and relatively sparser pod hairs (B. Maslin, pers. comm.[2]).

A taxon of *Sida* was identified which was found to have morphological affinities to the species complex, *Sida* sp. spiciform panicles (E. Leyland s.n. 14/8/90), but was sufficiently morphologically different to be considered as a distinct entity (R. Barker, pers. comm.[3]). Because there are very few collections of this entity and the taxonomy of *Sida* is still under review, the taxonomic status of this entity is currently unknown.

[2] Bruce Maslin, Senior Research Scientist, Western Australian Department of Conservation and Environment, Western Australian Herbarium, Kensington

[3] Robyn Barker, Research Associate, South Australian Department of Environment and Heritage, State Herbarium of South Australia, Kent Town

Cynoglossum sp. Inland Ranges (C.A. Gardner 14499) is a new entity that is a Western Australian variant of *Cynoglossum australe*. Among distinctive characters are its' large white flowers and having the corolla tube exceeding the calyx. This entity is restricted to inland ranges in Western Australia (G. Keighery, pers. comm. [4]), where it appears to be widely distributed.

Hybrids and Intergrades

Five hybrid entities were encountered on the Weld Range. Intergrades of *Maireana planifolia* x *villosa,* with intermediate characters are known from over the range of the parental species. Wilson (1984; P. Wilson, pers. comm. [5]) acknowledges that these species are variable and that this intermediate may represent a distinct taxon. Less frequently encountered was the putative hybrid, *Eriachne mucronata* x *helmsii*. *Eriachne mucronata* and *Eriachne helmsii* are very similar in morphology, are closely related and putative hybrids have been previously reported (Lazarides 1995). An intergrade was found with floral characters (namely the lemma indumentum) which were intermediate between the two taxa. Whilst *Eriachne mucronata* x *helmsii* has been reported from other states (Lazarides 1995), only a single collection has been lodged in the Western Australian Herbarium. This material was collected from Black Range Station (D.J. Edinger and G. Marsh DJE 4012), c. 180 km SE from the Weld Range, and its' identity confirmed by M. Lazarides.

Hybridization has been well documented among taxa within *Senna* (Randall & Barlow 1998), so it is not unexpected that this survey has identified two additional putative hybrid combinations new to the collections at the Western Australian Herbarium. *Senna glaucifolia* x sp. Meekatharra (A. Markey & S. Dillon 3149) was identified by its intermediate morphology between the assumed parental taxa, and this was verified by M. Trudgen. A second putative hybrid, *Senna stricta x artemisioides* subsp. *petiolaris* (E.N.S. Jackson 2888), was collected from both the Weld Range and Jack Hills (Meissner & Caruso 2008). These collections were matched to material previously determined as *Senna stricta* (E.N.S. Jackson 2888) and which had been subsequently cited in the treatment of the genus as examples of this taxon (Randall & Barlow 1998). However, closer examination of this particular voucher found inconsistencies with the published species description (Randall & Barlow 1998) and herbarium material previously confirmed to be *Senna stricta* and *Senna artemisioides* subsp. *petiolaris.* Instead, this distinct entity possessed characters that were intermediate between *Senna artemisioides* subsp. *petiolaris* and *Senna stricta*, namely that the petals were < 10 mm long and sparsely hirsute on outer surface, the petiole was subterete, the leaflets were not ventrally but laterally compressed and the extrafloral nectaries were raised. It was concluded that this was a putative new hybrid combination and distinct morphological entity within an exceedingly complex genus.

Range extensions

There are several notable range extensions for common taxa. The collections of *Crassula extrosa* and *Crassula tetramera* were extensions of 190 km north and c. 700 km east from their respective known ranges. However, range extensions of species of *Crassula* are more likely to be due to poor collection than actual scarcity in the Murchison region. Additionally, a variant of *Crassula tetramera* was collected from the Weld Range. This variant (*Crassula* aff. *tetramera*) differed from the former taxon by pentamerous floral parts, although *Crassula tetramera* itself is poorly collected for the State (with only ten collections currently lodged in the Western Australian Herbarium) and therefore it is difficult to gauge how unusual this aberrant form is.

The collection of *Stenanthemum petraeum* is a new record for this species on the Weld Range and represents a minor range extension of 120–160 km west of two known populations at Yoothapina Station (R.J. Cranfield 5678) and Youno Downs (A. Thompson 3703). This species is otherwise known from rocky substrates in central and northern Western Australia. The Weld Range population of the sheoak, *Allocasuarina acutivalvis* subsp. *acutivalvis* is a 200 km range extension north of its main distribution along the margins of the South West Botanical Province. This species was located as two small patches on the Weld Range. Only two male plants were observed at one site approximately 4 km east of 'The Gap' (Figure 1), and a small thicket was sampled on the eastern extent of the study area. In both instances, these tall shrubs were growing on the rocky, moderately steep mid-upper slopes of banded iron formation.

The apparent range extensions of species of *Cheilanthes* into the Murchison region may be artifacts of poor collection and misidentification rather than genuine increments in their known distribution. The collection of *Cheilanthes adiantoides* and *Cheilanthes distans* represent 200 km northern range extensions. In the case of the former species, the last recorded collection was from Burnerbinmah Station (Paynes Find), which was itself a new record outside the typical range for this species (Patrick 2002). However, *Cheilanthes adiantoides* was commonly encountered in this survey and it is suspected that either this species has been overlooked for collection or that previous collections in the Murchison region have been misidentified. Similarly, past collections of *Cheilanthes brownii* suggest that this species is more typical of the Kimberley and Pilbara regions that the Murchison. However, recent surveys of the Jack Hills, Weld Range and ranges south of Yalgoo have found this species to be also widespread in the Midwest region of Western Australia. Similarly, the poorly collected *Cheilanthes sieberi* subsp. *pseudovillea* is known only from northern sites, and,

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[5] Paul Wilson, Honorary Research Associate, Western Australian Department of Environment and Conservation, Western Australian Herbarium, Kensington

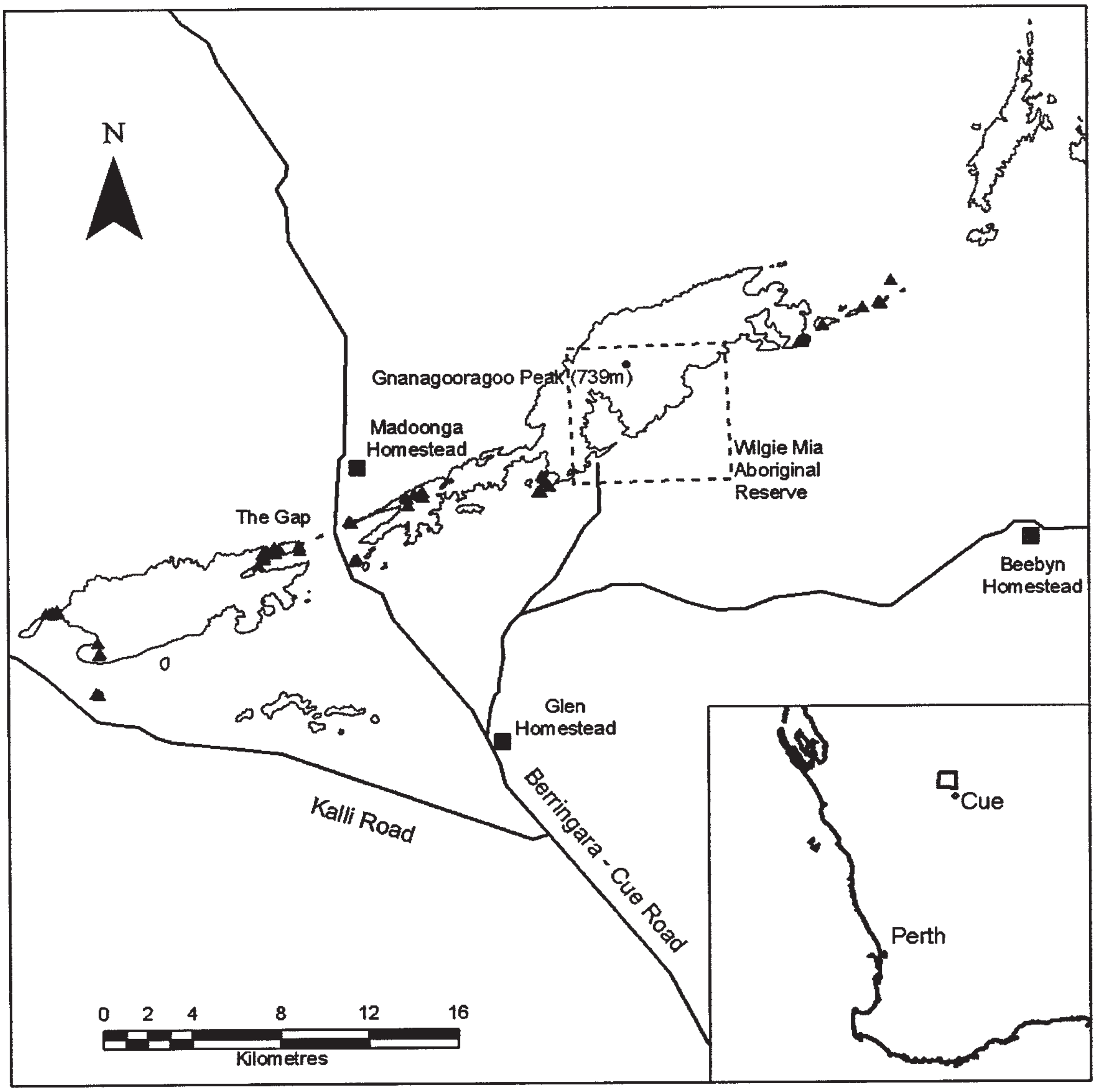

Figure 1. Map showing the location of the Weld Range relative to other landmarks, and distribution of vegetation quadrats established during the floristic survey.

if the identity of the Weld Range collection is confirmed as this taxon, this would represent a southern range extension in excess of 400 km.

Because it was not flowering the time of the survey, the *Triodia* collected in this survey could only be tentatively named as *Triodia* cf. *melvillii*, and this determination was based on the characteristically resinous leaves (Lazarides 1997, Lazarides et al. 2005). Should this population's identity be confirmed, the occurrence of *T.* cf. *melvillei* is an interesting range extension south for this taxon, being over 100 km from previous known collection location of 20 miles east of Meekatharra (S.J.J. Davies s.n.) and 100 km south of a new record for its occurrence on the Jack Hills. However, Speck (1963) reported scattered patches of *Triodia melvillei* among a ground layer of *Austrodanthonia* and *Eragrostis* under *Acacia ramulosa* var *linophylla* on sandplains north of the Weld Range. Curry et al. (1994) did not list this species in their inventory of the region. Whilst this species has been collected growing on massive BIF in the Pilbara (e.g. Karijini, S. van Leeuwen 3817), these are the southern-most records for this species on massive ironstone. A few individual plants of this species were found growing on rocky, sparsely vegetated slopes of hematite hills in the far south-eastern extent of the Weld Range. It is interesting to note that at the Jack Hills, this species forms a dominant stratum in a rare and restricted *Triodia* community which grows in a similar situation (Meissner & Caruso 2008). A *Triodia* community may also exist on the slopes of the Weld Range, but could not be confirmed in this survey due to the inaccessibility of the terrain. More extensive surveys would be required to ascertain if a *Triodia* community occurs on the Weld Range.

Floristic Communities

Only collections which were identifiable to at least species level were used in the analysis, which amounted to a total of 228 taxa. Seven taxa were amalgamated for the pattern analysis, namely those which were species complexes, (e.g. *Sida* sp. dark green fruits (S. van Leeuwen 2260) and *Sida* aff. sp. dark green fruits (S. van Leeuwen 2260)), closely related taxa which could not be resolved due to intergrades or an absence of flowering material (e.g. *Eriachne helmsii* and *E. mucronata*). The exception to amalgamating intergrades and hybrids were those of *Maireana planifolia* x *villosa* and *Senna* spp., as these are distinctive entities. The mulga complex, (*Acacia aneura* and related species), was resolved to four morphotypes which approximated the varieties described by Pedley (2001). This approach was the best means to recognize taxa within an exceedingly difficult species complex that is currently being revised (Miller et al. 2002).

Of these 228 taxa, 118 taxa were annuals and 21 taxa were perennial singletons. A comparison of the full dataset and the perennial dataset without singletons found a 76 % correlation between similarity matrices. For the 52 quadrats, the average species richness per quadrat was 37.3 ± 8.8, ranging from 18 to 56 taxa per quadrat. The floristic classification of the 52 sites using the perennial dataset resulted in recognition of eight community types and subtypes, which is illustrated in Figure 2. This summary dendrogram shows that the first major division separated Community type 6 from the other sites. This division is also discernable on the two-way table sorted by site and species classification (Appendix 2). This main division distinguished between sites on dolerite - influenced substrates from those on ironstone. Below this primary level of divergence, five floristic communities were identified for the crests, slopes and foothills on the BIF of the Weld Range. Two of these communities (1 and 5) were further resolved into subtypes. Indicator species analysis was used to resolve characteristic taxa for each community type or, occasionally, two community types (ie: *Eremophila latrobei* subsp *latrobei*, *Senna glaucifolia* and *Dodonaea pachyneura*) (Table 2).

Community type 1 is a moderately species rich group and had high representation of taxa from Species group F, and few or no species from Species groups B, G, H and I. The subdivision of this community is based largely on E and F Species groups, with community type 1b being more speciose. This subdivision also corresponds to a topographical separation. **Community type 1a** is typically dominated by *Acacia aneura*, *A. ramulosa* var *linophylla*, and / or *Acacia* sp. Weld Range (A. Markey & S. Dillon 2994) over a sparse shrub cover of *Eremophila* spp. Structurally, it consists of open shrublands on hillslopes with moderately inclined gradients, very rocky terrain and outcroping of BIF. This vegetation type occurred across the topographical profile of the range, from the lower slopes to hill tops, but was located mostly on the mid – upper slopes. The average species richness for this community type (32.7 ± 1.0 taxa per quadrat) is within the middle range for all community types, and it is only moderately rich in annuals (19.3 ± taxa per quadrat) (Table 3). Significant indicator species include *Eremophila glutinosa*, *Eremophila latrobei* subsp. *latrobei* (which is also an indicator species for Community type 1b) and

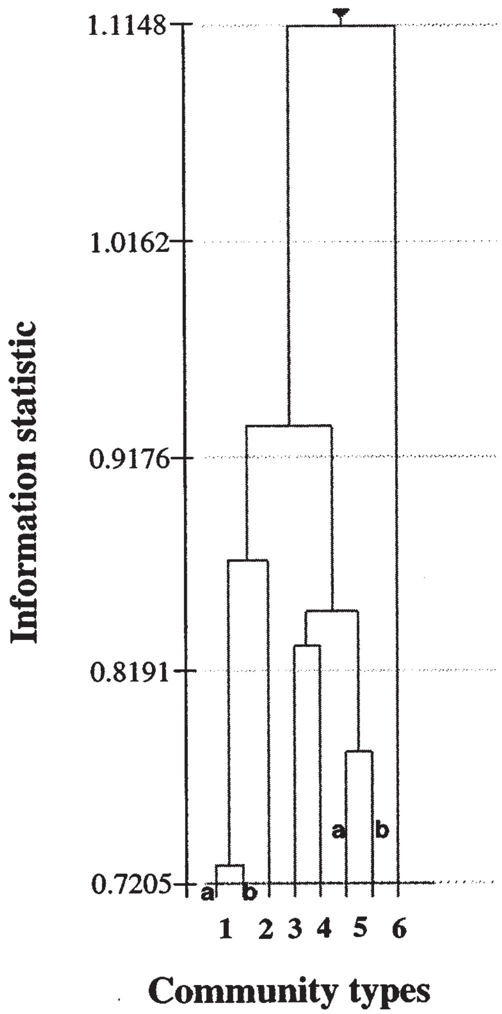

Figure 2. Summary dendrogram of the floristic community types on the Weld Ranges resolved from a data matrix of 89 taxa from 52 quadrats. Dendrogram resolved to the six group level, with subtypes resolved in floristic community types 1 and 5

Santalum spicatum (a species with few occurrences but with most of these within Community type 1a) (Table 2). The average species richness for this community is lower than for community type 1b (32.7 ± 1.0 vs 39.2 ± 5.9 taxa per quadrat) (Table 3).

Community type 1b typically consists of open shrublands and sparse shrublands of *Acacia aneura* (cf. var. *microphylla, aneura* and *argentea*), *Acacia* sp. Weld Range (A. Markey & S. Dillon 2994), and *Grevillea berryana* over a shrub layer of various species of *Eremophila* (*E. georgei*, *E. latrobei* subsp. *latrobei* and *E. glutinosa*) (Appendix 2). This community occurs mostly on rocky, gentle - moderate inclines, on higher slopes than type 1a. This community is the most commonly sampled, with 14 of the 52 sites falling within this category. *Eremophila latrobei* subsp. *latrobei* and *Thryptomene decussata* are the only two significant indicator species (Table 2). However, *Ptilotus schwartzii*, *Ptilotus obovatus*, *Grevillea berryana*, *Eremophila georgei* and *Thysanotus manglesianus* are also notable species within this community subtype (Appendix 2). The characteristic of rocky ironstone species, *Prostanthera petrophila* and *Cheilanthes sieberi* subsp. *sieberi* are found to be both almost exclusive to Community type 1 (1a and 1b).

Community type 2 consists of sparse – open shrublands of *Acacia aneura* cf. var. *microcarpa* and / or *A. aneura* cf. var. *aneura* over the mid-stratum shrub layer which includes species such as *Thryptomene decussata*, *Philotheca brucei* subsp *brucei* and numerous species of *Eremophila* (Appendix 2). This community is associated with massive outcrops and rocklands of BIF on moderate - steep hillslopes. Notable indicator species are *Cheilanthes adiantoides*, *Philotheca brucei* subsp. *brucei*, *Micromyrtus sulphurea*, *Dodonaea pachyneura* (also shared with Community type 4) and *Stylidium longibracteatum* (Table 2). These species typically grow in crevices and fissures formed in exposed outcrops of bedrock. Other common species were *Ptilotus obovatus* subsp. *obovatus* and *Harniera kempeana* subsp. *muelleri* (Appendix 2). This was a relatively species rich community, averaging 43.9 ± 6.4 taxa per quadrat. It was also rich in annuals, with a mean of 25.4 ± 7.2 annual taxa per quadrat. There was representation from Species groups D, part of Group E and some representation from the uncommon Species groups A, B and G (Appendix 2). This community type had species from Species group E in common with Community type 1b, which can be attributed to both community types occupying similar topographical locations.

Community type 3 is only represented by two sites, and is closest to community type 4, from which it is distinguished by a paucity of taxa from across all Species groups (Appendix 2). This community type is relatively species poor, with an average of 20.5 ± 3.5 taxa per quadrat and an average of 15 ± 2.8 annual taxa per quadrat (Table 3). This compares with the average species richness for Community type 4 at 32.7 ± 7.2 taxa per quadrat. More sampling will verify if this community is a subset of community type 4 or a distinctive community of the lower hillslopes. These species - depauperate shrublands are located on middle- and lower hillslopes on a moderate gradient (12°), with no outcropping BIF but an abundance of loose ironstone gravels and scree. The two sites sampled were both an open shrubland of *Acacia aneura* over isolated shrub species such as *Solanum ashbyae* and *Tribulus suberosus*. Only *Cheilanthes* cf. *sieberi* subsp. *pseudovillea* is identified as a significant indicator species of this community. However, the analysis was limited by the small sample size.

Community type 4 consists of open shrublands of *Acacia aneura* and emergent trees of *Acacia pruinocarpa* over shrublands of *Philotheca brucei* subsp. *brucei* and *Eremophila* spp. Only three sites are classified as this community type. The community is most similar to floristic community type 3, but is more species-rich and located further upslope on steep, rocky hillslopes with relatively high levels of exposed bedrock. The best indicator species include *Abutilon oxycarpum*, *Dodonaea pachyneura* and *Enneapogon caerulescens*, which are characteristic species of fractured rocky substrates.

Community type 5 has taxa from across most species groups (Appendix 2), and typically consists of open tall *Acacia* shrublands (*Acacia pruinocarpa*, *Acacia aneura* var. *tenuis* and *Acacia ramulosa* var. *linophylla*) mostly on lower slopes and outwashes of ironstone colluvium. This community appears to be distinguished from the other BIF communities by a more limited representation from Species Groups E and F, and some shared floristic affinities to Community type 6 (Species groups G, H and I). The split between Community type 5a and type 5b was marked by good representation in Species group C and an absence of taxa from Species groups G, H , I and a subset of species from Group F for the former subgroup. Community type 5a also has a relatively low species richness, averaging 28.0 ± 5.2 taxa per quadrat and a correspondingly low cover of annuals (Table 3). This compares with Community type 5b which, at an average of 36.2 + 3.4 taxa per quadrat, is more diverse.

Community type 5a consists of isolated, emergent trees of *Acacia pruinocarpa* above *Acacia aneura* / *Acacia ramulosa* var *linophylla* over an open mid-stratum of shrubs. This community is found on the gentle – moderately inclined lower hillslopes and outwash plains, with some low outcroppings of banded iron formation on the footslopes. Occasionally this unit is repeated on middle- and upper slopes. There are no significant indicator species unique to this community type, although *Acacia aneura* cf. var. *tenuis* has a moderate indicator value and was frequent within this community type (Table 2, Appendix 2). A trio of species from group F, namely *Acacia aneura* cf. var. *argentea*, *Sida* sp. Golden calyces glabrous fruit (H.N. Foote 32) and *Acacia pruinocarpa,* distinguish this community type from Community type 5b (Appendix 2).

Community type 5b is typically a sparse open *Acacia* shrubland (*A. aneura* cf. var. *tenuis*, *A. aneura* cf. var. *aneura* and / or Acacia *coolgardiensis* subsp. *effusa*) over sparse layer of shrubs of *Senna* spp. and *Tribulus suberosus*. The best indicator species include *A. aneura* cf. var. *tenuis*, *Senna glaucifolia* and *Hibiscus sturtii* (Table 3). Some species (groups G and H) are shared with Community type 6, in particular the species *Enneapogon caerulescens, Tribulus suberosus, Senna glaucifolia* and *Sida* sp. dark green fruits (S. van Leeuwen 2260). There was one uncharacteristic mid-slope site in this floristic community, which may have been due to this one steep, rocky slope spanning the steep transition from an upper slope Community type 1b to type 5b.

Community type 6 is a distinctive floristic community which separated from the other community types at the highest level in the dendrogram (Figure 2). It is also the community type which is solely associated with dolerite substrates. One site was located on a hillcrest of exposed volcanic rocks, whilst most other sites were located on mid –lower slopes, footslopes and a colluvial fan. Community type 6 consists of sparse – open shrubland of *Acacia* sp. Weld Range (A. Markey & S. Dillon 2994), *Acacia aneura* and *Acacia speckii* over sparse mid-stratum of *Eremophila macmillaniana*, *Eremophila mackinlayi* subsp. *spathulata* and *Senna* spp. Significant indicator species include *Senna glaucifolia*, *Sida* sp. dark green fruits

(S. van Leeuwen 2260), *Maireana georgei*, *Eremophila mackinlayi* subsp. *spathulata* and *Heliotropium ovalifolium* (Table 3). Species groups H and I are strongly associated with this community type (Appendix 2), and these species groups not only include significant indicator species (Table 2), but also other species of *Senna* and *Eremophila macmillaniana*. At an average of 49.8 ± 3.7 taxa per quadrat (Table 3), the species richness of Community type 6 was considerably higher than most other community types; with the exception of Community type 2.

Other communities not in classification

There were species-poor shrublands that were not fully sampled in this survey as the classification analyses are affected by the low number of taxa shared with other sites. These shrublands were typically dominated by only one or two species of myrtaceous shrubs such as *Homalocalyx echinulatus*, *Micromyrtus placoides* and *Aluta aspera* subsp. *hesperia*. These patches of shrubland are considered to be a relatively depauperate subset of the adjacent vegetation and part of a structural mosaic of vegetation on the lower slopes of these ironstone ranges, and a repository of uncommon shrubs which can be of conservation significance (e.g. *Micromyrtus placoides*).

Environmental Correlates

Owing to the small sample sizes of Community types 3 and 4, these were omitted from univariate analyses. Comparisons of environmental parameters are therefore conducted between the remaining six community types (Table 3). The elements cadmium, molybdenum and boron were omitted from analysis owing to levels being below the limit of instrument detection in over half of the soil samples. The remaining soil elemental concentrations, soil pH and effective cation exchange capacity (eCEC) were compared for intercorrelation using the Spearman rank correlation coefficient, the results of which are presented in Table 4. Most soil parameters are intercorrelated, except for potassium, sodium and lead (Table 4). The highest intercorrelations are among calcium, magnesium and eCEC, and only iron and phosphorus are correlated with the majority of site physical parameters (Table 4). Otherwise, only slope is positively correlated with soil chemistry, and it is inferred that sites of lower gradient are mineral enriched as they receive colluvium and leachates, whilst soils developing on steep terrain are relatively depauperate and leached (Litchfield 1963, Cole 1973, Gibson & Lyons 1998, Gray & Murphy 2002).

Univariate Analyses

Descriptions of the community types clearly suggest that topography (slope, altitude) and substrate are major correlates with community type. Of the physical site parameters, there were significant differences among groups for slope, topographical position, max size of surface rock, % cover category of exposed bedrock and altitude (Table 3). Rock fragment size was not significantly different among the community types, and this is not surprising as much of the surrounding slopes and outwash plains around the ranges were covered in rock fragments. Therefore, maximum surface rock size and percentage bedrock cover class were more meaningful measures of the terrain.

Community type 2 had, on average, steeper slopes, whilst the least inclined slopes were found in Community types 5a and 6. Community types 5b and 6 also occupied the lowest positions in the topographical profile and, consequently, the lowest altitudes. Community types 1a, 1b, 2 and 4 occupied the highest altitudes and topographical positions, steeper slopes, and highest amount of exposed bedrock cover. Among these four communities, Community type 2 had the highest values. Community types 3, 5a, 5b and 6 occurred at the lowest altitudes (on average) and Community types 3 and 6 with the lowest amount of exposed bedrock, whilst Community types 1b and 2 had the highest cover of exposed rock. It is important to note that there can be minor discrepancies between 'altitude' and 'topographic postion', since low crests and outcroppings were still scored as high points in the local landscape, although these were at lower altitudes than hill tops and ridges. This accounts for relatively high scores for topographical profile but low absolute altitudes in some community types (e.g. Community type 5a).

Non parametric analysis of variance found significant differences in all soil parameters except sodium among the remaining community types (Table 3). Whilst all soils were, on average, below neutral pH, Community types 1a and 1b had the most acidic soils (pH < 4.5), whilst the dolerite-associated Community type 6 was the least acidic. Although not compared statistically, community type 3 had acidic soils on a par with 1a and 1b. The average eCEC was higher in soils from community types 6. Community type 6 was also relatively rich in the minerals, calcium, cobalt, manganese, nickel, and had the lowest levels of lead, sulfur and iron (Table 3). To a lesser extent, soils from Community type 4 were also relatively rich in minerals and had a high eCEC although this community type was under-sampled and could not be compared statistically to the other communities.

SSH MDS Ordination

Relationships among the floristic community types are represented in a three dimensional ordination using SSH multidimensional scaling of the floristic data with a stress level of 0.21 (Figure 3 a and b). Among the community types, Community type 6 is the most clearly segregated. From principal axis correlation, it is evident that there are distinct environmental gradients associated with the site ordination. Vectors of environmental variables with a well supported correlation (from MCAO) are superimposed on the ordination (Figure 3). There are two major trends across the ordination; one that is associated with a soil nutrient gradient, and a second trend associated with site physical parameters (topography and substrate). As indicated by their co-linearity, groups of soil variables are highly correlated (Figure 2, Table 4). One intercorrelated set (eCEC, pH, Ca, Mg, Mn, Co and Ni) aligns with

Community type 6 on the ordination. This reiterates the previous findings from the univariate analysis that this Community type is associated with soils that are the least acidic, richer in exchangeable cations and the heavy metals Ni and Co, and are lowest in S. These were the soils mostly derived from weathered dolerites. Community type 5b is, to a lesser degree, also aligned along the high end of this gradient and is associated with relatively higher levels of Cu and K. This is probably associated with the lower-slope soils receiving leachates and colluvium from both BIF and dolerite sources (*cf.* Gray & Murphy 2002). Community type 2 and to a lesser extent, Community type 4 are aligned with relatively high Fe, Na, K, Zn and P levels, which suggests that the soils associated with these communities are being influenced by BIF parent rock. Sites classified as Community types 1a and 5a, and to a lesser extent community type 1b, all align at the lower extremes of these nutrient gradients (Figure 3). There were varying degrees of correlation between soil nutrients and site physical parameters, with Fe and P being the most co-linear with slope and altitude.

There was a strong gradient of correlated site physical variables (slope, topographic position, altitude, exposed bedrock cover and maximum size of surface rocks) (Figure 3). Community types 1b and 2 aligned with the most positive extremes of this gradient, and therefore were associated with steep terrain at higher altitudes and higher positions in the topographical profile (i.e. upper hill slopes and crests). Conversely, Community types 3 and 5b were the most associated with flat, terrain at lower topographic

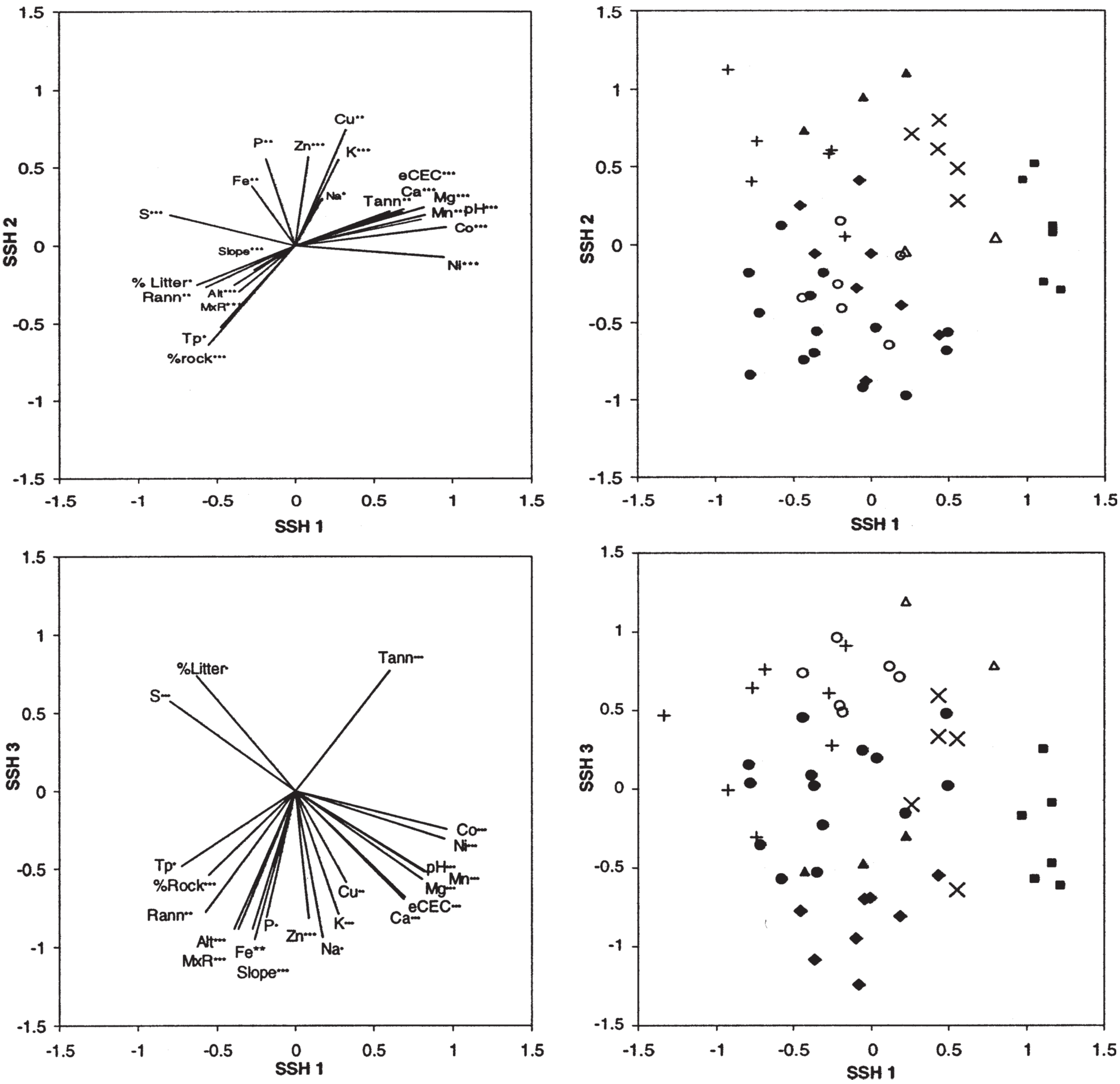

Figure 3. Ordination and vector diagrams of Weld Range floristic data, labelled by community type (1a ○,1b ●, 2 ◆ , 3 ▲, 4 Δ, 5a +, 5b ×, 6 ■). Vectors indicating best linear fit are drawn in positive direction. Only vectors with a significant correlation (from MCAO) are illustrated, with the level of significance for each parameter indicated by asterices (= $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$). See methods for environmental parameter codes. (a) Ordination axes 1 versus 2. (b) Ordination axes 1 versus 3.*

positions and lacking extensive outcropping of bedrock and large, rocky debris. A gradient of leaf litter was not correlated with other site parameters, and highest cover was aligned with Community types 1a and 5a, and lowest with Community types 6 and 5b. Although there was a climatic gradient across the ordination which was co-linear with altitude, there was no corresponding regional gradient (Figure 3). This reiterates the results from univariate analyses, where absolute differences between groups were found to be insignificant (Table 3).

DISCUSSION

Flora

Prior to this study, the flora and vegetation communities of the Weld Range had only been addressed within the context of larger regional surveys (Beard 1976; Curry et al. 1994; Speck 1963). This study addressed this dearth of information, and increased the number of taxa recorded for the Weld Range from 124 (collated from herbarium records immediately prior to this survey) to 244 taxa. Approximately 6 % of the flora has not been formally described. New records of priority taxa, undescribed entities and range extensions demonstrate the importance of the Weld Range as a habitat for uncommon and poorly known taxa, and suggest a continual need for biological survey the northern Yilgarn.

The Weld Range flora is dominated by relatively common and widespread taxa and distinguished by more geographically restricted or uncommon taxa Much of the flora is characteristic of the surrounding Yalgoo and Murchison IBRA regions of the Eremaean Province, although there is representation from taxa more characteristic of the Pilbara (e.g. *Heliotropium ovalifolium*) and a few taxa more typical of the Avon Wheatbelt, Mallee or Coolgardie IBRA regions (e.g. *Allocasuarina acutivalvis* subsp. *acutivalvis*). However, this survey did not locate taxa endemic to the Weld Range. This is not the first instance where no endemic taxa have been reported for greenstone and BIF ranges in the Western Australian goldfields; such is the case for the Jack Hills (Meissner & Caruso 2008) and Highclere Hills (Gibson & Lyons 2001). However, it did find taxa which are known from only a few, highly disjunct populations, these species are often restricted to rocky substrates, e.g. *Dodonaea amplisemina*. Future development proposals must consider that, as a large and isolated BIF landform, the Weld Range is a refuge for taxa of conservation significance.

Floristic communities

This study resolved more floristic communities on the Weld Range than had been previously described for the landform (Beard 1976; Curry et al. 1994; Speck 1963). The communities described for the Weld Range by Beard (1976), Speck (1963) and Curry et al. (1994) are only broadly comparable to those described in this survey. This is mostly due to differences in analytical methodology, nomenclature and because the previous authors described these communities for broad scale surveys.

It is possible that some floristic communities may be restricted to the Weld Range. Previous surveys (Beard 1976; Curry et al. 1994; Speck 1963), had considered the Weld Range and the nearby Jack Hills (c. 100 km north) to belong to the same geomorphological land system, and therefore share the same communities. However, other, more detailed studies on greenstone and BIF ranges in the eastern goldfields have found distinct differences in floristic communities between ranges that are only 100 km apart (Gibson & Lyons 1998). Furthermore, there are substantial differences in the geology of the two ranges, the Jack Hills possessing mainly banded iron-formation, chert, mica and quartz (Elias 1982). Therefore, it is not unreasonable to expect differences in floristic composition between the Weld Range and the Jack Hills.

Compared to the Weld Range, the vegetation of the Jack Hills is floristically depauperate and structurally sparse (Meissner & Caruso 2008). This may reflect the greater aridity of a region which is 100 km north of the Weld Range. Furthermore, the Jack Hills have a different suite of perennial taxa, and the floristic communities are different from those found on the Weld Range (Mattiske Consulting Pty Ltd 2005; Meissner & Caruso 2008). Of a combined flora of 306 native taxa, there are only 40 % of species in common (data from Meissner & Caruso (2008)). Even taxa common to both ranges were more restricted in their distribution over the topographical profile. For example, *Acacia pruinocarpa* is restricted to creeklines on the Jack Hills whilst it occurs at all elevations of the Weld Range (A. Markey, pers. obs).

Characteristic Jack Hills communities include an unusual spinifex hummock grassland community (*Triodia melvillei* and *Acacia cockertoniana*) on rocky upper slopes, *Acacia rhodophloia* woodlands and an open woodland of *Acacia aneura* and *Acacia citrinoviridis* (Mattiske Consulting Pty Ltd 2005; Meissner & Caruso 2008). Interestingly, *Acacia citrinoviridis* was not collected on the Weld by this survey, although Curry et al. (1994) noted the predominance in the hillslope shrublands of an entity they identified as *Acacia* aff. *citrinoviridis*. It is assumed that Curry et al. (1994) was referring to *Acacia* sp. Weld Range (Markey & Dillon 2995). One commonality shared between the two ranges is the predominance of *Acacia aneura* in the overstorey, although these mulga shrublands are floristically different. Another similarity is the distinctive influence of Pilbara vegetation for both sites, but this appears to be greater for the Jack Hills (Meissner & Caruso 2008), whilst the vegetation on the Weld Range contains more southern species such as *Allocasuarina acutivalis* subsp. *acutivalvis*. Both underlying geological and climatic differences between the Weld Range and adjacent Jack Hills, and differences in the biogeographical history of these two regions may also account for current floristic differences. Because of these differences in floristic composition, an effort must be made to ensure adequate and representative conservation for both of these ranges.

Despite the Weld Range being a linear landform spanning approximately half a degree of latitude and longitude, there was no geographical segregation of the floristic communities along the range. Either the length of the survey area (42 km) did not span a large enough range of climatic variation to have an effect on the vegetation, or the topography and substrate are uniform over the extent of the range. More sampling is required to address this, particularly in the far eastern extent of the range (where faulting has tipped the strike to a northern orientation), which was inaccessible at the time of this survey. This part of the Weld Range has been classified by Curry et al. (1994) as belonging to a different land system unit than the rest of the range, this being the Gabaninatha land system. Therefore, this area may harbour a different suite of floristic communities to those already described by this survey. Curry et al. (1994) mapped this land system as occurring south to Mt Magnet and supporting Stony Mulga Mixed Shrubland or Rocky Hill Mixed Shrubland with dominant species that differ from the eastern Weld Range (*Acacia aneura* and / or *Acacia quadrimarginea*). There were no instances on either the Weld Range (this study) or on the Jack Hills (Meissner & Caruso 2008) where *Acacia quadrimarginea* was recorded. Given more sampling on this far eastern extent of the Weld Range, this or a similar species may be located which corresponds to the community described by Curry et al. (1994).

The eight community types and subtypes described for the Weld Range differed in their associated edaphic and topographic parameters. The Weld Range consists of folded belts of BIF alternating with strata of dolerite, often with massive outcrops of the resistant BIF forming the hill crests and steep upper slopes whilst the middle - lower slopes and outwashes are colluvium derived from volcanic rocks (Elias 1982, Watkins et al. 1987). The primary division in the classification segregated floristic communities on dolerite from those growing on BIF. This association between floristic composition and geological substrate may, at least in part, relate to differences in soil chemistry as this reflects parent rock composition, particularly in erosional parts of the landscape where there is *in situ* soil development (Cole 1973; Britt et al. 2001; Gray & Murphy 2002). Soils derived from mafic and felsic volcanics were found to be the most mineral rich, iron deficient and least acidic (this study). Despite this, all the soils for the survey area were generally found to be of a low pH (< 6.0), although these values were within the range documented for the Weld land system (Curry et al. 1994). The range of soil pH reported here for the Weld Range is far less than has been documented for other studies on greenstone ranges, where the generation of calcretes from eroded greenstones produces basic (pH > 8.0) soils (Curry et al. 1994; Gibson & Lyons 2001; Litchfield 1963). It may be that such calcretes from eroded mafic rocks exist on the Weld Range and, consequently, these soils are likely to harbour a distinct floristic community on such basic soils (*cf.* Gibson & Lyons 2001).

Among ironstone communities, there were differences in their topographical distribution associated with slope, rock outcrop and edaphic factors and water retention in these habitats. This association has been documented in other ironstone communities in the Pilbara (van Etten and Fox 2004), the eastern goldfields (Gibson 2004; Gibson & Lyons 1998, 2001), the midwest (Meissner & Caruso 2008, Markey and Dillon 2008) and in both Brazil and Africa (Jacobi et al. 2007). Topography has some bearing on soil chemistry, although a direct relationship was not obvious in these analyses. However, soil development has been reported to be strongly correlated with altitude and topographic relief, with these factors exerting some influence on the vegetation (Cole 1973; Gibson & Lyons 1998, 2001). Considering soils overlying BIF bedrock, soils on rocky, upper slopes are skeletal or shallow, and are mineral poor except for iron and phosphorus. Conversely, soils on the colluvial outwash of greenstone ranges are deeper and tend to be mineral and nutrient enriched (Gibson & Lyons 1998, 2001; this study). These factors all appear to influence the distribution of floristic communities on the Weld Range.

Conservation

BIF ranges of the Yilgarn Craton are unique and relatively isolated environments which are at particular risk from a number of threatening processes. The Weld Range is covered by active pastoral leases and small area of Aboriginal Reserve (Wilgie Mia), and no portion of the Weld Range is within a conservation reserve. However, the vegetation of the Weld Range was found to be intact along the extent of the range, relatively free of invasive weeds and in reasonably good condition. This agrees with Curry et al. (1994), who found only 5% of the total Weld land system was in poor condition. Being of low pastoral potential, grazing pressure from livestock is minimal in the hilly terrain of the Weld and Gabanintha land systems, (Curry et al. 1994). However, feral goats are a problem in this area, and both large flocks (> 40 animals) and heavily browsed vegetation were frequently encountered over the length of the range. Despite this, it is appreciated that individual station managers have undertaken eradication programs on their leases. More effective control on a larger scale may require a regional approach coordinated between adjoining leases.

Local environmental damage from past mining activities is still evident after thirty years, and there was little evidence to suggest that these areas had been or would be rehabilitated. Such impacts include road and campsite clearings, graded drill pads and grid lines, abandoned sample bags and drill cores and even abandoned tailing dams. A new phase of mineral exploration commenced in late 2005, and it is urged that these current activities adhere to more strict guidelines for minimizing and ameliorating any impacts in an environment which is slow to recover.

Large scale, open cast mining activity poses the greatest threat to the floristic communities of the Weld Range, given they are closely associated with the physical environment along a topographic catena and may be geographically restricted to this particular landform. Complete restoration of these floristic communities within the immediate excavation area is unlikely given the magnitude of the impact that iron ore extraction will have on the underlying landform. As none of these communities are known from a conservation reserve, careful management of the communities on the Weld Range is required given that much of this range is under mining tenement and exploration activities have already commenced.

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Table 1

Taxa of conservation significance collected on the Weld Range. New records are where the species has not been previously known from the Weld Range. Disjunctions are where the Weld Range populations are discrete and over 100 km distant from the known range of the species. Widespread species are those not restricted to an area within a 100 km radius.

Family	Taxon	Conservation status	Population status	Distribution
Euphorbiaceae	*Phyllanthus baeckeoides*	P1	new record	disjunct
Euphorbiaceae	*Sauropus sp. Woolgorong*	P1	new record	disjunct
Lamiaceae	*Prostanthera petrophila*	P1	new record	widespread
Mimosaceae	*Acacia speckii*	P3	known	widespread
Myrtaceae	*Micromyrtus placoides*	P1	known	widespread
Sapindaceae	*Dodonaea amplisemina*	P1	new record	widespread
Rhamnaceae	*Stenanthemum patens*	P1	new record	disjunct
Lamiaceae	*Prostanthera ferricola*	P3	new record	widespread

Table 2

Significant indicator species and their indicator values (INDVAL %) for six floristic community types on the Weld Range, collated from indicator species analysis of quadrat floristic data at the eight group level. Only significant taxa, as determined from permutation testing, are included (level of significance, * = p < 0.05, ** = p < 0.01, *** = p < 0.001). Relatively high indicator values for each species are highlighted (Dufrêne & Legendre 1997).

Indicator Species	Community type							
	1a	1b	2	3	4	5a	5b	6
Eremophila latrobei subsp. *latrobei* ***	29	25	16	0	3	2	1	0
Eremophila glutinosa **	43	15	1	0	0	0	0	2
Monachather paradoxus *	25	6	6	6	0	14	16	0
Santalum spicatum *	33	0	8	0	0	0	0	0
Thryptomene decussata *	13	32	7	0	0	3	0	0
Cheilanthes adiantoides ***	0	2	75	0	0	0	0	0
Philotheca brucei subsp. *brucei* ***	2	7	44	0	0	1	2	0
*Micromyrtus sulphurea**	0	0	38	0	0	0	0	0
Stylidium longibracteatum *	0	0	38	0	0	0	0	0
Cheilanthes cf. *sieberi* subsp. *pseudovillea* *	0	1	0	44	0	0	0	0
Abutilon oxycarpum ***	0	0	1	0	73	0	0	2
Dodonaea pachyneura ***	0	3	41	0	41	1	0	0
Enneapogon caerulescens *	0	0	0	0	46	1	7	20
Acacia aneura cf. var. *tenuis* **	1	2	0	0	4	16	40	1
Senna glaucifolia *	1	1	0	0	4	1	38	27
Hibiscus sturtii var. *forrestii* *	0	0	1	0	0	0	34	10
Sida sp. dark green fruits ***	5	2	10	0	0	0	7	41
Acacia speckii **	0	0	6	0	0	0	0	64
Maireana georgei **	0	0	0	0	0	0	0	67
Eremophila mackinlayi subsp. *spathulata* **	0	0	0	0	0	0	0	67
Heliotropium ovalifolium **	0	0	0	0	0	0	0	67
Calytrix desolata *	0	0	0	0	0	0	0	50
Sclerolaena densiflora *	0	0	0	0	0	0	0	50
Sclerolaena eriacantha *	0	0	0	0	0	0	0	50
Senna artemisioides subsp. *helmsii* *	0	0	0	0	8	0	3	51
Dodonaea amplisemina *	0	0	3	0	0	0	0	40
Eremophila aff. *georgei* *	0	0	18	0	0	0	3	33
Number of quadrats	6	14	8	2	3	8	5	6

Table 3

Summary statistics (average ± s.e.) of environmental parameters for the upland floristic community types for the Weld Range. Differences between average rank of community types 1a, 1b, 2, 5a, 5b and 6 were tested using Kruskal-Wallis non-parametric analysis of variance (NS denotes $p > 0.05$, * indicates $p < 0.05$, ** indicates $p < 0.01$, *** indicates $p < 0.001$), followed by Dunn's multiple comparison test (LSD, $p < 0.05$) when significant differences where detected from Kruskal Wallis AOV. Despite significant results for AOV, posthoc tests were insignificant for K, Pb and altitude. Units for parameters; eCEC = cmol(+)/kg, minerals = mg/kg, annual temperature (Tann) = ° C and annual rainfall (Rann) = mm. Abbreviations: Rock Frag = surface rock fragment cover, Rock Max Size = maximum surface rock size category.

	Community type							
Variable	**1a**	**1b**	**2**	**3**	**4**	**5a**	**5b**	**6**
Soil parameters								
eCEC ***	1.01 ± 0.06 ^{ab}	1.18 ± 0.11 ^{ab}	1.88 ± 0.18 ^{bc}	0.85 ± 0.20	2.75 ± 0.45	0.77 ± 0.11 ^{a}	1.68 ± 0.38 ^{abc}	3.40 ± 0.33 ^{c}
pH ***	4.22 ± 0.02 ^{a}	4.32 ± 0.05 ^{a}	4.64 ± 0.12 ^{ab}	4.15 ± 0.05	4.63 ± 0.20	4.26 ± 0.10 ^{a}	4.66 ± 0.12 ^{ab}	5.67 ± 0.09 ^{b}
Ca ***	105.5 ± 10.2 ^{ab}	128.1 ± 13.5 ^{ab}	203.8 ± 21.5 ^{bc}	63.0 ± 14.0	306.7 ± 35.3	78.9 ± 13.6 ^{a}	180.2 ± 43.6 ^{abc}	398.3 ± 53.2 ^{c}
Co ***	0.09 ± 0.04 ^{ab}	0.10 ± 0.02 ^{ab}	0.46 ± 0.16 ^{abc}	0.17 ± 0.11	0.76 ± 0.57	0.07 ± 0.02 ^{a}	0.76 ± 0.22 ^{bc}	3.24 ± 0.45 ^{c}
Cu **	0.60 ± 0.04 ^{a}	0.66 ± 0.02 ^{a}	0.79 ± 0.08 ^{ab}	0.60 ± 0.10	3.60 ± 2.70	0.61 ± 0.05 ^{a}	0.78 ± 0.17 ^{ab}	1.40 ± 0.19 ^{b}
Fe *	42.7 ± 3.7 ^{ab}	68.4 ± 18.5 ^{ab}	102.9 ± 24.6 ^{b}	31.0 ± 5.0	144.3 ± 65.0	36.8 ± 7.0 ^{a}	69.0 ± 40.3 ^{ab}	39.8 ± 2.0 ^{ab}
K *	100.0 ± 3.4	105.5 ± 8.7	124.9 ± 15.7	120.0 ± 20.0	193.3 ± 43.3	79.1 ± 8.1	142.2 ± 40.3	117.0 ± 7.8
Mg ***	25.2 ± 1.8 ^{ab}	30.6 ± 3.1 ^{ab}	62.0 ± 5.3 ^{bc}	23.5 ± 7.5	82.0 ± 19.2	18.8 ± 2.4 ^{a}	48.4 ± 7.9 ^{abc}	131.7 ± 19.2 ^{c}
Mn ***	19.7 ± 2.5 ^{a}	23.6 ± 2.8 ^{a}	40.0 ± 10.7 ^{ab}	20.0 ± 6.0	75.7 ± 28.0	14.1 ± 4.1 ^{a}	46.2 ± 10.9 ^{ab}	113.2 ± 10.1 ^{b}
Na ^{NS}	4.3 ± 1.3	4.3 ± 0.7	8.5 ± 2.4	7.0 ± 3.0	10.3 ± 7.0	4.6 ± 2.4	3.4 ± 1.4	7.8 ± 3.3
Ni ***	0.11 ± 0.02 ^{ab}	0.15 ± 0.04 ^{ab}	0.21 ± 0.01 ^{abc}	0.15 ± 0.05	0.20 ± 0.06	0.08 ± 0.01 ^{a}	0.24 ± 0.04 ^{bc}	1.08 ± 0.27 ^{c}
P **	11.3 ± 3.1 ^{ab}	26.1 ± 10.4 ^{b}	47.1 ± 14.7 ^{b}	7.5 ± 2.5	103.0 ± 59.9	9.0 ± 2.9 ^{ab}	46.2 ± 41.0 ^{ab}	4.8 ± 0.95 ^{a}
Pb *	0.48 ± 0.02	0.45 ± 0.03	0.32 ± 0.03	0.35 ± 0.05	1.33 ± 1.08	0.48 ± 0.03	2.04 ± 1.64	0.43 ± 0.02
S ***	9.2 ± 0.6 ^{bc}	7.6 ± 0.2 ^{bc}	6.1 ± 0.4 ^{ab}	10.0 ± 1.0	8.7 ± 3.2	9.6 ± 0.5 ^{c}	6.4 ± 0.5 ^{abc}	2.5 ± 0.2 ^{a}
Zn *	1.37 ± 0.37 ^{a}	1.68 ± 0.18 ^{ab}	2.95 ± 0.38 ^{b}	0.95 ± 0.25	5.67 ± 1.16	1.34 ± 0.29 ^{a}	3.50 ± 1.69 ^{ab}	1.90 ± 0.16 ^{ab}
Ca:Mg ^{NS}	4.2	4.3	3.3	2.8	4.0	4.1	3.6	3.3
Climate estimates								
Tann ^{NS}	21.4 ± 0.0	21.3 ±0.01	21.3 ±0.01	21.6 ±0.0	21.4 ±0.1	21.4 ±0.1	21.5 ±0.1	21.5 ±0.1
Rann ^{NS}	211.0 ± 0.5	212.7 ±1.0	213.0 ±0.9	208.5 ±1.5	211.7 ±1.4	210.8 ±1.1	210.4 ±1.9	209.8 ±1.1
Rcv ^{NS}	52.3 ± 0.1	52.0 ±0.2	52.0 ±0.1	52.6 ±0.0	52.1 ±0.2	52.3 ±0.1	52.0 ±0.2	52.4 ±0.2
Physical Site Parameters								
Slope ***	11.5± 0.7 ^{abc}	14.4± 1.8 ^{bc}	23.4± 3.2 ^{c}	12.0± 0.0	19.3± 1.8	5.5± 0.8 ^{a}	11.0± 4.6 ^{abc}	6.8± 1.1 ^{ab}
Topography **	3.6 ± 0.5 ^{ab}	3.8 ± 0.3 ^{b}	3.7 ± 0.3 ^{ab}	2.5 ± 0.5	3.5 ± 1.0	2.8 ± 0.6 ^{ab}	2.1 ± 0.4 ^{ab}	1.8 ± 0.3 ^{a}
Rock Frag ^{NS}	4.7 ± 0.4	4.6 ± 0.1	4.6 ± 0.3	5.0 ± 0.0	5.0 ± 0.0	5.0 ±0.3	5.0 ± 0.3	5.2 ± 0.2
Rock max size **	4.8 ± 0.3 ^{ab}	5.1 ± 0.2 ^{ab}	5.6 ± 0.2 ^{b}	4.5 ± 0.5	5. 7 ± 0.3	4.4 ± 0.2 ^{a}	5.0 ± 0.3 ^{ab}	4.2 ± 0.2 ^{a}
% Rock *	2.8 ± 0.7 ^{ab}	3.6 ± 0.3 ^{b}	3.5 ± 0.4 ^{b}	0.0 ± 0.0	3.0 ± 1.0	1.4 ± 0.7 ^{ab}	1.2 ± 0.6 ^{ab}	0.3 ± 0.3 ^{a}
% litter ^{NS}	19.2 ± 6.6	8.6 ± 1.8	8.4 ± 3.8	9.0 ± 6.0	3.7 ± 1.3	14.6 ± 4.6	12.4 ± 5.4	3.0 ± 0.9
% bare ^{NS}	72.7 ± 3.6	74.6 ± 3.2	72.8 ± 4.8	79.5 ± 7.5	70.0 ± 15.3	71.2 ± 5.8	56.0 ± 12.1	83.7 ± 3.1
Altitude *	544.5 ± 4.6	563.6 ± 9.5	573.8 ± 10.0	516.5 ± 6.5	551.7 ± 15.5	534.4 ±10.4	542.4 ± 19.0	537.8 ± 11.7
Latitude ^{NS}	-26.952±0.021	-26.955±0.014	-26.922±0.015	-26.975±0.017	-26.962±0.007	-26.987±0.007	-26.958 ± 0.006	-26.939±0.014
Longitude ^{NS}	117.59± 0.069	117.61± 0.037	117.70± 0.043	117.52± 0.070	117.60± 0.040	117.51± 0.020	117.61 ± 0.021	117.67± 0.038
Number of species / quadrat								
All taxa [1]	32.7 ± 1.0	39.2 ± 5.9	43.9 ± 6.4	20.5 ± 3.5	32.7 ± 7.2	27.9 ± 5.2	36.2 ± 3.4	49.8 ± 3.7
Annuals only	19.3 ± 2.7	23.6 ± 5.0	25.4 ± 7.2	15.0 ±2.8	22.0 ± 6.9	17.2 ± 4.5	21.8 ± 5.1	30.3 ± 4.2
Number of quadrats	6	14	8	2	3	8	5	6

[1]: including singleton taxa

Table 4

Matrix of Spearman rank correlation coefficients for environmental variables collated from 52 quadrats established on the Weld Range. Only correlations significant at $p < 0.01$ are shown. Full details of environmental parameter codes are given in the methods section.

	eCEC	pH	Ca	Co	Cu	Fe	K	Mg	Mn	Na	Ni	P	Pb	S	Zn	Tann	Rann	Rcv	Slope	Topography	Rock Frag	MxR	%Rock	%litter	%Bare	Altitude	Latitude
Soil Parameters																											
eCEC																											
pH	0.823																										
Ca	0.985	0.809																									
Co	0.740	0.764	0.729																								
Cu	0.677	0.726	0.659	0.696																							
Fe	0.586	.	0.566	.	0.363																						
K	0.745	0.560	0.701	0.413	0.502	0.656																					
Mg	0.958	0.816	0.920	0.770	0.638	0.514	0.668																				
Mn	0.749	0.810	0.744	0.819	0.821	.	0.551	0.698																			
Na	0.341	.	.	.	.	.	.	0.405	.																		
Ni	0.781	0.693	0.752	0.821	0.573	.	0.460	0.835	0.631	0.351																	
P	.	.	.	.	.	0.806	0.566	.	.	.	.																
Pb	-0.327	.	.	.	.	-0.502	-0.356	-0.383	.	.	.	-0.418															
S	-0.617	-0.654	-0.610	-0.747	-0.545	.	.	-0.686	-0.655	.	-0.635	.	.														
Zn	0.693	0.582	0.672	0.497	0.619	0.645	0.650	0.637	0.568	.	0.476	0.533	.	-0.425													
Climate Estimates																											
Tann	.	.	.	.	.	-0.339	.	.	.	.	.	-0.412	.	.	.												
Rann	.	.	.	.	.	0.385	.	.	.	.	.	0.436	.	.	.	-0.968											
Rcv	.	.	.	.	.	-0.362	.	.	.	.	.	-0.366	.	.	.	0.953	-0.948										
Physical Site Parameters																											
Slope	0.404	.	0.396	.	.	0.665	0.529	0.335	.	.	.	0.671	-0.317	.	0.610	-0.399	0.410	-0.363									
Topography	.	.	.	-0.369	.	0.557	.	.	.	.	.	0.678	.	.	0.343	-0.387	0.407	-0.339	0.394								
Rock Frag	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.							
MxR	.	.	.	.	.	0.623	0.429	.	.	.	.	0.718	-0.328	.	0.575	-0.445	0.421	-0.413	0.735	0.578	.						
%Rock		.	.	.	.	0.656	.	.	.	.	.	0.736	.	.	.	-0.493	0.503	-0.456	0.514	0.702	-0.527	0.690					
% litter	.	.	.	.	.	.	.	.	.	-0.391	-0.334	.	.	.	.	.	.	.	.	.	.	.	.				
%Bare	.	.	.	.	.	.		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.			
Altitude	.	.	0.329	.	.	0.540	0.350	.	.	.	.	0.520	.	.	.	-0.878	0.915	-0.862	0.553	0.411	.	0.523	0.558	.	.		
Latitude	0.455	0.364	0.479	0.425	.	.	.	0.460	.	.	0.467	.	.	-0.386	.	.	.	.	0.359	.	.	.	.	.	.	.	
Longitude	0.464	0.332	0.497	0.453	.	.	.	0.481	.	.	0.490	.	.	-0.391	.	.	.	.	.	.	.	.	.	.	.	.	0.953

APPENDIX 1

Flora list for the Weld Range, complied from field data. Nomenclature follows Packowska and Chapman (2000). Introduced taxa are denoted by an asterisk and phrase names (informal names) at the Western Australian Herbarium are followed by a reference collection number. Informal names are currently used at Western Australian Herbarium and refer to a taxon that is a new entity awaiting a formal, published description

Acanthaceae

Harnieria kempeana subsp. *muelleri*

Adiantaceae

Cheilanthes cf. *distans*
Cheilanthes cf. *sieberi* subsp. *pseudovillea*
Cheilanthes adiantoides
Cheilanthes brownii
Cheilanthes sieberi subsp. *sieberi*

Aizoaceae

* *Cleretum papulosum* subsp. *papulosum*
Tetragonia cristata

Amaranthaceae

Amaranthus mitchellii
Ptilotus aervoides
Ptilotus exaltatus
Ptilotus gaudichaudii var. *parviflorus*
Ptilotus grandiflorus var. *grandiflorus*
Ptilotus helipteroides
Ptilotus obovatus var. *obovatus*
Ptilotus polystachyus var. *polystachyus*
Ptilotus roei
Ptilotus rotundifolius
Ptilotus schwartzii

Anthericaceae

Arthropodium dyeri
Murchisonia volubilis
Thysanotus manglesianus

Apiaceae

Daucus glochidiatus
Hydrocotyle pilifera var. *glabrata*
Trachymene cyanopetala
Trachymene ornata
Trachymene pilbarensis

Asclepiadaceae

Marsdenia australis
Rhyncharrhena linearis

Asteraceae

Actinobole oldfieldianum
Actinobole uliginosum
Angianthus tomentosus
Brachyscome cheilocarpa
Brachyscome ciliocarpa
Brachyscome perpusilla
Calocephalus knappii
Calocephalus multiflorus
Calocephalus sp. Pilbara-Desert (M.E. Trudgen 11454)
Calotis hispidula
Calotis multicaulis
Cephalipterum drummondii
Chthonocephalus pseudevax
Chthonocephalus viscosus
Dielitzia tysonii
Gilberta tenuifolia
Gilruthia osbornei
Gnephosis brevifolia
Gnephosis tenuissima
Helipterum craspedioides
* *Hypochaeris glabra*
Isoetopsis graminifolia
Lawrencella davenportii
Lawrencella rosea
Lemooria burkittii
Millotia myosotidifolia
Minuria leptophylla
Myriocephalus guerinae
Myriocephalus pygmaeus
Myriocephalus rudallii
Olearia humilis
Olearia stuartii
Podolepis gardneri
Pogonolepis stricta
Rhodanthe battii
Rhodanthe charsleyae
Rhodanthe chlorocephala subsp. *splendida*
Rhodanthe citrina
Rhodanthe forrestii
Rhodanthe laevis
Rhodanthe maryonii
Rhodanthe oppositifolia subsp. *oppositifolia*
Senecio glossanthus
Senecio pinnatifolius
* *Sonchus oleraceus*
Waitzia acuminata var. *acuminata*

Boraginaceae

Cynoglossum sp. Inland Ranges (C.A. Gardner 14499)
Halgania cyanea var. Allambi Stn (B.W. Strong 676)
Heliotropium ovalifolium

Brassicaceae

Lepidium oxytrichum
* *Sisymbrium erysimoides*
Stenopetalum anfractum
Stenopetalum filifolium

Caesalpiniaceae

Senna artemisioides subsp. *oligophylla* x *helmsii* (G. Cassis PILB 193)
Senna artemisioides subsp. *helmsii*
Senna artemisioides subsp. x *sturtii*
Senna glaucifolia
Senna glaucifolia x sp. Meekatharra (A. Markey & S. Dillon 3149)
Senna sp. Meekatharra (E. Bailey 1-26)
Senna stricta x *artemesioides* subsp. *petiolaris* (E.N.S. Jackson 2888)

Campanulaceae

Wahlenbergia gracilenta
Wahlenbergia tumidifructa

Caryophyllaceae

Gypsophila tubulosa

Casuarinaceae

Allocasuarina acutivalvis subsp. *acutivalvis*

Chenopodiaceae

Chenopodium curvispicatum
Chenopodium melanocarpum f. *melanocarpum*
Chenopodium saxatile
Dysphania kalpari
Dysphania rhadinostachya subsp. *rhadinostachya*
Maireana georgei
Maireana melanocoma
Maireana planifolia x *villosa* (A. Markey & S. Dillon 3479)
Maireana villosa
Sclerolaena densiflora
Sclerolaena eriacantha

Crassulaceae

Crassula colorata var. *acuminata*
Crassula extrorsa
Crassula tetramera
Crassula aff. *tetramera* (pentamerous variant)

Convolvulaceae

Porana cf. *commixta*

Cucurbitaceae

* *Cucumis myriocarpus*

Cuscutaceae

* *Cuscuta epithymum*

Cyperaceae

Schoenus nanus

Euphorbiaceae

Euphorbia australis
Euphorbia boophthona
Euphorbia drummondii subsp. *drummondii*
Phyllanthus baeckeoides
Phyllanthus erwinii
Sauropus sp. Woolgorong (M. Officer s.n. 10/8/94)

Geraniaceae

Erodium cygnorum

Goodeniaceae

Brunonia australis
Goodenia berardiana
Goodenia havilandii
Goodenia macroplectra
Goodenia occidentalis
Goodenia tenuiloba
Scaevola spinescens
Velleia glabrata
Velleia hispida
Velleia rosea

Haloragaceae

Haloragis odontocarpa
Haloragis trigonocarpa

Juncaginaceae

Triglochin sp. B Flora of Australia (P.G. Wilson 4294)

Lamiaceae

Prostanthera althoferi subsp. *althoferi*
Prostanthera ferricola
Prostanthera petrophila
Spartothamnella teucriiflora

Lobeliaceae

Lobelia heterophylla
Lobelia winfridae

Loranthaceae

Lysiana murrayi

Malvaceae

Abutilon cryptopetalum
Abutilon oxycarpum subsp. *prostratum*
Hibiscus sturtii var. *forrestii*
Sida sp. dark green fruits (S. van Leeuwen 2260)
Sida aff. sp. dark green fruits (S. van Leeuwen 2260)
Sida sp. Excedentifolia (J.L. Egan 1925)
Sida sp. Golden calyces glabrous fruit (H.N. Foote 32)
Sida sp. (A. Markey & S. Dillon 3071)
Sida ectogama

Mimosaceae

Acacia aneura cf. var. *aneura*
Acacia aneura cf. var. *argentea*
Acacia aneura cf. var. *microcarpa*
Acacia aneura cf. var. *tenuis*
Acacia coolgardiensis subsp. *effusa*

Acacia exocarpoides
Acacia grasbyi
Acacia minyura
Acacia pruinocarpa
Acacia ramulosa var. *linophylla*
Acacia rhodophloia
Acacia sp. Weld Range (A. Markey & S. Dillon 2994)
Acacia speckii

Myoporaceae

Eremophila aff. *georgei* (A. Markey & S. Dillon 2928)
Eremophila clarkei
Eremophila exilifolia
Eremophila forrestii subsp. *forrestii*
Eremophila georgei
Eremophila glutinosa
Eremophila jucunda subsp. *jucunda*
Eremophila latrobei subsp. *latrobei*
Eremophila mackinlayi subsp. *spathulata*
Eremophila macmillaniana
Eremophila oppositifolia subsp. *angustifolia*
Eremophila simulans subsp. *simulans*

Myrtaceae

Aluta aspera subsp. *hesperia*
Calytrix desolata
Corymbia lenziana
Homalocalyx echinulatus
Micromyrtus placoides
Micromyrtus sulphurea
Thryptomene decussata

Nyctaginaceae

Boerhavia coccinea

Papilionaceae

Chorizema genistoides
Indigofera monophylla
Swainsona affinis

Plantaginaceae

Plantago aff. *hispida* (A. Markey & S. Dillon 3440)

Poaceae

Aristida contorta
Austrostipa elegantissima
Austrostipa nitida
Austrostipa scabra
Austrostipa trichophylla
Bromus arenarius
Cymbopogon ambiguus
Digitaria brownii
Enneapogon caerulescens
Eragrostis pergracilis
Eriachne helmsii
Eriachne mucronata
Eriachne mucronata x *helmsii* (A. Markey & S. Dillon 3228)
Eriachne pulchella subsp. *pulchella*
Monachather paradoxus
Neurachne minor
Paspalidium basicladum
* *Pentaschistis airoides*
* *Rostraria pumila*
Thyridolepis multiculmis
Triodia cf. *melvillei*
Tripogon loliiformis

Polygalaceae

Polygala isingii

Polygonaceae

* *Acetosa vesicaria*

Portulacaceae

Calandrinia creethae
Calandrinia eremaea
Calandrinia sp. The Pink Hills (F. Obbens FO 19/06)
Calandrinia sp. Bungalbin (G.J. Keighery & N. Gibson 1656)
Calandrinia translucens

Primulaceae

* *Anagallis arvensis* var. *caerulea*

Proteaceae

Grevillea berryana
Hakea preissii
Hakea recurva

Rhamnaceae

Stenanthemum patens
Stenanthemum petraeum

Rubiaceae

Psydrax latifolia
Psydrax rigidula
Psydrax suaveolens
Synaptantha tillaeacea var. *tillaeacea*

Rutaceae

Philotheca brucei subsp. *brucei*

Santalaceae

Exocarpos aphyllus
Santalum lanceolatum
Santalum spicatum

Sapindaceae

Dodonaea adenophora
Dodonaea pachyneura
Dodonaea petiolaris
Dodonaea amplisemina
Dodonaea viscosa subsp. *angustissima*

Solanaceae

Nicotiana cavicola
Nicotiana occidentalis subsp. *obliqua*
Nicotiana rosulata subsp. *rosulata*
Solanum ashbyae
Solanum coactiliferum

Stackhousiaceae

Stackhousia muricata

Stylidiaceae

Stylidium longibracteatum

Urticaceae

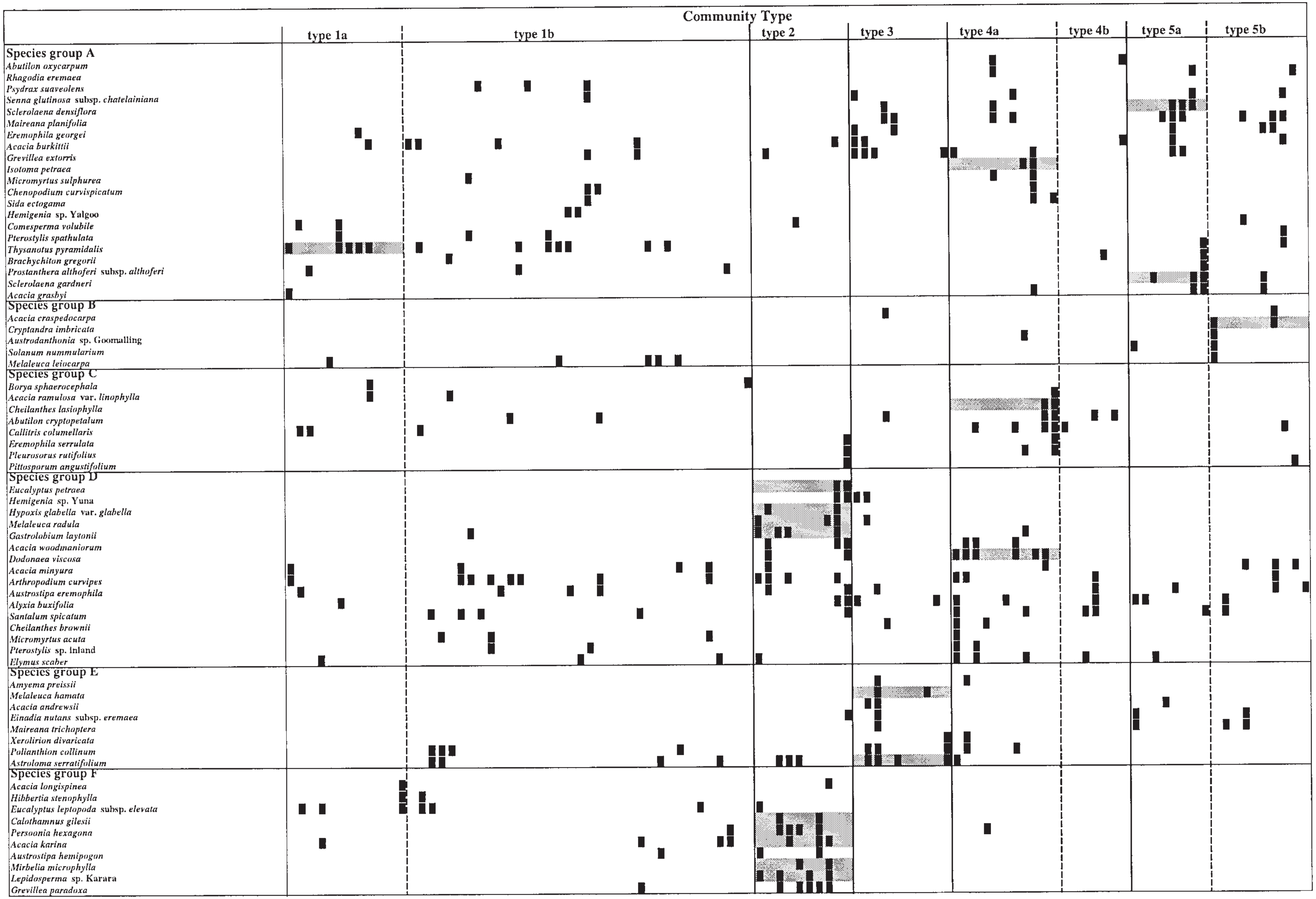
Parietaria cardiostegia

Zygophyllaceae

Tribulus suberosus
Zygophyllum lobulatum
Zygophyllum tesquorum

APPENDIX 2

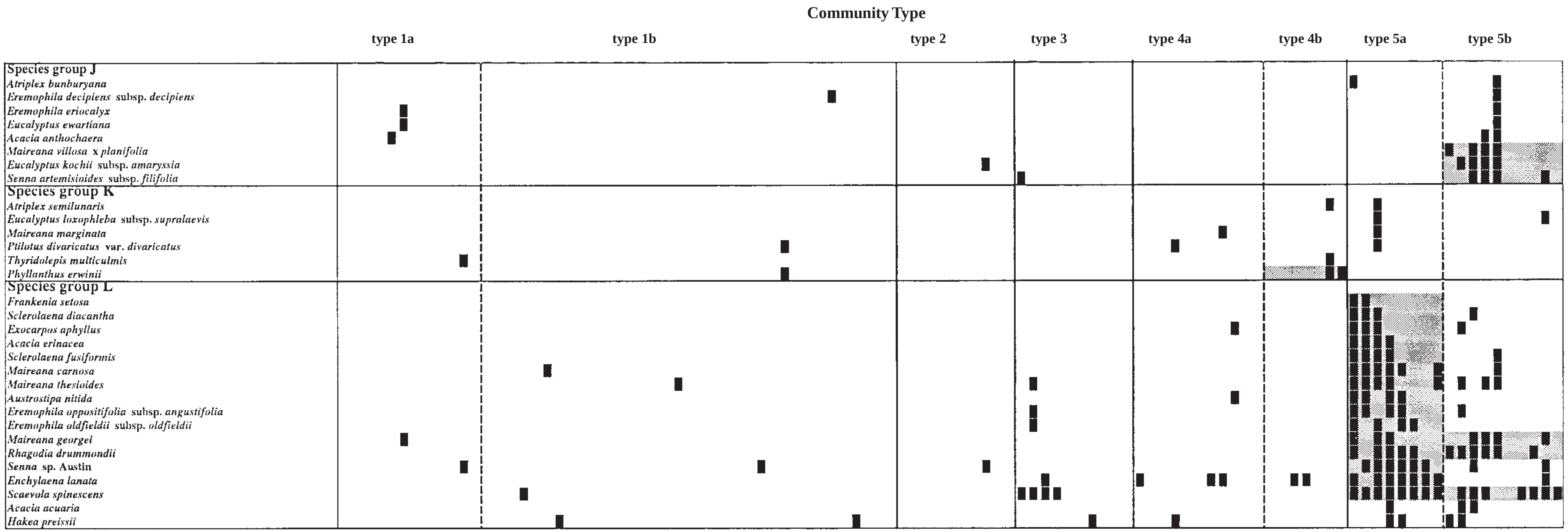
Two way table of site and perennial taxa used in classification and ordination analysis, sorted by quadrat and taxon classification. Species occurences per quadrat are indicated by a square. Species with significant INDVAL statistics are indicated by shading in the respective community type where these values were highest (see Table 2)




Species group G
Calytrix uncinata
Stylidium longibracteatum
Thryptomene costata
Dodonaea petiolaris
Persoonia manotricha
Cheiranthera filifolia var. simplicifolia
Ptilotus drummondii var. drummondii
Eremophila glutinosa
Acacia aulacophylla
Prostanthera patens
Micromyrtus trudgenii
Wurmbea sp. Paynes Find
Acacia umbraculiformis
Solanum ellipticum
Austrostipa trichophylla
Sida sp. Golden calyces glabrous fruit
Cheilanthes sieberi subsp. sieberi
Thryptomene decussata
Solanum lasiophyllum
Austrostipa scabra
Senna charlesiana
Dodonaea inaequifolia
Austrodanthonia caespitosa
Hakea recurva
Austrostipa elegantissima
Ptilotus obovatus var. obovatus
Acacia tetragonophylla
Species group H
Philotheca deserti subsp. deserti
Acacia coolgardiensis subsp. latior
Acacia sibina
Amphipogon caricinus var. caricinus
Acacia coolgardiensis subsp. effusa
Drummondita fulva
Hibbertia arcuata
Olearia humilis
Eremophila forrestii subsp. forrestii
Dianella revoluta var. divaricata
Cyanicula amplexans
Drosera macrantha subsp. macrantha
Hemigenia sp. Cue
Leucopogon sp. Clyde Hill
Melaleuca nematophylla
Allocasuarina acutivalvis
Xanthosia bungei
Thysanotus manglesianus
Acacia assimilis subsp. assimilis
Calycopeplus paucifolius
Species group I
Prostanthera magnifica
Aluta aspera subsp. hesperia
Grevillea obliquistigma subsp. obliquistigma
Acacia aneura var. cf. major
Acacia aneura var. cf. aneura
Mirbelia bursarioides
Philotheca sericea
Eremophila latrobei subsp. latrobei
Cheilanthes adiantoides
Acacia ramulosa var. ramulosa
Eremophila clarkei
Philotheca brucei subsp. brucei
Arthropodium dyeri
Sida sp. dark green fruits
Acacia exocarpoides
Monachather paradoxus
Rhyncharrhena linearis
Comesperma integerrimum

APPENDIX 2

(cont.)



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Bibliography of marine scientific research relevant to the Ningaloo Marine Park and Adjacent Waters

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ABSTRACT

This bibliography contains a comprehensive list of 648 references relevant to the conservation of the Ningaloo Marine Park (NMP) and the Muiron Islands Marine Management Area (MIMMA) (Fig 1). The reference list contains both published and unpublished literature and is current as of June 2006. The list originated from a database held by the Department of Environment and Conservation (DEC) Exmouth District Office, which was updated and compiled into a bibliographic report in 2000 (Bancroft & Davidson, 2000) and again in 2006 (Armstrong, 2006a). The Armstrong (2006a) bibliographic report has an accompanying report (Armstrong, 2006b) which lists all current and proposed research projects relevant to the NMP and MIMMA, as of June 2006. Collectively, these reports address a high priority management strategy within the NMP and MIMMA management plan (CALM, 2005c) to "*develop and maintain a database of historical and current research in the reserves*". The reports were made widely available to all providers of marine science in Western Australia to facilitate a strategic and collaborative approach towards marine research in the NMP. A major research effort is currently underway as part of the Western Australian Marine Science Institution (Node 3) and the Australia's Commonwealth Scientific and Industrial Research Organisation's (CSIRO) Wealth from Oceans Flagship – Ningaloo Research Cluster. The bibliography will be used to identify gaps in the knowledge and information base necessary for management of the NMP, so that research can be prioritised to close those gaps.

Keywords: Ningaloo Marine Park, research, bibliography, monitoring

METHODS

The list of titles extracted from the Bancroft and Davidson (2000) report was updated with current research projects listed in the Ningaloo Research Program Project and Funding Guidelines (D'Adamo, 2006). Literature searches were conducted in online library catalogues of the Australian Institute of Marine Science (AIMS), Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO), WA Department of Fisheries (DoF), and all Western Australian universities as well as other Australian universities with a marine focus, such as James Cook University, Charles Darwin University and Southern Cross University. Lists of all relevant references from each of the above sources were created, and where possible each list was sent to an appropriate contact from that organisation for review. Relevant references from the DEC research licensing database, held at DEC's Wildlife Conservation Section of the Wildlife Branch, were also incorporated. General internet searches using the Google search engine were also conducted.

Copies of the draft bibliographic list were sent to appropriate DEC staff, the Manager of the Ningaloo Research Program (NRP), and the Chief Scientist of AIMS (WA), so that any inaccuracies or omissions could be identified and corrected.

The bibliography was complied as an electronic database using EndNote (Version 8). Reference details including keywords, abstracts and research notes were assigned to references where possible. The search function of EndNote can be used to locate specific research subjects, authors, project titles etc within the bibliography. The EndNote version of the bibliography can be obtained in electronic form from the Marine Science Program (MSP) within the Science Division of the Western Australian Department of Environment and Conservation.

ACKNOWLEDGEMENTS

The report upon which this bibliography is based (Armstrong, 2006a) was funded by Node 3 of the Western Australian Marine Science Institution (WAMSI). The report was initiated and reviewed by Dr Nick D'Adamo, former Node 3 leader and Dr Chris Simpson, Program Leader of DEC's Marine Science Program. The comments of the anonymous reviewers were appreciated.

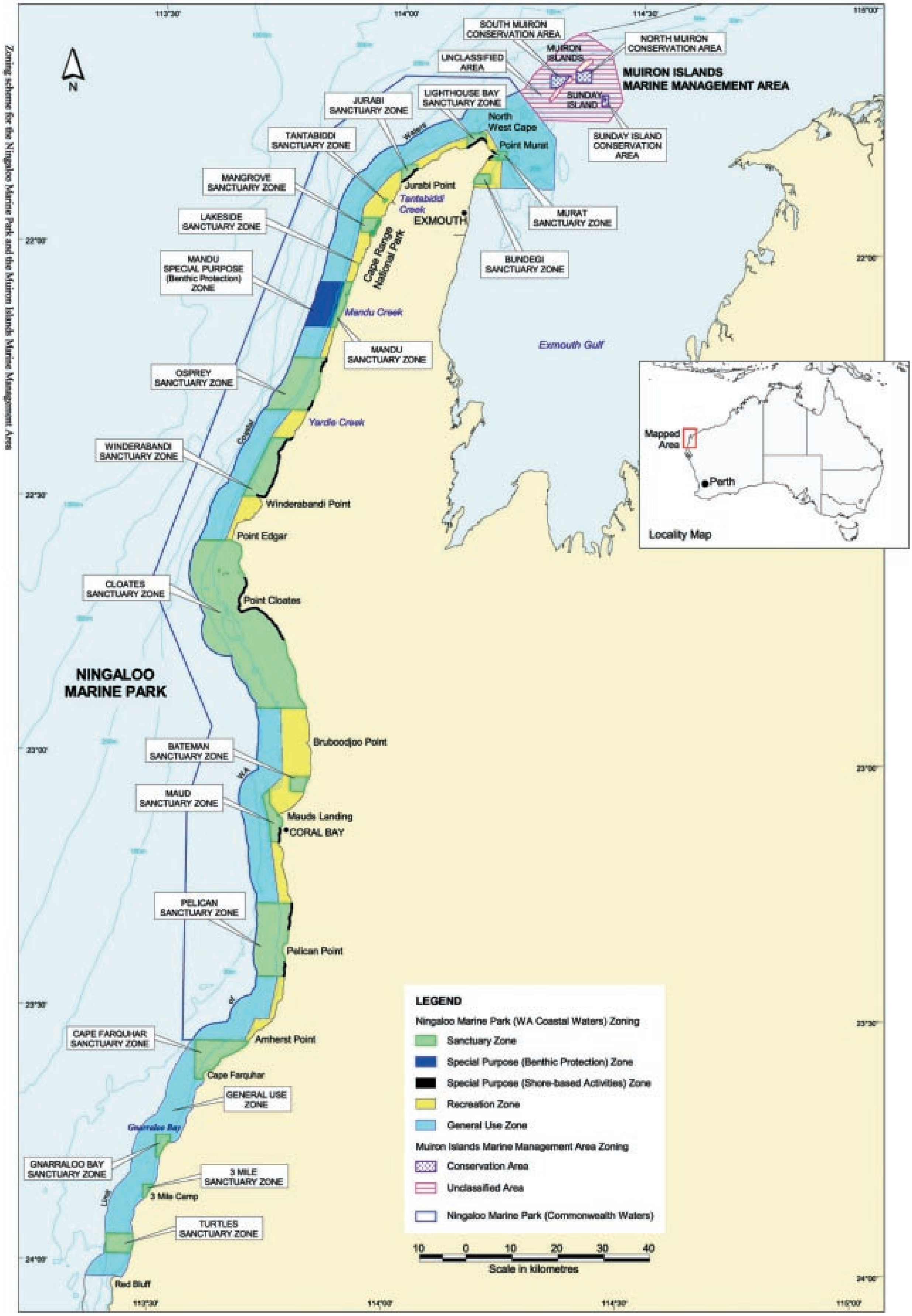

Figure 1. Map and zoning scheme of the Ningaloo Marine Park and Muiron Islands Marine Management Area.

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