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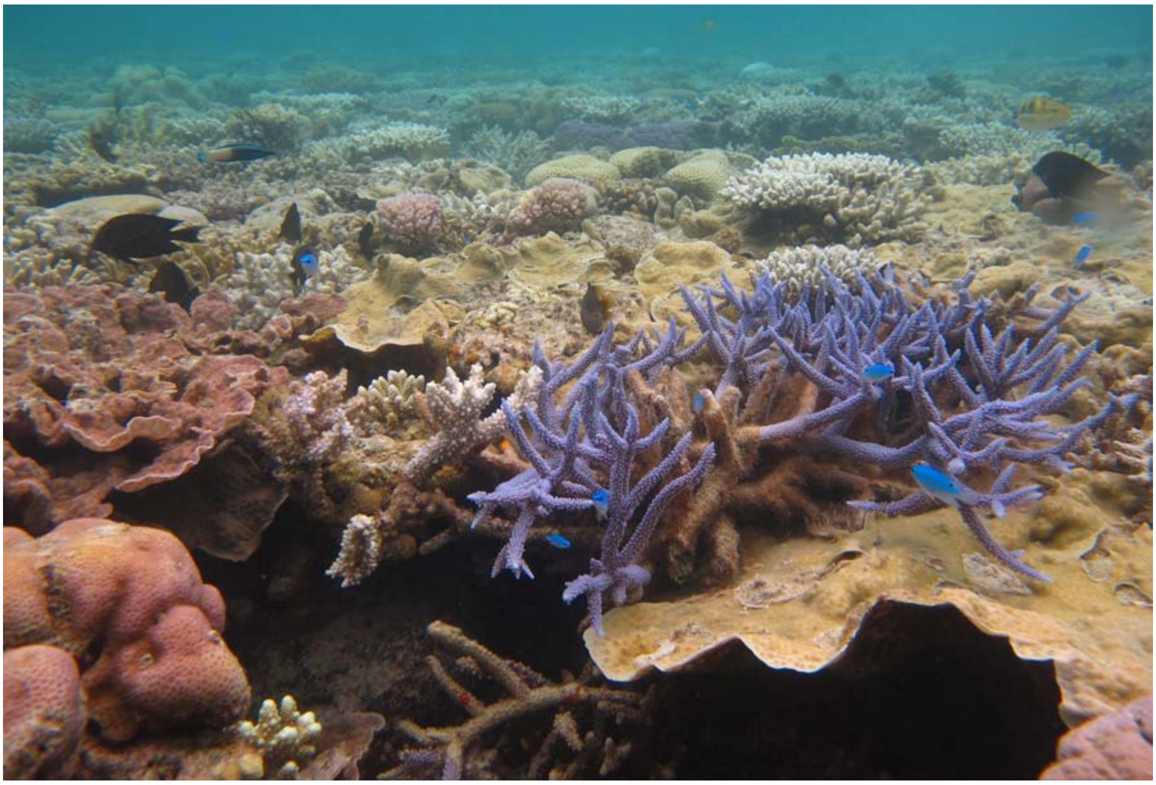

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Weedy native plants in Western Australia: an annotated checklist

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ABSTRACT

An annotated checklist of 78 Western Australian native plant species with naturalized populations in Western Australia is presented. Information on natural and weedy distributions, habitat and establishment is presented for each species, along with voucher specimen details. Further information is provided on doubtfully naturalized species, species contributing to disruption of genetic integrity, and species of uncertain occurrence status.

Keywords: checklist, naturalised Western Australian vascular plants

INTRODUCTION

Any plant outside the checks and balances of its natural habitat can potentially be a weed. Western Australian native species are no exception and some are already serious weeds of the natural environment (Keighery 2002). With increasing attempts to restore, rehabilitate and revegetate disturbed land in Western Australia, it is vital that we understand the natural distribution and ecology of our native flora. This enables the use of local provenance material that should minimize the actual and potential introduction of potentially damaging weedy taxa. This paper seeks to list known weedy native species and provide information on their distribution and basic ecology. Native species with known weedy populations are listed in Appendix 1 (layout follows Keighery 2005). Appendix 2 lists doubtfully naturalized species, and Appendix 3 details species for which further study is required to ascertain native or naturalized distributions or status.

METHODS

This study is based on the examination of herbarium collections from KPBG (Kings Park and Botanic Garden herbarium) and PERTH (Western Australian Herbarium), supplemented with field observations by the author and literature records where relevant. Herbarium codes follow Index Herbariorum (http://sweetgum.nybg.org/ih/), and all specimens cited are housed in PERTH, unless otherwise noted. Taxonomy used follows Florabase (Western Australian Herbarium 1998–) or Australia's Virtual Herbarium (The Council of Heads of Australasian Herbaria 2012), and regional distributions follow IBRA 7 Regions of Western Australia (Department of Sustainability, Environment, Water, Population and Community 2012). Natural distributions were sourced from the revisions and studies cited or from Florabase and the Australian Virtual Herbarium.

RESULTS AND DISCUSSION

Our understanding of the distribution and ecology of many native species has improved greatly over the past 50 years. However, erroneous interpretation of the origins or status of native plant populations can lead to misleading impressions of the true native ranges of a species, especially in broad-scale public databases such as those derived from herbarium data, such as Florabase (Western Australian Herbarium 1998–) or Australia's Virtual Herbarium (The Council of Heads of Australasian Herbaria 2012). This can affect the conservation status of a species, our understanding of a species' climatic envelop for climate change studies, and the ranges for local provenance of seed sources for rehabilitation. For example, there is a naturalized population of the highly restricted *Reedia spathacea* at Hamel, on the Swan Coastal Plain, several hundred kilometres north of the natural range of this localised endemic, and this could be misinterpreted as a localised, possibly threatened, occurrence of this species in the absence of data on the origin of this population. Similar issues can be noted in the south coast endemics *Kennedia nigricans* (weedy populations on the Swan Coastal Plain), *Hakea laurina* (weedy populations in the Jarrah Forest and Swan Coastal Plain) and *Kunzea baxteri* (weedy populations in the Esperance Sandplains). Perhaps the most extreme example of such misinterpretation was the listing of a naturalized population of *Melaleuca diosmifolia* Andrews in the Stirling Ranges as a new record for this priority species in Florabase, despite the population being targeted for removal in the Management Plan (Allen & Herford 1999).

Of the 78 species listed here as having naturalized populations (Appendix 1), over 95% of these resulted from deliberate introductions into bushland areas or localized spread from nearby plantings. Although many of the species discussed below will likely remain only minor weeds of remnant bushland, there are a series of species (*Agonis flexuosa*, *Allocasuarina huegeliana, Calothamnus* spp., *Ceratopteris thalictroides, Chamelaucium uncinatum*, *Eucalyptus megacornuta, Hakea costata* and *Melaleuca lanceolata*) that have the capacity to completely alter the structure of communities that they invade. These are as damaging to the conservation of the remnant bushland invaded as are many exotic invasive species.

Currently, some horticulturalists and reserve managers are suggesting using species from 'drier' regions for revegetation in the light of climate change predictions (Department of Climate Change 2012). However, many of the serious bushland weeds documented in this paper—because they were the species used in horticulture and available for beautification, enhancement or revegetation attempts—are from 'wetter' regions than the areas they are invading and adversely affecting. This suggests that such species shifts are at best premature and could potentially cause serious weed problems in remnant bushland and result in an even greater loss of biodiversity than predicted through climate change models alone. Like any imported species, a risk assessment of the propensity to become weedy should be performed prior to any proposal to plant it in or around natural bushland. However, such assessments are complicated by the fact that we still lack basic biological information (e.g. limitations to population size, ecological range, etc.) for most native species.

Another ten species (Appendix 2) were recorded as doubtfully naturalized in areas outside their native ranges, but as yet are not truly established as self-sustaining populations, and should be monitored for potential further spread or eradicated if possible. Weeds can threaten biodiversity at the genetic level through mixing of local and introduced gene pools. Although poorly documented, there are several examples of genetic 'pollution' of local plant forms in Western Australia (e.g. see *Chamelaucium uncinatum*, Appendix 1). Other known examples include *Eucalyptus gomphocephala* DC: the seed produced by trees in Kings Park has many hybrid genes present (Coates et al. 2002), apparently because of extensive crossing to many species planted in the Botanic Gardens and along road verges in Kings Park. *Corymbia ficifolia* (F Muell.) KD Hill & LAS Johnson has also hybridized extensively with *C. calophylla* (Lindl.) KD Hill & LAS Johnson in Kings Park (GJ Keighery 16254) from plantings of trees along Fraser Avenue. There has also been extensive planting at Kings Park of non-local forms of *Acacia pulchella* and *Anigozanthos manglesii* D Don. The genetic consequences of these actions are presently unknown.

With increasing movement of plant species and local provenances through the landscape the potential for increased hybridisation and genetic 'pollution' is obvious. Forty-three taxa (Appendix 3) are listed for which further taxonomic/genetic study is required to ascertain native or naturalised distributions or status.

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APPENDIX 1

Annotated list of Western Australian native species with naturalized populations.

FERNS

***Ceratopteris thalictroides* (L.) Brongn. (Indian water fern)**

NATURAL DISTRIBUTION: North Kimberley, Dampier Land, Victoria–Bonaparte IBRA Regions.

WEEDY DISTRIBUTION: Pilbara IBRA Region.

HABITATS: Permanent pools of the Fortescue and Robe Rivers.

FIRST RECORD: Millstream, *CA Gardner 3110*, 22 Aug. 1932.

OTHER RECORDS: Crystal Pool, Millstream, *RF Black s.n.*, 5 Sept. 1974; Deepdale Station, Robe River, *A Brealey s.n.*, 1995; Chinderwah Pool, Millstream, *P Bremmer s.n.*, 3 Oct. 1987; Crystal Pool, *MIH Brooker 2067*; Robe River, Pannawonica to Millstream road, *S Hunger & N Kilian 4256*; Millstream, *E Leyland s.n.*, 8 April 1990; Millstream, *AA Mitchell 1490*; *AA Mitchell 2671*; Robe River, *C Olsson 95*; Millstream, *GG Smith s.n.*, 2 Oct. 1976; Robe River, *MET Trudgen & S Maley MET 10097*; Millstream, *K Vollprecht s.n.*, 4 Aug. 1958; Millstream, *JAL Watson s.n.*, 6 Dec. 1958; Lily Ponds, Millstream, *PG Wilson & R Rowe 1011*.

NOTES: Millstream Station was first selected in 1864 under owners Alex McRae and Trevor McKenzie, and run by them until 1879 when the lease was purchased by Walter Padbury and William Loton (Withnell Taylor 2002) and run by them until 1914. Numerous species were introduced around the homestead to add shade and beautification along the river during this period. These included Tamarisk (*Tamarix aphylla*), Albizia (*Albizia lebbek*) and along the river Cotton Palms (*Washingtonia filifera*), Date Palms (*Phoenix dactylifera*), Bamboo (*Arundo donax*), Borassus Palm (*Borassus ?aethiopica*), yellow Oleander (*Thevetia peruviana*) and Oleander (*Nerium oleander*) (illustrated in Gordon 2004, p. 73). Several ornamental aquatics, Waterlilies (*Nymphaea macrosperma*) and the Indian Water Fern were planted into Chinderwarriner Pool adjacent to homestead. Hawkesbill turtles were even introduced into these pools in the 1930s (Gordon 2004, p. 17.), but they did not persist.

It is possible that plants of *Ceratopteris thalictroides* introduced into Millstream are not of Western Australian provenance since the species is found throughout the tropics.

GYMNOSPERMS

CUPRESSACEAE

***Callitris canescens* (Parl.) ST Blake**

NATURAL DISTRIBUTION: Coolgardie, Murchison, Avon Wheatbelt, Esperance Sandplains, Geraldton Sandplains, Mallee, Swan Coastal Plain IBRA Regions

WEEDY DISTRIBUTION: Swan Coastal Plain, Jarrah Forest IBRA Regions.

HABITATS: Riverine edges.

FIRST RECORD: Jane Brook, John Forrest National Park, *G Keighery 11447*.

OTHER RECORDS: Hamel (cultivated?) *JJ Harding s.n.*, Jan. 1950; Botanic Garden (cultivated), *Anon. s.n.*

NOTES: I have observed this species along road verges, seeding in arboreta and from amenity plantings.

***Callitris columellaris* F Muell. (white cypress pine)**

NATURAL DISTRIBUTION: North Kimberley, Central Kimberley, Victoria–Bonaparte, Coolgardie, Central Ranges, Gascoyne, Great Sandy Desert, Great Victoria Desert, Little Sandy Desert, Murchison, Pilbara, Yalgoo, Geraldton Sandplains, Mallee IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain, Jarrah Forest IBRA Regions.

HABITATS: disturbed wandoo woodland, road verges.

FIRST RECORD: Dryandra, *G Keighery 12281*.

OTHER RECORDS: North Dandalup, *G Keighery s.n.*, 25 Aug. 1991.

NOTES: I have observed this species on road verges, seeding in arboreta and from amenity plantings. Naturalized plants could be of non-Western Australian origin.

***Callitris pyramidalis* (Miq.) JE Piggin & JJ Bruhl (swamp cypress)**

NATURAL DISTRIBUTION: Geraldton Sandplains, Avon Wheatbelt, Swan Coastal Plain, Jarrah Forest IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Tuart/banksia woodlands.

FIRST RECORD: Listed as a weed in Kings Park by Barrett and Tay (2005). No voucher located.

OTHER RECORDS: None known.

NOTES: Previously in the genus *Actinostrobus*. Recorded along road verges, seeding in arboreta and from amenity plantings.

***Callitris verrucosa* (Endl.) F Muell.**

NATURAL DISTRIBUTION: Coolgardie, Murchison, Great Victoria Desert IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain, Jarrah Forest IBRA Regions.

HABITATS: Wandoo woodland, tuart/banksia woodlands.

FIRST RECORD: Dryandra Forest, *G Keighery 12275*; Kings Park, *G Keighery 16407, 16408, 16409*.

OTHER RECORDS: Listed as a weed in Kings Park by Bennett (1995).

NOTES: Recorded along road verges, seeding in arboreta and from amenity plantings. The taxonomy of this and the following species follows Hill (1998) rather than Farjon (2005), who combined C. *preissii*, *C. tuberculata* and *C. preissii* subsp. *murrayensis* under *C. preissii*.

Callitris preissii sensu Hill is distinguishable on cone morphology, is highly disjunct from the other members of this complex and is genetically distinct (R Barrett, pers. comm.). Populations on the Swan Coastal Plain form a Threatened Ecological Community (Keighery et al. 1997). For these reasons material of the other *Callitris* taxa and/or populations should never be planted near natural stands.

Callitris preissii **Miq. (Rottnest Island pine)**

NATURAL DISTRIBUTION: Swan Coastal Plain IBRA Region.

WEEDY DISTRIBUTION: Swan Coastal Plain, Warren IBRA Region.

HABITATS: Coastal heath, tuart/banksia woodlands.

FIRST RECORD: Windy Harbour, *G & B Keighery 380*.

OTHER RECORDS: A weed in tuart woodland in Kings Park, but native to river escarpment in Kings Park.

NOTES: Recorded along road verges, seeding in arboreta and from amenity plantings.

Callitris roei **Benth. (Roe's cypress)**

NATURAL DISTRIBUTION: Coolgardie, Avon Wheatbelt, Mallee IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Tuart/banksia woodlands.

FIRST RECORD: Law Walk, Kings Park, *G Keighery 17210*.

OTHER RECORDS: None known. Listed as a weed in Kings Park by Barrett and Tay (2005).

NOTES: I have observed this species along road verges, seeding in arboreta and from amenity plantings.

MONOCOTYLEDONS

ARACEAE

Colocasia esculenta **(L.) Schott var** ***aquatilis*** **Hassk. (taro)**

NATURAL DISTRIBUTION: North Kimberley, Central Kimberley, Ord Victoria Plains IBRA Regions.

WEEDY DISTRIBUTION: Central Kimberley, Dampier Land IBRA Regions.

HABITATS: Creeks and fresh water seeps.

FIRST RECORD: Beagle Bay, *KF Kenneally 10630*.

OTHER RECORDS: Beagle Bay, *AA Mitchell 3283*.

NOTES: The record of this native variant at Beagle Bay is definitely an introduction as plants were introduced by the administrators at Beagle Bay mission as a potential food source in 1900. However, this species is still restricted to a few fresh water seeps in this arid area. This variety was reported as introduced into a creek line at Mount Hart Station Homestead in 1980 and spreading rampantly downstream along a tributary of the Barker River. It is currently being eradicated (B Marmion, Minister for the Environment and Water, Media Statement, 27-10-2011; http://www.mediastatements.wa.gov.au). However, recent examination of fresh collections of this population by the author has found that it is the ornamental cultivar Fontanesii of the introduced var. *esculenta*.

CYPERACEAE

Reedia spathacea **F Muell.**

NATURAL DISTRIBUTION: Warren IBRA Region.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Swamps.

FIRST RECORD: Hopper et al. (1992); no voucher located.

OTHER RECORDS: None known.

NOTES: Recorded from a wetland at Hamel, south of Pinjarra. This area is the former site of the Forests Department Nursery from 1916 to 1990. Numerous species were cultivated and planted out around the old nursery site, including karri (*Eucalyptus diversicolor* F Muell.), waratah (*Telopea speciosissima* [Sm.] R. Br.) and *Lambertia inermis* R. Br. Several of these plantings, such as *Phorium tenax* JR Forst. & G Forst. and *Banksia integrifolia* L.f. have since naturalized.

HYDROCHARITACEAE

Hydrilla verticillata **(L.f.) Royle**

NATURAL DISTRIBUTION: Central Kimberley, Ord Victoria Basin, Ord Victoria Plains IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Permanent lakes, soaks and rivers.

FIRST RECORD: Soak on west side of aerodrome, Rottnest Island, *NG Marchant 69.*

OTHER RECORDS: Kent Street Weir, *Nelson s.n.*, 2 Feb. 1960; *NG Marchant s.n.*, 16 Feb. 1960; Helena River at Guildford, *JG Patterson s.n.*, 5 March 1969; Glendalough drain, north-end Mongers Lake, *Perth City Council s.n.*, 19 Sept. 1974.

NOTES: Only recorded from highly modified wetlands in the Perth Metropolitan area. Treated as introduced to the Perth region in Marchant et al. 1987. Research is required into the origin and relationships of the south western populations of this species.

POACEAE

Austrostipa tenuifolia **B (Steud.) SWL Jacobs & J Everett**

NATURAL DISTRIBUTION: Yalgoo,Coolgardie, Geraldton Sandplain, Avon Wheatbelt, Jarrah Forest, Swan Coastal Plain IBRA Regions.

WEEDY DISTRIBUTION: Jarrah Forest, Swan Coastal Plain IBRA Regions.

HABITATS: *Melalaeuca lanceolata/Callitris preissii* woodland and coastal heath.

FIRST RECORD: Muchea Nature Reserve, *GJ Keighery 16864*.

OTHER RECORDS: Woodvale Nature Reserve, *G Keighery 17219*; Beechina*, U Bell 67*.

NOTES: Spreading along road verges due to grading and mowing. Introduced by vehicles into Woodvale and Kings Park, now spreading rapidly along firebreaks and tracks. Southern end of natural range around Gingin on Swan Coastal Plain. The record of this species from Kings Park is also an introduction (Barrett & Tay 2005) as it was not recorded in detailed surveys previously and is restricted to road and trail verges.

Chloris pumilio **R. Br. (windmill grass)**

NATIVE DISTRIBUTION: North Kimberley, Central Kimberley, Dampier Land, Victoria Bonaparte, Ord Victoria Plains, Tanami, Pilbara, Little Sandy Desert, Ashburton, Carnarvon, Geraldton Sandplain IBRA Regions.

WEEDY DISTRIBUTION: Avon Wheatbelt IBRA Region.

HABITATS: Weedy road sides.

FIRST RECORD: 7.6 km north of Three Springs, *BJ Lepschi & TR Lally 2690*.

OTHER RECORDS: None known.

NOTES: Introduced via trucks moving stock.

***Pseudoraphis spinescens* (R. Br.) Vickery (spiny mud grass)**

NATIVE DISTRIBUTION: Kimberley, North Kimberley, Central Kimberley, Dampier Land, Victoria Bonaparte IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Fresh water swamps and lakes.

FIRST RECORD: Herdsman Lake Regional Park, *G Keighery 17314*.

OTHER RECORDS: None known.

NOTES: How this species was introduced into the Swan Coastal Plain is unknown, but it may have been naturally introduced by waterbirds.

DICOTYLEDONS

ASTERACEAE

***Xerochrysum braceatum* (Vent.) Tzvelev (golden everlasting)**

NATURAL DISTRIBUTION: Pilbara, Avon Wheatbelt, Esperance Sandplains, Geraldton Sandplains, Mallee, Swan Coastal Plain, Jarrah Forest, Warren IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Tuart/banksia woodland.

FIRST RECORD: Woodvale Nature Reserve, *V English VE 02/95*.

OTHER RECORDS: Recorded as naturalized in Kings Park by Barrett and Tay (2005).

NOTES: Probably adventive rather than truly naturalized, occurring after fire in bushland and seeding from adjacent plantings. Plants have not been recently located at both sites. The record for the Pilbara is also highly disjunct and requires further study.

CAESALPINACEAE

***Labichea lanceolata* Benth. subsp. *lanceolata* (tall labichea)**

NATURAL DISTRIBUTION: Esperance Sandplains, Geraldton Sandplains, Swan Coastal Plain, Jarrah Forest IBRA Regions

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: *Eucalyptus marginata* woodland over low woodland of *Banksia attenuata* and *B. menziesii*.

FIRST RECORD: East of Bowling Club, Kings Park, *GJ & BJKeighery 249*.

OTHER RECORDS: Barrett and Tay (2005) record this as naturalized at several sites in Kings Park.

NOTES: A dense monoculture of this species has formed through suckering in Kings Park, where it spread from amenity plantings.

CASUARINACEAE

***Allocasuarina huegeliana* (Miq.) LAS Johnson (rock she-oak)**

NATURAL DISTRIBUTION: Coolgardie, Murchison; Avon Wheatbelt, Esperance Sandplains, Geraldton Sandplains, Mallee, Swan Coastal Plain, Jarrah Forest IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Plantings of this species have resulted in dense monocultures in Kings Park in banksia woodland after fires have killed the adults and stimulated germination of seedlings.

FIRST RECORD: Boomerang Walk, Kings Park, Perth, *GJ Keighery 13990*.

OTHER RECORDS: Bancell Road Reserve, north-east Yarloop, *G & B Keighery 369*.

NOTES: Soil dumping in old gravel pits has introduced this species into Bancell Road. In the Kings Park site, this species forms a dense monoculture and has the capacity to completely alter the understorey of banksia woodlands. This species is also spreading into heathlands in the western Wheatbelt in the absence of fire.

DILLENIACEAE

***Hibbertia cuneiformis* (Labill.) Sm. (cutleaf hibbertia)**

NATURAL DISTRIBUTION: Esperance Sandplains, Swan Coastal Plain, Jarrah Forest, Warren IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Banksia woodland, coastal heath, *Eucalyptus rudis*/*Melaleuca preissiana* woodland.

FIRST RECORD: Hollywood Reserve, Nedlands, *GJ Keighery 16675*.

OTHER RECORDS: Blue Gum Lake, *K Brown 505*; Piney Lakes Reserve, Melville, *G & B Keighery 1316*; Pinnaroo Cemetery Bushland, *G Keighery 17313*; Kings Park, *G. Keighery 17104*; Woodvale Nature Reserve, *G Keighery 17311*.

NOTES: Keighery (1998) discussed how this species, planted as an amenity species in the Naval Base on Garden Island, was self-seeding into disturbed bushland. At the other reserves mentioned above this species is seeding and spreading into relatively undisturbed bushland. At Woodvale and Piney Lakes the seeds are being introduced by birds from nearby gardens, as there are no plantings in these reserves. The species is also considered a potentially serious bushland weed in eastern Australia (Elliot & Jones 1990).

EUPHORBIACEAE

***Euphorbia australis* Boiss. (namana)**

NATURAL DISTRIBUTION: North Kimberley, Central Kimberley, Ord Victoria Plains, Dampier Land, Carnarvon, Central Ranges, Gascoyne, Gibson Desert, Great Sandy Desert, Great Victoria Desert, Little Sandy Desert, Murchison, Pilbara, Tanami IBRA Regions.

WEEDY DISTRIBUTION: Avon Wheatbelt, Esperance Sandplains, Geraldton Sandplains, Swan Coastal Plain, Jarrah Forest, Warren IBRA Regions.

HABITATS: Weed of gardens, paddocks and wasteland.

FIRST RECORD: Merredin, *CV Cahill s.n.*, July 1952.

OTHER RECORDS: Saint James Church, Greenough, *G Keighery 16598*; Fonty's Pool, Manjimup, *L Fontanini 97*; 2.5 km west of Mundijong, *R Davis 8796*.

NOTES: Listed as a weed in Kings Park by Bennett (1995), probably introduced by soil movement along tracks. This species and the one listed below are native to the tropics and naturalized in disturbed areas in temperate Western Australia.

Euphorbia drummondii **Boiss. (caustic weed)**

NATURAL DISTRIBUTION: North Kimberley, Central Kimberley, Ord Victoria Plains, Dampier Land, Victoria Bonaparte, Carnarvon, Coolgardie, Central Ranges, Gascoyne, Gibson Desert, Great Sandy Desert, Great Victoria Desert, Hampton, Little Sandy Desert, Murchison, Nullarbor, Pilbara, Tanami, Yalgoo IBRA Regions

WEEDY DISTRIBUTION: Esperance Sandplains, Swan Coastal Plain, Avon Wheatbelt IBRA Regions.

HABITATS: Weed in gardens, paddocks and waste land.

FIRST RECORD: South Perth, *G Perry 1294.*

OTHER RECORDS: Fremantle, *G Keighery 16348*; 20 km north of Dalwallinu, *M Clarke s.n.*, April 2006.

NOTES: Listed as a weed in Kings Park by Bennett (1995), probably introduced by soil movement along tracks.

Homalanthus novoguineensis **(Warb.) Lauterb. & K Schum.**

NATURAL DISTRIBUTION: North Kimberley, Ord Victoria Plains, Victoria Bonaparte IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain, Jarrah Forest IBRA Regions.

HABITATS: Fresh water wetlands and creek lines.

FIRST RECORD: Nerrigen Brook, Armadale, *GJ & BJ Keighery s.n.*, 10 Jan. 1999.

OTHER RECORDS: Harvey River, *GJ Keighery 16889*; Yagan Reserve, *GJ Keighery 16858*; Broadwater Nature Reserve, *G.J. Keighery 16944*; Rosa Glen, *B Raynor s.n.*, 3Nov. 2006.

NOTES: Plants of this species grown in Perth were originally sourced from nurseries in eastern Australia, therefore, it is probable that material of this species naturalized in the south-west originates from eastern Australia.

FABACEAE

Kennedia nigricans **Labill. (black kennedia)**

NATURAL DISTRIBUTION: Esperance Sandplains IBRA Region.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Swamps, coastal sands, damplands.

FIRST RECORD: Mayfield Road, Waroona Shire, *GJ Keighery 14413*.

OTHER RECORDS: Melaleuca Park, *GJ Keighery 14467*; Two Rocks, *KC Richardson 119*.

NOTES: Self-seeding in several sites on the Swan Coastal Plain. Locally abundant along Mayfield Road verge.

GOODENIACEAE

Lechenaultia biloba **Lindl. (blue leschenaultia)**

NATURAL DISTRIBUTION: Avon Wheatbelt, Geraldton Sandplains, Jarrah Forest, Swan Coastal Plain IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Jarrah/banksia low woodland.

FIRST RECORD: Shenton Bushland, *GJ Keighery 17333*.

OTHER RECORDS: None known.

NOTES: This species was introduced into Shenton Bushland in gravel used for road surfacing. It is normally found in the Perth area along the Darling escarpment and adjacent alluvial and colluvial soils of the Ridge Hill Shelf and Guildford Formation. Currently it is maintaining itself by vegetative spread and occupies about 300 m^2.

LAMIACEAE

Dasymalla teckiana **(F Muell.) BJ Conn & M Henwood**

NATURAL DISTRIBUTION: Avon Wheatbelt, Coolgardie, Yalgoo IBRA Regions.

WEEDY DISTRIBUTION: Jarrah Forest IBRA Region.

HABITATS: Open rail verges.

FIRST RECORD: John Forrest National Park, *GJ Keighery 11446*.

OTHER RECORDS: None known.

NOTES: Introduced to John Forrest National Park by railway construction. Previously known as *Pityrodia teckiana* (F Muell.) E Pritzel.

MELIACEAE

Melia azederach **L. (cape lilac, white cedar)**

NATURAL DISTRIBUTION: North Kimberley, Ord Victoria Plains, Central Kimberley IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain, Jarrah Forest IBRA Regions.

HABITATS: Jarrah woodland, sumps, road verges.

FIRST RECORD: Kwinana Beach, *G Keighery 9229*.

OTHER RECORDS: Kalgoorlie, *G Barrett s.n.*, Feb. 1992; Garden Island, *B Wykes 38/96*; Rottnest Island, *E Rippey 18*; Lake Joondalup, *L Sage s.n.*, 6 Nov. 1997; Stony Brook, *A McGilvray 4208*; McLarty Settlement, *G Keighery 13233*; Beckenham, *G Keighery 11444*.

NOTES: Does not appear to invade bushland, confined to highly disturbed sites. Frequently recorded in drainage sumps. The origin of naturalized plants is uncertain as early plantings were stated to be from seeds gathered in India or Cape Town, whereas the 90+ year old plantings at Houghton's Winery are supposedly from the Kimberley.

FABACEAE

Acacia acuminata **Benth. (jam)**

NATURAL DISTRIBUTION: Coolgardie, Murchison, Yalgoo, Avon Wheatbelt, Esperance Sandplains, Geraldton Sandplains, Jarrah Forest, Mallee IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain, Jarrah Forest IBRA Regions.

HABITATS: Jarrah woodland, winter wet *Callitris* shrubland.

FIRST RECORD: May Drive, Kings Park, *GJ & BJ Keighery 269*.

OTHER RECORDS: Listed as a weed in Kings Park by Bennett (1995).

NOTES: Introduced in John Forrest National Park and probably to the Swan Coastal Plain at Mundijong by railway construction. Planted as a feature in Kings Park and seeds prolifically after wildfires.

Acacia amblyophylla **F Muell.**

NATURAL DISTRIBUTION: Carnarvon, Yalgoo IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Tuart/banksia woodland.

FIRST RECORD: Lovekin to May Drive, Kings Park, *GJ Keighery 16085*.

OTHER RECORDS: None known.

NOTES: Planted as a feature in Kings Park; seeds into bushland after fires.

Acacia blakelyi **Maiden**

NATURAL DISTRIBUTION: Avon Wheatbelt, Geraldton Sandplains, Jarrah Forest, Swan Coastal Plain IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Tuart/banksia woodland.

FIRST RECORD: Boomerang Walk, Kings Park, *GJ Keighery 13062*.

OTHER RECORDS: Listed as a weed in Barrett and Tay (2005).

NOTES: Planted along tracks, seeding and established prolifically after fire. Several hundred mature plants now occur in Kings Park.

Acacia celastrifolia **Benth. (glowing wattle)**

NATURAL DISTRIBUTION: Coolgardie, Avon Wheatbelt, Geraldton Sandplains, Esperance Sandplains, Mallee, Jarrah Forest, Swan Coastal Plain IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain and Jarrah Forest IBRA Regions.

HABITATS: Jarrah woodland and forest.

FIRST RECORD: 1 km north-east of Dwellingup, *G Keighery 13132*.

OTHER RECORDS: South-east of Pinjarra, *G & B Keighery 567*.

NOTES: Forms of this species have been widely used as road side plantings and for revegetation purposes, and plants now occur as localised escapes in the Darling Range and near Yarloop.

Acacia hilliana **Maiden**

NATURAL DISTRIBUTION: Ord Victoria Plains, Dampier Land, Great Sandy Desert, Little Sandy Desert, Pilbara, Tanami, Central Ranges IBRA Regions.

WEEDY DISTRIBUTION: Jarrah Forest IBRA Region.

HABITATS: Winter-wet flats.

FIRST RECORD: Caladenia Hill Farm, 30 km east-north-east of Mount Barker, *M Luscombe 138*.

OTHER RECORDS: None known.

NOTES: Garden escape, perhaps not truly naturalized; requires an on-site inspection.

Acacia lasiocalyx **CRP Andrews (silver wattle)**

NATURAL DISTRIBUTION: Coolgardie, Murchison, Avon Wheatbelt, Geraldton Sandplains, Jarrah Forest, Esperance Sandplains, Mallee IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Tuart/banksia woodland.

FIRST RECORD: Kings Park, 11 April 1973, *Selk 2266* (KPBG).

OTHER RECORDS: May Drive, Kings Park, *GJ Keighery 15357*.

NOTES: Planted as a feature at the end of the 'vista' in Kings Park in the 1960s. Seeds prolifically into adjacent bushland following fire; now largely eradicated.

Acacia microbotrya **Benth. (manna wattle)**

NATURAL DISTRIBUTION: Murchison, Geraldton Sandplains, Avon Wheatbelt, Swan Coastal Plain, Jarrah Forest, Mallee, Esperance Sandplain IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Wet heath, tuart woodlands, banksia woodlands.

FIRST RECORD: Kings Park, *Selk 2357* (KPBG).

OTHER RECORDS: Collie River, Eaton, *G Keighery 14124*; Mundijong Road, Mundijong, *G Keighery 16271*; Point Walter Reserve, Melville, *G Keighery 17204*; Smyth Road Bushland, Nedlands, *G Keighery 17205*.

NOTES: Amenity plantings of this species have escaped in Kings Park (Bennett 1995). This species suckers strongly after fire, forming large clones.

Acacia lasiocarpa **Benth. var. *lasiocarpa* (panjang)**

NATURAL DISTRIBUTION: Avon Wheatbelt, Geraldton Sandplains, Jarrah Forest, Swan Coastal Plain IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Disturbed *Melaleuca preissiana* low woodland and old railway embankment.

FIRST RECORD: Emma Treeby Reserve, Jandakot, *G Keighery 17980.*

OTHER RECORDS: None known.

NOTES: Introduced to Emma Treeby Reserve in the limestone fill for railway and roads through this naturally swampy area. *Acacia lasiocarpa* var. *bracteolata* Maslin occurs naturally in this area. The nominate variety occurs on calcareous sands and limestone outcrops near the coast.

Acacia pulchella **R.Br. var. *pulchella* (prickly Moses)**

NATURAL DISTRIBUTION: Avon Wheatbelt, Geraldton Sandplains, Esperance Sandplains, Jarrah Forest, Swan Coastal Plain, Warren IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Jarrah woodland.

FIRST RECORD: Shenton Bushland, *KL Brown 287*.

OTHER RECORDS: Recorded as a weed from Kings Park by Barrett and Tay (2005), but no voucher seen.

NOTES: The normal taxon found in Shenton Bushland is *Acacia pulchella* var. *glaberrima* Meisn. This variety occupies well-drained sandy soils compared with the nominate variety, which occurs on heavier soils (laterites, loams, granite) or swamps in the Perth area, although the ranges overlap considerably. One of four species (*Acacia flagelliformis*, *Lechenaultia biloba* and *Dillwynia* aff. *cinerascens* [*GJ & BJ Keighery 562*]) introduced to Shenton bushland via laterite from the Perth Hills being used as road surfacing material. *Acacia pulchella* var. *glaberrima* and *Lechenaultia biloba* have spread, either clonally (*Lechenaultia*) or by seed (*Acacia*). *Acacia flagelliformis* and *Dillwynia* aff. *cinerascens* (*GJ & BJ Keighery 562*) have persisted with little evidence of spread.

Albizia lebbek **(L.) Benth. (woman's tongue)**

NATURAL DISTRIBUTION: North Kimberley, Central Kimberley, Ord Victoria Plains IBRA Regions.

WEEDY DISTRIBUTION: Pilbara, Dampier Land IBRA Regions.

HABITATS: Invading creek lines in the Pilbara, spreading around the edges of Lake Kununurra and Lily Creek Lagoon in the Kimberley.

FIRST RECORD: Port Hedland, *ET Bailey 1-53*.

OTHER RECORDS: Dampier, *GJ& BJ Keighery 899*; Derby, *GJ Keighery 17503*.

NOTES: This species is naturalizing around many towns in the Kimberley and Pilbara where it has been extensively planted for shade. For example, it has been reported as spreading around Kununurra from non-local plantings (AN Start, pers. comm.), but no specimens from this area have been seen. The origin of *Bailey s.n.* is unknown, and it could represent cultivated or naturalized material. The form naturalized in the Pilbara and Kimberley is very different in appearance to plants from native Kimberley populations. Planted at Millstream Station in the early twentieth century and being eradicated (Anon. 2007).

***Paraserianthes lophantha* (Willd.) IC Nielsen subsp. *lophantha* (albizia)**

NATURAL DISTRIBUTION: Geraldton Sandplains, Swan Coastal Plain, Jarrah Forest, Warren, Esperance Sandplains IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Not recorded, but natural populations occur in wetlands and around granite rocks.

FIRST RECORD: Kings Park, no voucher seen.

OTHER RECORDS: None known.

NOTES: Recorded as a weed in Kings Park and Bold Park by Barrett and Tay (2005). A serious weed in Victoria and Tasmania in eastern Australia and in the Pacific Islands, South Africa, New Zealand and California.

MYRTACEAE

***Agonis flexuosa* (Willd.) Sweet var. *flexuosa* (peppermint)**

NATURAL DISTRIBUTION: Swan Coastal Plain, Jarrah Forest, Warren IBRA regions.

WEEDY DISTRIBUTION: Swan Coastal Plain, Jarrah Forest IBRA Regions.

HABITATS: *Banksia* low woodland with emergent tuart tall woodland in Kings Park, tuart tall woodland in Yanchep.

FIRST RECORD: Boomerang Walk, Kings Park, Perth, *GJ Keighery 16191*.

OTHER RECORDS: Yanchep National Park, *GJ Keighery 17015*; Lesmurdie Falls National Park, *GJ Keighery 17109*.

NOTES: In the Perth Metro area, the natural range is on the coastal Quindalup dunes and along the Swan River, between Fremantle and Claremont and north to Bold Park. Roadside plantings of this species were made in Kings Park in the 1930–40s and have subsequently spread widely into the bushland, especially after fires stimulated germination of seedlings. Currently being removed as part of the management plan for Kings Park.

***Callistemon phoenicus* F Muell. (lesser bottlebrush)**

NATURAL DISTRIBUTION: Pilbara, Murchison, Yalgoo, Coolgardie, Avon Wheatbelt, Geraldton Sandplains, Mallee, Jarrah Forest, Esperance Sandplains IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Wandoo, tuart/banksia woodland.

FIRST RECORD: Kings Park, Perth, *GJ Keighery 16402*.

OTHER RECORDS: Keighery and Keighery (2007) have recorded this species spreading from plantings in Middle Swan.

NOTES: Normally on or around winter-wet flats in the drier portions of this species' range, the capacity of this species to invade dry sites around Perth is surprising.

***Calothammnus chrysantherus* F Muell.**

NATURAL DISTRIBUTION: Carnarvon, Yalgoo, Avon Wheatbelt, Geraldton Sandplain IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Tuart/banksia woodland.

FIRST RECORD: Nature Trail, Kings Park, *GJ Keighery 16084*.

OTHER RECORDS: None known.

NOTES: Seeding and established in bushland in Kings Park, south-east of the DNA tower. Numbers of plants present at this site have increased dramatically over the past decade.

***Calothamnus graniticus* Hawkeswood subsp. *graniticus*.**

NATURAL DISTRIBUTION: Jarrah Forest IBRA Region.

WEEDY DISTRIBUTION: Swan Coastal Plain, Jarrah Forest IBRA Region.

HABITATS: Tuart/banksia woodland, road verges, jarrah woodland.

FIRST RECORD: 1 km north-east of Dwellingup, *GJ Keighery 13133*.

OTHER RECORDS: Kings Park, *GJ Keighery 16918*.

NOTES: Seeding and established along roadsides north of Dwellingup and in Kings Park. Possibility of hybridization exists between scarp (subsp. *leptophyllus* Hawkeswood) and Cape Naturaliste (subsp. *graniticus*) subspecies.

***Calothamnus quadrifidus* R. Br. subsp. *quadrifidus* (one-sided bottlebrush)**

NATURAL DISTRIBUTION: Carnarvon, Coolgardie, Geraldton Sandplains, Avon Wheatbelt, Jarrah Forest, Swan Coastal, Mallee and Esperance Sandplains Plains IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Wandoo/Marri woodland, Banksia woodland.

FIRST RECORD: Opposite Onslow Road, Kings Park, *GJ Keighery 16360*.

OTHER RECORDS: Talbot Road Reserve, Shire of Swan, *G & B Keighery 573*.

NOTES: Friends of Koondoola Bushland in the City of Wanneroo have removed over 5000 seedlings of this species, originating from amenity plantings, from banksia woodland in Koondoola (Keighery & Keighery 2007). The species also has self-perpetuating populations in Kings Park and from roadside plantings. There is significant risk of hybridization between local and introduced forms of this species.

***Calothamnus quadrifidus* subsp. *homalophyllus* (F Muell.) AS George & N Gibson (Murchison clawflower)**

NATURAL DISTRIBUTION: Avon Wheatbelt, Geraldton Sandplain IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Tuart/banksia woodland.

FIRST RECORD: Kings Park, *G Keighery 16914*.

OTHER RECORDS: None known.

NOTES: Plantings of this subspecies have resulted in dense monocultures in Kings Park after seeding into tuart/banksia woodland. Hybrids have been formed between this species and *C. validus* (*G Keighery 16917*) in Kings Park (Keighery & Keighery 2007).

Calothamnus quadrifidus **subsp. *teretifolius* AS George & N Gibson (ironstone clawflower)**

NATURAL DISTRIBUTION: Swan Coastal Plain IBRA Region.

WEEDY DISTRIBUTION: Swan Coastal Plain and Jarrah Forest IBRA Regions.

HABITATS: Jarrah /marri and banksia woodland.

FIRST RECORD: Gravel Pit, Evans Road, *RJ Cranfield 15704*.

OTHER RECORDS: Wonnerup East Road, *RJ Cranfield 17648*; 5 km north of Brockman Highway on Sues Road, *RJ Cranfield 17654*; Ambergate Regional Park, *RJ Cranfield 17676*.

NOTES: Plantings of this subspecies have occurred along main road verges (e.g. Sues Road), next to experimental arboreta and in gravel pits in many parts of the Blackwood Plateau. This gives an apparently much wider range and ecological amplitude to what is an extremely restricted ironstone endemic of the base and slopes of the Whicher Range.

Calothamnus rupestris **Schauer (mouse ears)**

NATURAL DISTRIBUTION: Avon Wheatbelt, Swan Coastal Plain, Jarrah Forest IBRA Regions.

WEEDY DISTRIBUTION: Jarrah Forest IBRA Region.

HABITATS: Road verges, jarrah/bullich/blackbutt Forest.

FIRST RECORD: Ten Mile Dam, Bramley National Park, *G & B Keighery 996*.

OTHER RECORDS: None known.

NOTES: Naturalized from plantings along road verges and forming a dense monoculture, subsequently spreading downslope into adjacent bushland.

Calothamnus validus **S Moore (Barrens clawflower)**

NATURAL DISTRIBUTION: Esperance IBRA Region.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Tuart/banksia woodland.

FIRST RECORD: Kings Park, *G Keighery 16916.*

OTHER RECORDS: None known.

NOTES: Naturalized from plantings and forming dense monocultures in Kings Park.

Chamelaucium uncinatum **Schauer (Geraldton wax)**

NATURAL DISTRIBUTION: Swan Coastal Plain, Geraldton Sandplains IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain, Jarrah Forest and Avon IBRA Regions.

HABITATS: Banksia low woodland, tuart tall woodland, coastal heath.

FIRST RECORD: Wambyn Nature Reserve, west of York, *GJ Keighery & JJ Alford 16*.

OTHER RECORDS: Wannamal, *GJ Keighery 16105*; Blue Gum Lake, *K Brown 310*; Talbot Road Reserve, Shire of Swan *GJ Keighery 11831;* Wireless Hill, Applecross, *GJ Keighery 14292*; Bullsbrook Nature Reserve, *GJ Keighery 11831, 14414* & *G Keighery & B Keighery 582*; Devil's Elbow, Peppermint Grove, *GJ Keighery 13088*; 1 km north of Quairading on Tammin Road, *GJ Keighery 15510*; Boomerang Walk, Kings Park, Perth, *GJ Keighery 15689*; Woodvale Nature Reserve, *GJ Keighery 15948*; Troy Avenue, Marmion, *GJ Keighery 16632*; Yanchep National Park Entrance, *GJ Keighery 13618*; Burleigh Park, Chittering, *GJ & BJKeighery 145*; Shenton Bushland, Nedlands, *GJ & BJKeighery 561*.

NOTES: The natural range of this species in the Perth region is on the coastal Quindalup dunes in the Perth Metropolitan area. Hybridization with local native forms is occurring in Bold Park (Barrett et al. 1999).

Eucalyptus conferruminata **subsp. *recherche* D Nicolle & ME French (Bald Island marlock)**

NATURAL DISTRIBUTION: Esperance IBRA Region.

WEEDY DISTRIBUTION: Warren IBRA Region.

HABITATS: Karri forest, road verges.

FIRST RECORD: Forest Grove National Park, *GJ Keighery 16628*.

OTHER RECORDS: I have observed this species seeding around roadside plantings at Augusta.

NOTES: Recorded as probably naturalized in Cape Le Grande National Park (Nicolle et al. 2008); in this area the subspecies is confined to offshore islands. A possible voucher is *Wajon 184*.

Eucalyptus eyrthrocorys **F Muell. (illyarrie)**

NATURAL DISTRIBUTION: Geraldton Sandplains IBRA Region.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Tuart/banksia woodland. Limestone shrubland.

FIRST RECORD: Mount Eliza, Kings Park, Perth, *GJ Keighery 16081*.

OTHER RECORDS: None known, listed as a weed in Kings Park by Bennett (1995).

NOTES: Seeded into bushland along limestone scarp in Kings Park, now largely removed.

Eucalyptus gomphocephala **DC (tuart)**

NATURAL DISTRIBUTION: Swan Coastal Plain IBRA Region.

WEEDY DISTRIBUTION: Geraldton Sandplains, Esperance Plain IBRA Regions.

HABITATS: Road verges, paddocks.

NOTES: This species is self-seeding from plantations at Geraldton and Esperance. It has persisted for many years at the old telegraph station at Eucla. It is also naturalising from plantations in Victoria (Carr 1993).

Eucalyptus lane-poolei **Maiden (butter gum)**

NATURAL DISTRIBUTION: Geraldton Sandplains IBRA Region.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Tuart/banksia woodland.

FIRST RECORD: Listed as a weed in Kings Park by Bennett (1995) and Barrett and Tay (2005).

OTHER RECORDS: None known.

NOTES: Bennett (1995) notes that *E. lane-poolei* self-seeded in Kings Park but has since died out. The species is listed as present by Barrett and Tay (2005). A survey to establish whether this species is still present would be desirable.

***Eucalyptus megacornuta* CA Gardner (warty yate)**

NATURAL DISTRIBUTION: Esperance IBRA Region.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Tuart/banksia woodland.

FIRST RECORD: Kings Park Arboretum, 7 May 1972, *Selk 493* (KPBG).

OTHER RECORDS: None known.

NOTES: Listed as a weed in Kings Park by Barrett and Tay (2005). Invasion into bushland by this species at Kings Park is discussed by Ruthrof (2004).

***Eucalyptus utilis* Brooker & Hopper**

NATURAL DISTRIBUTION: Mallee, Esperance Plains IBRA Regions.

WEEDY DISTRIBUTION: Jarrah Forest, Swan Coastal Plain IBRA Region.

HABITATS: *Melaleuca lanceolata/Callitris preissii* woodland and coastal heath.

FIRST RECORD: Moses Rock, *GJ & BJ Keighery 1064*.

OTHER RECORDS: Longreach Point, Rottnest, *GJ.& BJ Keighery 1790*.

NOTES: Self-seeding from plantings, now spreading rapidly. This species has spread into coastal heath at Rottnest following a wildfire that caused mass germination of seed.

***Kunzea baxteri* (Klotzsch) Schauer**

NATURAL DISTRIBUTION: Esperance IBRA Region

WEEDY DISTRIBUTION: Swan Coastal Plain, Jarrah Forest, Esperance Sandplain IBRA Regions.

HABITATS: Heath, jarrah and wandoo woodland.

FIRST RECORD: Bluff Knoll, *GJ Keighery 12179*.

OTHER RECORDS: Walyunga National Park, *G Keighery 13060*; 5 km. north of Dwellingup, *G & B Keighery 543*; Waroona, *G & B Keighery 1041*.

NOTES: This species and the following species were planted as ornamental features around the car park at Bluff Knoll in the late 1960s. With subsequent fires and the opening up of surrounding heath through the effects of dieback, both species are spreading down-slope. Plantings of this species at the entrance to Walyunga National Park are also spreading into adjacent wandoo woodland, and large populations have also established in old gravel pits and mine sites north of Dwellingup, from rehabilitation and amenity plantings by Alcoa.

***Melaleuca diosmifolia* Andrews**

NATURAL DISTRIBUTION: Esperance, Jarrah Forest IBRA Regions.

WEEDY DISTRIBUTION: Esperance, Swan Coastal Plain IBRA Region.

HABITATS: Mallee heath.

FIRST RECORD: Bluff Knoll carpark, *G Keighery 12178*.

OTHER RECORDS: None known.

NOTES: Spreading from plantings (with *Kunzea baxteri*) into dieback-affected heath at Bluff Knoll. Collections of this weed have been cited as a newly-discovered population of this Priority 3 species (Thomson et al. 1993).

***Melaleuca lanceolata* Otto (Rottnest tea tree)**

NATURAL DISTRIBUTION: Coolgardie, Hampton, Murchison, Nullarbor, Avon Wheatbelt, Geraldton Sandplains, Mallee, Esperance Sandplains, Jarrah Forest, Swan Coastal Plain, Warren IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Tuart and banksia woodland.

FIRST RECORD: Boomerang Walk, Kings Park, Perth, *GJ Keighery 15687*.

OTHER RECORDS: None known.

NOTES: Plantings of this species have resulted in a dense monoculture in Kings Park in banksia woodland after fires have killed the adults and stimulated germination of seedlings. These dense stands have virtually no understorey species present in what is normally a species-rich open woodland.

This species has a number of poorly-defined morphological forms formerly treated as subspecies. If seed material from outside the Swan Coastal Plain was used in Kings Park, a non-local form could have been introduced.

***Melaleuca megacephala* F Muell.**

NATURAL DISTRIBUTION: Yalgoo, Geraldton Sandplains IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: *Banksia attenuata/B. menziesii* woodland.

FIRST RECORD: Reid Highway Bushland, Malaga, *GJ & BJ Keighery 1865*.

OTHER RECORDS: None known.

NOTES: Self-seeding from plantings, now spreading rapidly.

***Melaleuca nesophila* F Muell. (freeway melaleuca)**

NATURAL DISTRIBUTION: Esperance IBRA Region.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Banksia woodlands, sandy road verges.

FIRST RECORD: Old Two Rocks tip, *KC Richardson 28*.

OTHER RECORDS: None known.

NOTES: Spreading from plantings along many roads around Perth, especially along Morley Drive in Perth.

Melaleuca pentagona* Labill. var. *pentagona

NATURAL DISTRIBUTION: Esperance IBRA Region.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Tuart and banksia woodland.

FIRST RECORD: No voucher located.

OTHER RECORDS: None known.

NOTES: Listed as a weed in Kings Park by Bennett (1995) and Barrett and Tay (2005). I have recorded numerous seedlings around planted material and the species is apparently naturalising.

***Verticordia monadelpha*. Turcz. var *monadelpha* (pink woolly featherflower)**

NATURAL DISTRIBUTION: Geraldton Sandplains, Avon Wheatbelt IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Banksia and tuart Woodland.

FIRST RECORD: Lovekin Drive, Kings Park, Perth, *GJ Keighery 16192*.

OTHER RECORDS: None known.

NOTES: Self-seeding in Kings Park from seed scattered in bushland as part of a 'beautification program' in the 1960s.

NYCTAGINACEAE

***Boerhavia coccinea* Mill. (tar vine)**

NATURAL DISTRIBUTION: North Kimberley, Central Kimberley, Ord Victoria Plains, Dampier Land, Victoria Bonaparte,Carnarvon, Central Ranges, Gascoyne, Gibson Desert, Great Sandy Desert, Great Victoria Desert, Murchison, Pilbara, Tanami, Geraldton Sandplains IBRA Regions.

WEEDY DISTRIBUTION: Coolgardie, Avon Wheatbelt, Geraldton Sandplains IBRA Regions.

HABITATS: Road verges, paddocks and wasteland.

FIRST RECORD: Moora, *K. Dean s.n., April 1965*.

OTHER RECORDS: Cunderdin, *G Keighery 7354*; Yandanooka, *A Carr 326, R. Soullier 452*; Mogumber, *BJ Lepschi & TR Lally BJL2478*; Green Hills Siding, *BJ Lepschi & TR Lally BJL342*; Wyalkatchem Railway Siding, *BJ Lepschi & SG Webster BJL3867*; Kalgoorlie, *G Barrett s.n.*, 3 May 1993.

NOTES: Spreading along transport corridors. Apparently native to islands and near-coastal areas south to Geraldton. Early collection by weed scientist from Moora, then Cunderdin in 1985 and the rest late 1990s.

***Boerhavia schomburkiana* Oliv.**

NATIVE DISTRIBUTION: North Kimberley, Central Kimberley, Dampier Land, Victoria Bonaparte, Carnarvon, Central Ranges, Murchison, Pilbara IBRA Regions.

WEEDY DISTRIBUTION: Avon Wheatbelt, Geraldton Sandplains IBRA Regions.

HABITATS: Riverine banks, wetlands, paddocks, road verges.

FIRST RECORD: Northam, *CV Cailes s.n., November 1952*.

OTHER RECORDS: Northam Blades Brook, York, *JW Green 4968*; Avon River Bank, York, *G Keighery 7356*; Maiseys Wetland, Dowerin, *G Keighery 12262*; Jingemia Hill, Watheroo National Park, *G Keighery 15929*; Gwambygine Pool, York, *C Howell 271*.

NOTES: Spreading along transport corridors (railways and roadsides).

NYMPHACEAE

***Nymphaea macrosperma* Merr. & LM Perry (water lily)**

NATIVE DISTRIBUTION: North Kimberley, Victoria Bonaparte IBRA Regions.

WEEDY DISTRIBUTION: Pilbara IBRA Region.

HABITATS: Riverine pools.

FIRST RECORD: Crystal Pool, *RF Black, s.n.*, 5 Sept. 1974.

OTHER RECORDS: Chinderwariner Pool, Millstream, *C Olsson 61*; Millstream, *K Vollprecht s.n.*, no date.

NOTES: Introduced as an ornamental, probably from overseas stock.

PITTOSPORACEAE

***Pittosporum angustifolium* Lodd. (weeping pittosporum)**

NATIVE DISTRIBUTION: Ord Victoria Plain, Carnarvon, Central Ranges, Gascoyne, Gibson Desert, Great Victoria Desert, Nullarbor, Murchison, Pilbara, Tanami, Yalgoo, Coolgardie, Geraldton Sandplains, Avon Wheatbelt, Mallee, Esperance Sandplains, Swan Coastal Plain IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Tuart/banksia woodland.

FIRST RECORD: Woodvale Nature Reserve, *G Keighery 16270 & 16430*.

OTHER RECORDS: None known.

NOTES: Self-seeding into tuart/banksia woodland at Woodvale Nature Reserve from plantings.

PORTULACACEAE

***Portulaca oleracea* L. (purslane)**

NATURAL DISTRIBUTION: North Kimberley, Ord Bonaparte, Ord Victoria Plains, Central Kimberley, Dampier Land, Tanami, Little Sandy Desert, Great Sandy Desert, Central Ranges, Pilbara, Carnarvon, Ashburton, Murchison IBRA Regions.

WEEDY DISTRIBUTION: Victoria Bonaparte, Dampier Land, Avon Wheatbelt, Esperance Sandplains, Geraldton Sandplains, Mallee, Swan Coastal Plain IBRA Regions.

HABITATS: Road verges, vacant lots, gardens.

FIRST RECORD: Gardner (1925) treated southern plants of this species as introduced. In southern Western Australia, this species is always found in 'weedy' habitats, unlike northern (tropical) occurrences which are mostly in natural habitats.

OTHER RECORDS: Northampton, *IB Shepherd 212*; 6.6 km south of Mogumber, *R Davies 2970*; Scarborough, *JF Smith 76*; Brixton Regional Park, *G Keighery 15933*; Lake Ngartiminny, *R Cranfield 22563*; 50 km north-east of Hyden, *JM Plint 328*; One mile east of Ravensthorpe, *E Tink 575 & 577*; 3 km north-west of One Arm Point, *BJ Carter 1168*; Disused tip north of meat works, *AA Mitchell 2144*.

NOTES: Bean (2007) lists this species as alien; however, Danin et al. (1978, pp. 177 and 201) in their worldwide review of this species noted, 'In Australia there is a high diversity of forms which differ from those in all other parts of the world' and, 'Most specimens that we have seen from different parts of Australia and New Zealand do not agree with our description of the subspecies from other parts of the world', which hardly fits an alien taxa. Native to tropical and arid Western Australia. Weedy form in temperate Western Australia and a few towns in the tropical north.

PROTEACEAE

Banksia undata* Endl. AR Mast & KR Theile var. *undata

NATURAL DISTRIBUTION: Jarrah Forest IBRA Region.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: sandy jarrah–marri woodland.

FIRST RECORD: Shenton Park Bushland, *G & B Keighery 1793*.

OTHER RECORDS: None known.

NOTES: Initial introduction via garden plantings around buildings, subsequently self-seeding into adjacent wetland. Previously known as *Dryandra praemorsa* var. *praemorsa.*

***Conospermum huegelii* Endl.**

NATURAL DISTRIBUTION: Swan Coastal Plain, Jarrah Forest IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: sandy swamps.

FIRST RECORD: Emma Treeby Reserve, Jandakot, *G Keighery 16006*.

OTHER RECORDS: None known.

NOTES: Initial introduction via railroad works or by rail traffic; subsequently self-seeding into adjacent wetland. Normally found on alluvial or shallow granite soils along the Darling Escarpment.

***Grevillea curviloba* McGill. subsp. *curviloba* (grevillea)**

NATIVE DISTRIBUTION: Swan Coastal Plain IBRA Region.

WEEDY DISTRIBUTION: Swan Coastal Plain, Jarrah Forest IBRA Regions.

HABITATS: Drainage sumps and road verges

FIRST RECORD: Burley Park Reserve, Bullsbrook, *G & B Keighery 146*.

NOTES: This extremely localized and rare subspecies has been widely used as a roadside planting throughout the Perth area and is now seeding around Perth from these old plantings.

***Grevillea leucopteris* Meisn. (white plume grevillea)**

NATIVE DISTRIBUTION: Avon Wheatbelt, Geraldton Sandplains, Swan Coastal Plain IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Drainage sumps and road verges.

FIRST RECORD: Gill Charwell Reserve, Boronia Road, *G Keighery 12280*.

NOTES: Populations self-seeding around Perth from old plantings.

***Grevillea rosieri* McGill.**

NATIVE DISTRIBUTION: Avon Wheatbelt, Geraldton Sandplains, Swan Coastal Plain IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Road verges.

FIRST RECORD: 1.4 km along Offer Road from Henty road, Burekup, *G & B Keighery* 150.

NOTES: Populations self-seeding around Burekup from old plantings.

***Hakea bucculenta* hybrids CA Gardner (red pokers)**

NATURAL DISTRIBUTION: Carnarvon, Yalgoo, Geraldton Sandplains, Swan Coastal Plain IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Wandoo/powderbark wandoo woodlands.

FIRST RECORD: Dryandra State Forest, *G Keighery 12746*.

OTHER RECORDS: None known.

NOTES: Hybrid swarm of *Hakea bucculenta* ? *multilineata* invading wandoo and powderbark wandoo woodlands at Dryandra.

***Hakea multilineata* Meisn. (grass leaf hakea)**

NATURAL DISTRIBUTION: Coolgardie, Jarrah Forest, Avon Wheatbelt, Esperance Sandplains, Mallee IBRA Regions.

WEEDY DISTRIBUTION: Jarrah Forest IBRA Region.

HABITATS: Wandoo/powderbark wandoo woodlands.

FIRST RECORD: Dryandra, *G Keighery 12280*.

OTHER RECORDS: None known, but I have recently observed self-seeding in plantings in the Perth Hills.

NOTES: This and the previous species were planted in the arboretum at Dryandra and have self-seeded after fires, invading wandoo and powderbark wandoo woodlands at Dryandra.

***Hakea costata* Meisn. (ribbed hakea)**

NATURAL DISTRIBUTION: Jarrah Forest, Swan Coastal Plain IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Tuart/banksia woodland.

FIRST RECORD: Kings Park, *G Keighery 16083*.

OTHER RECORDS: Listed as a weed in Kings Park by Bennett (1995).

NOTES: This species was planted along the nature trail in Kings Park. It slowly spread over the past 30 years until a fire caused massive seed fall and germination, creating a monoculture of this species over several 100 m^2 with over 1000 mature plants.

***Hakea laurina* R. Br. (pincushion hakea)**

NATURAL DISTRIBUTION: Avon Wheatbelt, Esperance Sandplains, Mallee IBRA Regions.

WEEDY DISTRIBUTION: Jarrah Forest, Swan Coastal Plain IBRA Region.

HABITATS: Jarrah woodland.

FIRST RECORD: Lesmurdie, *J Gathe 21*.

OTHER RECORDS: 3 km east of Porongurup, *G & B Keighery 384*; Waroona, *G & B Keighery 1039*.

NOTES: Widely planted and beginning to naturalise widely; potentially a serious weed. A weed in eastern Australia (Carr 1993).

***Hakea pycnoneura* Meisn.**

NATURAL DISTRIBUTION: Yalgoo, Avon Wheatbelt, Esperance Sandplains, Geraldton Sandplains, Mallee IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Tuart/banksia woodland.

FIRST RECORD: Kings Park, *G Keighery 14028*.

OTHER RECORDS: Listed as a weed in Kings Park by Barrett and Tay (2005).

NOTES: Self-seeding in Kings Park plantings at the Arthur Fairall Playground in 1970, over 168 mature plants are now located in mixed tuart/banksia woodland after fire.

Hakea recurva* Meisn. subsp. *recurva

NATURAL DISTRIBUTION: Carnarvon, Murchison, Yalgoo, Geraldton Sandplain, Avon Wheatbelt, Coolgardie IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: *Banksia attenuata/B. menziesii* woodland.

FIRST RECORD: Reid Highway Bushland, Malaga, *GJ & BJ Keighery 1866*.

OTHER RECORDS: None known.

NOTES: Self-seeding from roadside plantings; now spreading rapidly.

RUTACEAE

***Diplolaena dampieri* Desf. (southern diplolaena)**

NATURAL DISTRIBUTION: Warren, Jarrah Forest, Swan Coastal Plain IBRA Regions.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Tuart/banksia woodland.

FIRST RECORD: Woodvale Nature Reserve, *GJ Keighery 14389*.

OTHER RECORDS: None known.

NOTES: Self-seeded into banksia woodland at Woodvale Nature Reserve from plantings; now spreading rapidly. Northern end of natural range ends at Rockingham.

SAPINDACEAE

***Diplopeltis petiolaris* Benth.**

NATURAL DISTRIBUTION: Geraldton Sandplains IBRA Region.

WEEDY DISTRIBUTION: Swan Coastal Plain IBRA Region.

HABITATS: Banksia low woodland.

FIRST RECORD: Marmion Bushland, Perth, *GJ Keighery 16634*.

OTHER RECORDS: None known.

NOTES: The substantial population of this species recorded at Marmion Bushland is either a large range disjunction (from near Dongara) or more likely a naturalized population from previous plantings at the nearby closed CSIRO Marine Research Laboratories.

SOLANACEAE

***Solanum hoplopetalum* Bitter & Summerh. (thorny solanum)**

NATURAL DISTRIBUTION: Murchison, Yalgoo, Nullarbor, Geraldton Sandplains, and possibly Coolgardie, Avon Wheatbelt, Mallee IBRA Regions

WEEDY DISTRIBUTION: Geraldton Sandplains, Avon Wheatbelt, Swan Coastal Plain, Jarrah Forest, Esperance Sandplains, Mallee IBRA Regions.

HABITATS: At least 75 records in PERTH note road verges, paddocks, tracks, gravel pits as the habitat; few record this species in undisturbed bushland. The only records for the lower south-west (Swan Coastal Plain and Jarrah Forest) are entirely from road and rail verges.

FIRST RECORD: No locality (probably Narrogin), Narrogin Road Board s.n., 1 March 1923.

OTHER RECORDS: Selection from naturalized range: Riverside, Ajana, *D Porter 75*; Petrudor Rock Reserve, *M Hislop 1884*; 5.2 km north of Boyup Brook, *R Davis 4597*; 6 km north of Bullsbrook, *B Lepschi & T Lally 3332*; 2.5 km east of Kulin, Murray 488, Hopetoun Road, *E Tink 469*.

NOTES: Expanding along transport corridors. Lepschi (1996) notes that the natural range of *Solanum hoplopetalum* was arid and semi-arid Western Australia, and probably extended to parts of the Avon Wheatbelt and Mallee IBRA Regions. He did not consider that the species was native to Geraldton Sandplains, Swan Coastal Plain, Jarrah Forest or Esperance Sandplains IBRA Regions.

***Solanum lasiophyllum* Dunal ex Poir. (flannel bush)**

NATURAL DISTRIBUTION: Ord Victoria Plains, Great Sandy Desert, Little Sandy Desert, Gibson Desert, Central Ranges, Pilbara, Ashburton, Carnarvon, Murchison, Yalgoo, Nullarbor IBRA Regions, and possibly Geraldton Sandplains, Coolgardie, Avon Wheatbelt, Mallee IBRA Regions

WEEDY DISTRIBUTION: Geraldton Sandplains, Avon Wheatbelt, Swan Coastal Plain, Jarrah Forest, Mallee IBRA Regions.

HABITATS: Nearly all records from the weedy area of the species' range are from road verges or paddocks.

FIRST RECORD: Gingin, *CA Gardner 550*.

OTHER RECORDS: Selection from naturalized range: 23 km south-west of Wongan Hills, *B Lepschi & T Lally 2637*; 5 km north of Harvey, *G Keighery 16033*; 10 km east of Kulin, *AO Quicke 83*.

NOTES: B. Lepschi (pers. comm., 2012) noted that the natural range of *Solanum lasiophyllum* is likely to be similar to that of *S. hoplopetalum* but extends further south; naturalized populations are found from Jurien Bay south to Busselton.

APPENDIX 2

Doubtfully naturalized taxa.

ASTERACEAE

***Rhodanthe chlorocephala* subsp. *rosea* (Hook.) Paul G Wilson**

This taxon is commonly planted along road verges; however, like many planted or casually naturalized annuals it may not persist. It is, however, recorded as naturalized in Kings Park by Bennett (1995), but no voucher has been seen. There was also a record from Kensington Bushland (*BJ Lepschi & MH Brims 1944*) in 1995. Given the increasing use of this species in roadside plantings further records could be expected.

CASUARINACEAE

***Allocasuarina campestris* (Diels) LAS Johnson**

Collected from Kings Park in 1972 (*Selk 1887* [KPBG]), and recorded as 'established in bushland' on the specimen labels, but not recorded by Bennett (1995) or Barrett and Tay (2005). Presumably this taxon has not persisted at this site.

MYRTACEAE

***Beaufortia elegans* Schauer**

Collected from Kings Park in 1972 (*Selk 1889* [KPBG]), and on the specimen label recorded as 'established in bushland' on specimen labels, but not recorded by Bennett (1995) or Barrett and Tay (2005). Presumably this taxon has not persisted at this site.

***Eremaea fimbriata* Lindl.**

Collected from Kings Park in 1972 (*Selk 1888* [KPBG]), and on the specimen label recorded as 'established in bushland', but not recorded by Bennett (1995) or Barrett and Tay (2005). Presumably this taxon has not persisted at this site.

***Eucalyptus todtiana* F Muell.**

Bennett (1995) records this species as persisting in Kings Park from original plantings. I am uncertain if this species has naturalized or is merely persisting at this site, as I have not seen any evidence of naturalized populations and the species is not mentioned in Barrett and Tay (2005).

***Melaleuca calothamnoides* F Muell.**

Naturalized (adventive) from plantings in bushland at Kings Park (*G & B Keighery 203*).

POACEAE

***Heteropogon contortus* (L.) P Beauv. ex Roem. & Schult.**

This species (*G Keighery 16299*) was introduced by vehicles into Woodvale Nature Reserve during the past five years. Plants of *Heteropogon* were subsequently eliminated.

RUTACEAE

***Diplolaena angustifolia* Hook.**

Naturalized (adventive) from plantings in bushland at Kings Park (*G Keighery 17136*). Currently only a few plants are present.

APPENDIX 3

Problematic species (naturally weedy taxa, native weeds of agriculture, range expanders and species with unclear native status) requiring further study.

Determining the natural and non-natural ranges of native taxa with weedy tendencies is difficult, and there are still several major issues to resolve, including:

1. *Native species that are naturally weedy, with unknown or poorly understood natural ranges*

These include many wetland species such as *Azolla filiculoides* Lam. and *A. pinnata* R. Br. (Azollaceae). Both of these ferns are native species but occur readily in man-made habitats (dams, ponds, etc.), and they are now rarely encountered in the wild. There seems no doubt that their current range does not reflect their natural range, and it is likely that the second species is an introduction into Western Australia, since the only known record is from an urban artificial wetland. Also in this category are *Bolboschoenus caldwellii* (V Cook) Sojak (Cyperaceae), *Epaltes australis* (Asteraceae), *Glinus lotoides* (Molluginaceae), *Gratiola pubescens* R. Br. (Plantaginaceae), *Lemna disperma* Hegelm. (Araceae), *Ottelia ovalifolia* (R. Br.) Rich. (Hydrocharitaceae) and several *Ruppia* (Ruppiaceae) species.

2. *Native species that are expanding their ranges as suitable habitats occur*

The perennial form of *Ptilotus polystachyus* (Gaudich.) F Muell. (Amaranthaceae) is a common weed of old paddocks and road verges. It has become more frequent in many reserves on the Swan Coastal Plain over the past 20 years. This species is probably expanding its range into the higher rainfall areas of southern Western Australia. It is dispersing naturally via wind, road works (e.g. grading) and vehicle traffic.

Wheeler et al. (1992, p. 856) noted that *Josephinia eugeniae* F Muell. (Pedaliaceae) is native to the Kimberley, Pilbara, Ashburton, Carnarvon and Murchison but 'introduced further south to near Mullewa and Cue.' However, there is currently little disjunction between the southern and northern limits of this species' range in the pastoral region, except for a single record at Canna in the agricultural zone.

3. *Native species that are agricultural weeds within their native ranges*

Podotheca gnaphaloides Graham (Asteraceae) is very common in poorly managed pastures on the Swan Coastal Plain, *Vittadinia australasica* (Turcz.) NT Burb. (Asteraceae) is an occasionally abundant paddock weed in the northern wheatbelt, and *Muehlenbeckia adpressa* (Labill.) Meisn. (Polygonaceae) is a weed of neglected pastures in the southern wheatbelt (Hussey et al. 2007). These agricultural weeds are not treated further in this paper.

4. *Species whose status as naturalized or native is unresolved*

ASTERACEAE

***Cotula coronopifolia* L.**

There has been considerable discussion about the status of this species (e.g., see Romanowski 1994, 1995 and Heyligers 1995). Currently, Bean (2007) and Thompson (2007) regard the species as introduced from South Africa; however, distinct fresh and brackish ecotypes occur in Western Australia, suggesting the situation is more complex. Romanowski (2011) also noted that there is a Holocene pollen record for this species that indicates its long-term presence in Australia.

***Helichrysum luteoalbum* (L.) Rchb.**

Variously treated as native (Walsh & Entwisle 1999) or introduced (Lazarides et al. 1997) in Australia, but within Western Australia this species behaves as a weed, at least in the southern part of the state. For example, it has invaded Woodvale Reserve over the past 10 years, having never been previously recorded.

***Senecio condylus* I Thomps.**

This species is a common roadside weed, especially along freeways around Perth. It has never been recorded in undisturbed bushland. This newly described species (Thompson 2005) may prove to be an introduction into Western Australia.

CHENOPODIACEAE

***Salsola tragus* L.**

Rilke (1999) and Bean (2007) regard this species as alien. However, recent genetic data (Borger et al. 2008) shows that the Western Australian populations are native and should be regarded as *S. australis* R. Br. (Chinnock 2010).

JUNCACEAE

***Juncus bufonius* L.**

Bean (2007) listed this species as alien, because it is remote from its presumed native range and it is weedy in Australia. However, Kirschner (2002) showed that the distribution of *J. bufonius* is less disjunct compared to its weedy segregate *J. hybridus* Brot. and noted that distinct forms are found in Australia.

5. *Pantropical weedy species*

Wheeler et al. (1992) listed 21 species for which native or naturalized status is equivocal. These are listed here with additional comments:

- *Aeschynomene indica* L. (Fabaceae). Pantropical.
- *Ammannia auriculata* Willd. (Lythraceae). Weed, introduced from tropical Asia, (native to tropical Africa, America and Asia) with rice crops.
- *Brachyachne ambigua* Ohwi (Poaceae). Although listed as a native in the Flora of the Kimberley, collections are noted as a town weed in Wyndham.
- *Canavalia ensiformis* (L.) DC. (Fabaceae). Native to tropical America, often not listed as a weed, for example Lazarides et al. (1997).
- *Cyanthillium cinereum* (L.) H Rob. (Asteraceae). Pantropical weed.
- *Cyperus brevifolius* (Rottb.) Hassk. (Cyperaceae). Naturalized or possibly native to the Kimberley Region.
- *Echinochloa elliptica* PW Michael & Vickery (Poaceae). A native species, frequently a weed of rice crops.
- *Hedyotis corymbosa* (L.) Lam. (Rubiaceae). Collected once from disturbed ground, probably introduced.
- *Ipomoea aquatica* Forssk. (Convolvulaceae). Pantropical, treated as native to Queensland and the Northern Territory though perhaps introduced to Western Australia.
- *Herissantia crispa* (L.) Brizicky (Malvaceae). Pantropical weed, possibly native to tropical America;
- *Indigofera glandulosa* JC Wendl. (Fabaceae). Probably introduced from India.
- *Mnesithea granularis* (L.) de Koning & Sosef (Poaceae). Pantropical.

- *Panicum trichoides* Sw. (Poaceae). Treated by Wheeler et al. (1992) as possibly introduced to Australia, and by Webster (1987) as doubtfully native to Australia. Native to tropical America and Asia, introduced to tropical Africa.
- *Paspalum scrobiculatum* L. (Poaceae). Webster (1987) listed this as native, but as part of the *P. longifolium* Roxb. complex which is itself listed as a weed by Webster, though often listed as native and as such in the Australian Virtual Herbarium.
- *Phyllanthus amarus* Schumach. & Thonn. (Phyllanthaceae). Pantropical weed, native to tropical America;
- *Phyllanthus* sp. A [= *Phyllanthus lacerosus* Airy Shaw] (Phyllanthaceae). Native taxon, occurring in Western Australia, Northern Territory, Queensland and New South Wales.
- *Sporobolus* sp. A [= *Sporobolus blakei* De Nardi ex BK Simon] (Poaceae). Currently treated as native to Australia in Australian Virtual Herbarium.
- *Tribulus cistoides* L. (Zygophyllaceae). Pantropical weed.
- *Triumfetta* sp. C [= *T. pentandra* A Rich.] (Malvaceae). May be naturalized.
- *Urochloa reptans* (L.) Stapf. (Poaceae). Status uncertain. Webster (1987) listed this as doubtfully native to Australia.
- *Urochloa subquadriparia* (Trin.) RD Webster (Poaceae). Status uncertain. Webster (1987) listed this as introduced to Australia.

6. Eastern Australian-centred taxa

There are several species whose ranges are centred on eastern Australian that are currently considered introduced into Western Australia. *Acaena echinata* Nees (Rosaceae) was considered introduced by Orchard (1969), but is now regarded as native. *Acaena ovina* A Cunn. could also be considered as a native species, as there is no evidence that this taxon is introduced to Western Australia. *Acacia paradoxa* DC. (Fabaceae) appears to behave as a native species around Albany, but is naturally weedy and probably introduced to many sites outside this area. Both of these species should be subject to further taxonomic/genetic studies, and all of the above taxa require careful study to resolve the issues discussed.

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

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ABSTRACT

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

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

INTRODUCTION

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

STUDY SITE

The northern portion of the Forrestania Greenstone Belt is situated in the south-central portion of the Coolgardie Bioregion, near the boundary of the Mallee Bioregion (Interim Biogeographic Regionalisation of Australia—IBRA; Thackway & Cresswell 1995) and is part of the Roe Botanical District (Beard 1990). The belt is located approximately 90 km south of Southern Cross and c. 85 km north east of Hyden (Fig. 1). The Forrestania Greenstone Belt trends north to south, and is c. 100 km in length and c. 15 km west to east. The focus of this study is the northern 40 km of the belt. The latitudinal and longitudinal boundaries of the study area are roughly 32° 00’ S, 32° 25’ S and 119° 40’ E, 119° 50’ E, respectively. The land tenure for this greenstone belt, located in the Yilgarn Shire, is unallocated crown land.

Land use history

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

Climate

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

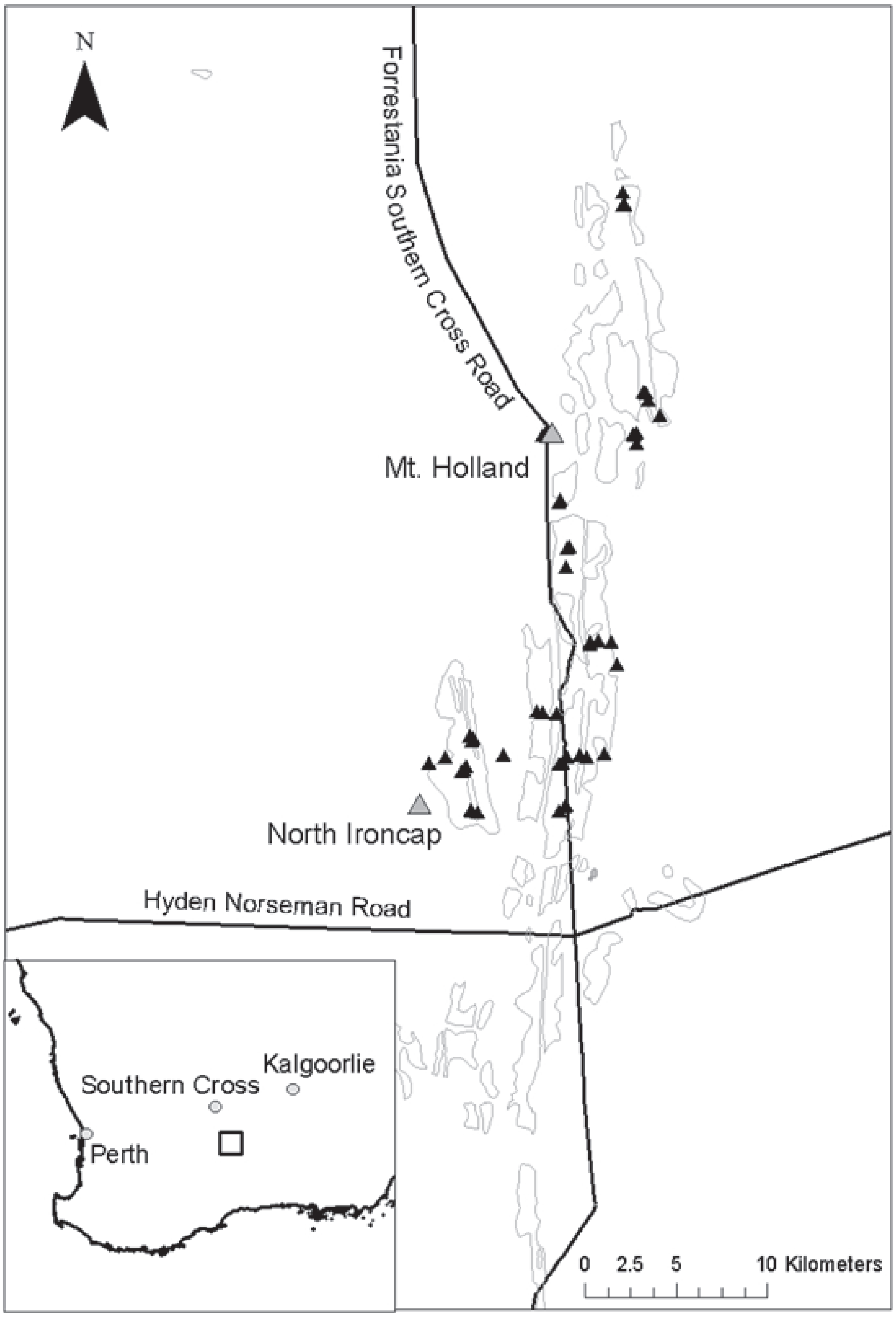

Figure 1. Map showing the location of the northern Forrestania Greenstone Belt survey area, with major landforms and landmarks indicated. The locations of the 50 permanent quadrats are marked by solid triangles (▲).

Hyden (c. 85 km south-west of the study area) is 343.3 mm, based on records from 1928 to 2010, with the months of June and December having the highest (50.6 mm) and lowest (13.7 mm) mean monthly rainfall, respectively. The average annual maximum is 24.8 °C and average annual minimum is 9.8 °C for the Hyden area, based on records from 1970–2009. The highest temperatures occur between December and March, with mean maximum temperatures exceeding 29 °C. The lowest daily minimum temperatures occur between June and September, where mean minimum temperatures are below 6 °C.

Geology

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

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

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

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

Vegetation

The northern Forrestania Greenstone Belt is characterised by mallee communities, with *Eucalyptus eremophila* a significant element (Beard 1990). Beard (1981) classified the associated vegetation as the Forrestania System, part of the Swan 1:1,000,000 map sheet. The Forrestania System constitutes a mosaic of vegetation communities, primarily driven by the geology of the landscape (Beard 1981). The primary basaltic greenstones support eucalypt woodlands, where the communities of mallee, scrub heath and thicket are generally associated with the granite and quartzite geologies. Beard (1981) mapped the main portion of the Forrestania Greenstone Belt as *Eucalyptus salmonophloia* and *E. longicornis* on greenstone. The northern portion, encompassing the study area, also included *E. eremophila* scrub with pockets of heterogeneous scrub heath. Mount Holland supports a dense thicket of *Allocasuarina campestris* and *Calothamnus quadrifidus* (Beard 1981).

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

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

METHODS

Between the 22 September and 7 October 2009, fifty 20 × 20 m permanent quadrats were established throughout the northern portion of the Forrestania Greenstone Belt. The quadrat locations were chosen using an environmentally stratified but non-random method because of the extensive mineral exploration and mining-related disturbance in the area. The quadrats represented the topographical, geological and geomorphological variation across the length and breadth of the belt, and captured the associated vegetation communities that characterise the various geologies. The landscape positions of the sites encompassed a broad topological sequence from gentle hill crests to the colluvial deposits. Methods used followed those of previous surveys on greenstone belts in the Yilgarn Craton (e.g. Markey & Dillon 2008a, 2008b; Meissner & Caruso 2008a, 2008b, 2008c). Quadrat locations were selected to represent areas subject to minimal disturbance or modification, although the whole region has been and still is the focus of mineral exploration. Thus sites were avoided where evidence of disturbance (e.g. clearing, exploration, mining) was obvious.

The quadrats were marked by four steel fence droppers, and their locations recorded by a Garmin Map76 GPS. Photographs were taken at a set distance of 5 m from each corner. Site physical characteristics (landform, slope, aspect, litter and bare ground cover, size of coarse fragments, cover of surface rock fragments and bedrock, soil colour and texture) were recorded as a series of descriptive attributes and semi-quantitative scales as defined by McDonald et al. (1998). Landform description was based on topographical position (crest, upper slope, mid-slope, lower slope or flat) and landform element type (e.g. hillcrest, hillslope, breakaway; McDonald et al. 1998). Coarse fragments and rock outcrop data were recorded as specific geologies present and as part of a seven-point class scale representing percent (%) cover. The seven cover classes were: zero % cover (0); <2% cover (1); 2–10 % (2); 10–20 % (3); 20–50 % (4); 50–90 % (5); >90% (6). Site disturbance was ranked between zero and three, with zero (0) representing no effective disturbance and three (3) being extensively cleared. Runoff was assigned to a scale of six classes (0 = no runoff, 1 = very slow, 2 = slow, 3 = moderately rapid, 4 = rapid, 5 = very rapid; McDonald et al. 1998).

Vegetation structure was determined by assigning dominant taxa to each stratum in the landscape, noting emergent taxa where appropriate, based on McDonald et al. (1998). All vascular plants were recorded from within the plot and assigned a cover class (D >70%; M 31–70%; S 10–30%; V <10%; I = isolated plants and L = isolated clumps). Material was collected for verification and vouchering at the Western Australian Herbarium (WA Herbarium). Additional specimens were collected adjacent to the plots, which contributed to the overall species list for the survey area. Where sufficient representative plant material was available, it was lodged at the WA Herbarium. Nomenclature follows Florabase (Western Australian Herbarium 2010). For this study, the reference to weed taxa refers to invasive species categorised as alien or introduced to the area and corresponds with the Florabase classification.

Soil chemical attributes were analysed for each quadrat. Soil was collected from 20 regularly-spaced intervals across the quadrat, then bulked and sieved. The <2 mm fraction was analysed by a Inductively Coupled Plasma – Atomic Emission Spectrometer (ICP–AES) for B, Ca, Cd, Co, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S and Zn using the Mehlich No. 3 procedure (Mehlich 1984). Soil pH was measured on 1:5 soil-water extracts in 0.01 M $CaCl_2$ (method S3; Rayment & Higginson 1992). Organic carbon content was determined using a modified Walkley–Black method (method 6A1) and the calculation of total soil nitrogen (N) was based on a modified Kjeldahl digest (method S10; Rayment & Higginson 1992).

The classification and ordination analyses were undertaken on a presence/absence data matrix of 176 perennial taxa occurring at more than a single site, which was consistent with previous greenstone belt studies (Gibson 2004a, 2004b; Gibson et al. 2012). The dissimilarity between sites was determined using the Bray–Curtis measure and the Resemblance routine in PRIMER v6 (Clarke & Gorley 2006). The Bray–Curtis measure is a widely-used assessment of ecological distance, which reflects differences in relative abundance and compositional change (Legendre & Legendre 1998; Anderson & Robinson 2003), and provides quantitative output for similarity between samples (Faith et al. 1987). Using the Bray–Curtis similarity matrix, the sites were classified based on the flexible unweighted pair-group mean average method (UPGMA, $\beta = -0.1$) using PATN v3.11 (Belbin 1989). The results provided the basis for grouping the taxa into ecological groups. A two-way table was derived from the classification for species grouping and the dendrogram of site grouping. The species–site similarity matrix was then subjected to Non-metric Multi-dimensional Scaling (NMS). An environmental data matrix that included soil chemical properties and site physical characteristics was created, which was then fitted to the NMS ordination using Spearman correlation values in Primer v6. The resulting figure displayed lines of best-fit in the NMS ordination. The continuous environmental variables were normalised prior to fitting the environmental vectors.

The similarity percentages (SIMPER) analyses provided information on those species typically found within each community. The SIMPER routine in PRIMER determines those taxa contributing the greatest similarity within a community and dissimilarity amongst communities (Clarke & Warwick 2001). Those taxa contributing 10% or more to the similarity within each community type were reported. Where no individual species contribution reached the 10% threshold, taxa constituting 50% cumulative contribution were included. When ties occurred at the 50% level, all taxa in the tie were reported.

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

RESULTS

Summary information

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

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

Rare and priority taxa

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

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

New taxa

Three new taxa were identified during the survey. Single specimens of each taxon were collected. One taxon, *Hibbertia croninensis* ms, had previously been collected but was identified as *H.* aff. *oligantha* (PERTH 03033856).

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

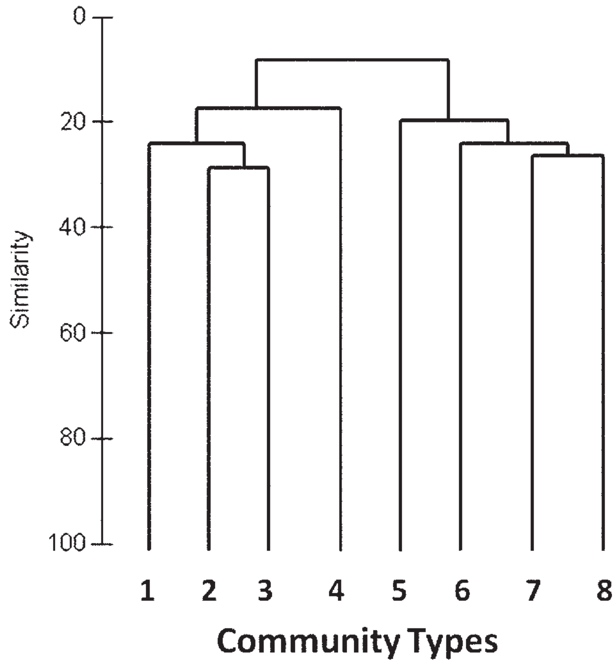

Figure 2. Summary dendrogram of community types for the northern Forrestania Greenstone Belt. The eight community types displayed in the dendrogram were derived from the classification analyses of the 176 taxa from 46 sites; the four sites excluded from the analyses are not displayed.

Table 1

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

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

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

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

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

Range extensions

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

Hybrids/integrades

Three interspecific hybrids were collected during the survey. Two of the hybrids, *Acacia* and *Dodonaea*, were matched with collections vouchered in the WA Herbarium, and the *Persoonia* hybrid is recognised in taxonomic description within Flora of Australia (Weston 1995). Five collections were made of the interspecific hybrid of *A. poliochroa* × *A. merralii*, which is known to occur in the vicinity of the Forrestania Greenstone Belt. Two subspecies of *D. viscosa* are known to intergrade; this survey identified two specimens of the *D. viscosa* subsp. *angustissima*/subsp. *spathulata* intergrade. A single collection was identified as a hybrid of *P. coriacea* × *P. helix*. This hybrid is a recognised entity, where the two taxa overlap in distribution. The taxonomic description also notes that there is uncertainty relating to the degree of twisting in the leaves and whether that is a natural variation or an indication of hybridization (Weston 1995).

Floristic communities

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

The NMS output (2D stress = 0.16, 3D stress = 0.12) displays the relationship between the sites, based on the resemblance matrix with environmental vectors overlain (Fig. 3). The environmental vectors overlain on the NMS ordination highlight the influence of edaphic factors on vegetation communities, with all the most highly correlated environmental parameters being soil characteristics. Vectors extending close to the edge of the circle indicate stronger correlation to those communities (Fig. 3). Strong correlations occurred between environmental vectors and community groups (Table 3). Soil chemical parameters, soil pH, electrical conductivity, B, Ca, K, Mg and Na exhibited the greatest intercorrelations ($r_s \geq 0.8$).

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

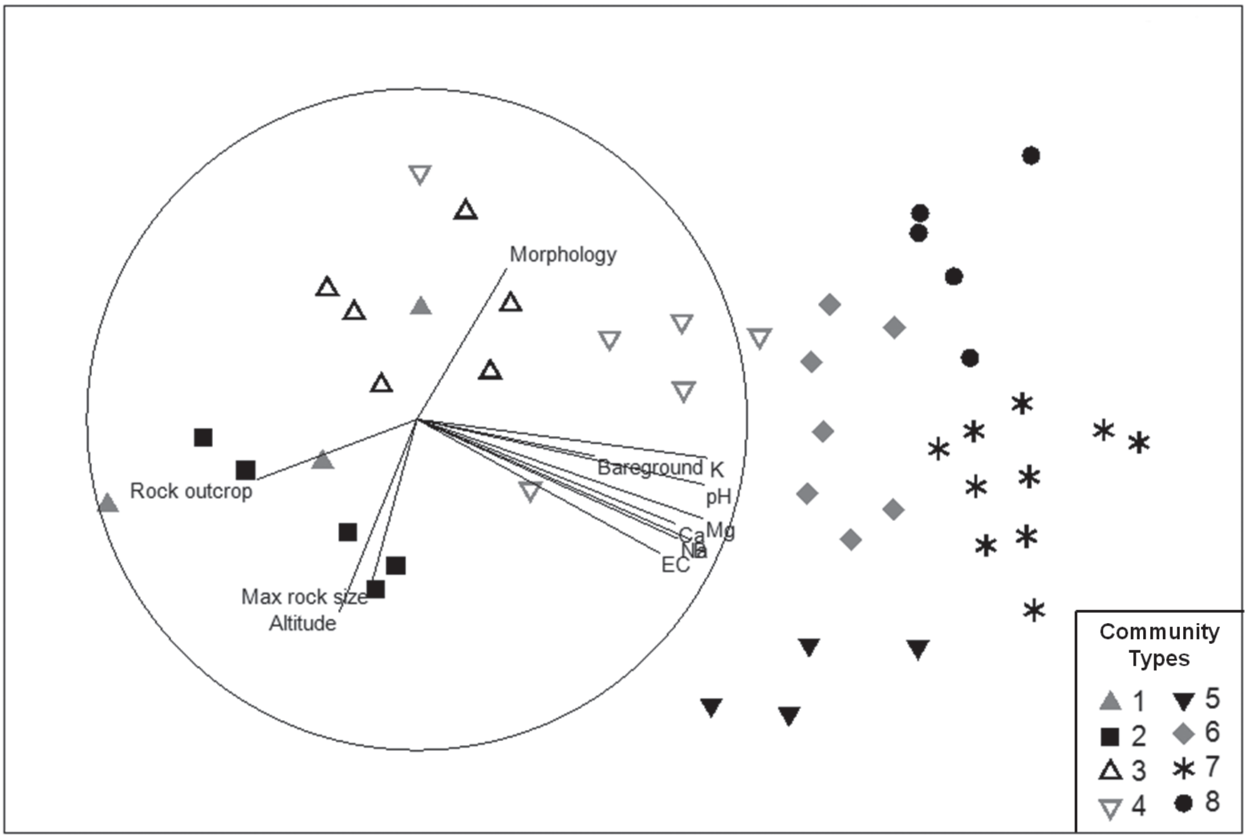

Figure 3. 2D graph of the first two axes of the NMS ordination of survey plots of the northern Forrestania Greenstone Belt (stress = 0.16). Survey plots are separated by community groups and are overlain with environmental vectors, using the lines of best-fit in multi-dimensional space. Vectors extending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

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

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

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

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

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

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

Table 2

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

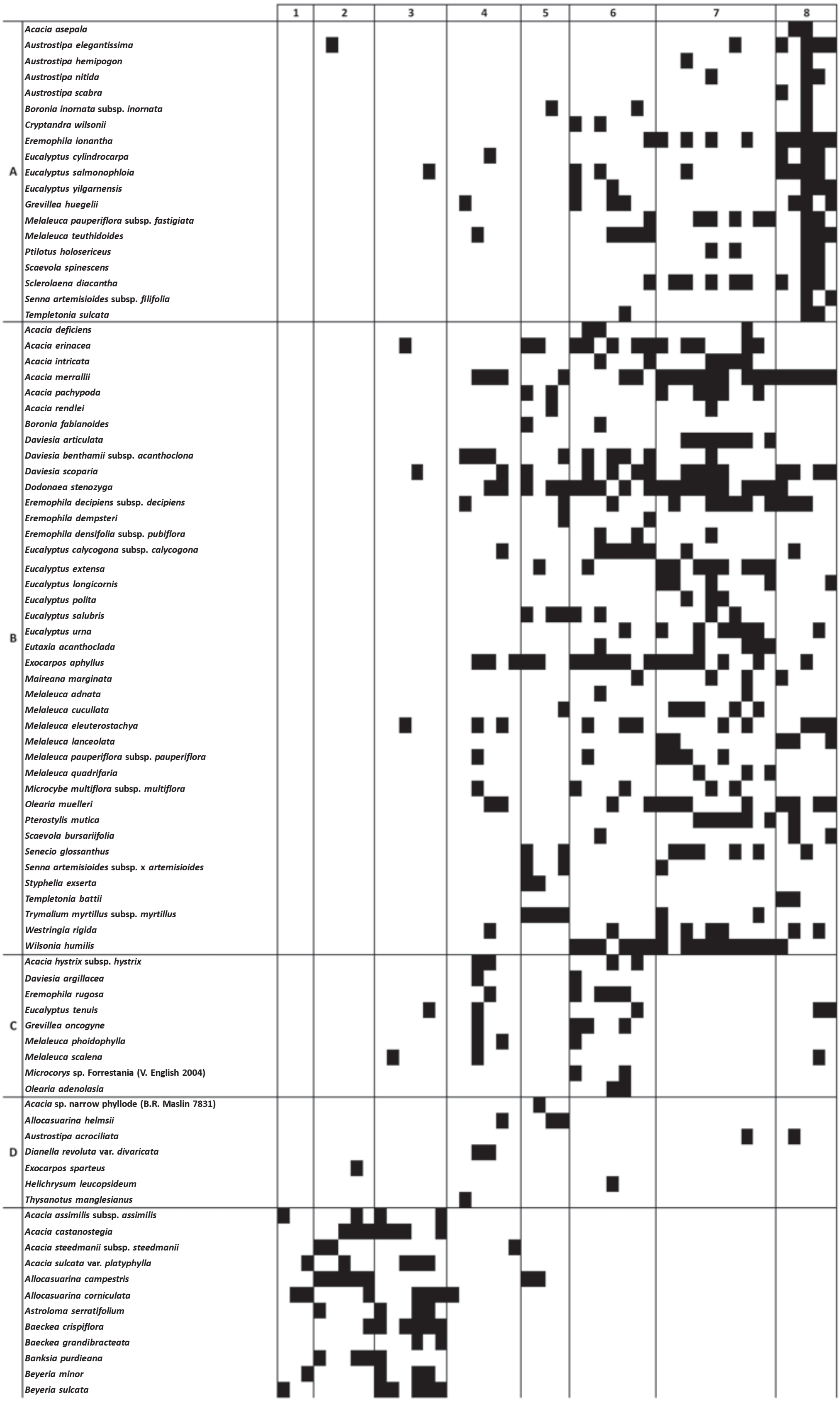

Table 2 (cont.)

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

Table 3

Summary statistics for environmental variables, separated by community type for the northern Forrestania Greenstone Belt. Mean values with standard deviation are listed for community types. Differences were determined using Kruskal–Wallis non-parametric one-way analysis of variance. Significance values are shown by * ($p < 0.05$ = *; $p < 0.01$ = **; $p < 0.001$ = ***; $p < 0.0001$ = ****) and the inclusion of $^{+}$ indicates no significant difference between mean values. Post-hoc differences were set at $\alpha = 0.05$. Units of measurements for the parameters are: soil chemicals = mg/kg; abundance of fragments and outcrop abundance = categorical maximum (0 = 0%, 1 = <2%, 2 = 2–10%, 3 = >10–20 %, 4 = >20–50 %, 5 = >50–90 %, 6 = >90%); topographical position: 1 = crest, 2 = upper slope, 3 = mid-slope, 4 = lower slope, 5 = flat; species richness = number of taxa per quadrat.

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

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

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

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

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

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

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

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

Soils were typically brown to red-brown sandy clay loams with variable acidic to neutral soil pH (5.7–7.6). Coarse rock fragments, primarily composed of undifferentiated greenstone, were variable in abundance, with no bedrock exposed at any of the sites. Cation concentrations were relatively high, but also variable (Table 3).

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

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

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

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

Environmental variables

The northern Forrestania Greenstone Belt was characterised by subtle topographic variation and gentle slopes, except for the isolated banded ironstone hills (Mount Holland and North Ironcap). Elevation ranged from 386–478 m. Variation in topographical position is highlighted on the NMS ordination in the form of topographical position (i.e. crest to outwash) and altitude (Fig. 3). Soils collected during the survey were skeletal to shallow in depth and typically light brown to red-brown sandy loams and sandy clay loams. Seven sites were classified as loam (1), clay loam sand (1) or clay loam (5). Coarse rock fragments were abundant at most survey sites, with an average cover category of 4.24, which corresponds to 20–50% cover (Table 3). The majority of sites lacked surface expression of bedrock, with only 14 sites having outcrops of bedrock, which were predominantly banded ironstone. The sites typically had a high proportion of bare ground (mean 91.8% ± 3.5 SD) and sparse cover of leaf litter (mean 22.4% ± 14.8 SD; Table 3).

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

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

Mean values for the environmental parameters were compared between the community types (Table 3). The Kruskal–Wallis statistics provided evidence that there were significant differences between types for environmental parameters. Community types 1–4 tended to have lower values for soil chemical properties than types 5–8; this was particularly evident with cation concentrations and soil pH. Mean values for community types 1 and 3 were significantly lower than those of community type 7 for Ca, K, Mg, Na and soil pH. Community types 2 and 4 also had statistically lower mean values for K, Na and soil pH, compared with community type 7. Community type 7, characterised by alkaline soils, also had significantly greater mean values for other soil chemical properties (Table 3), with the exception of community type 1 having the highest Fe concentrations. Differences amongst mean values for site parameters were less pronounced. Community type 8 was lower in the landscape, with significantly lower mean altitude than community types 1 and 2, which were identified as upland areas. Furthermore, community type 8 was less rocky (i.e. lowest abundance of coarse fragments) than communities types 2 and 3. Community type 2 had significantly greater mean runoff values compared with community types 6 and 8.

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

DISCUSSION

Flora and vegetation communities

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

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

Although the area has a history of exploration and mining, the number of weed taxa was relatively low compared with other greenstone belts with historical disturbance. The Bullfinch Greenstone Belt, which is the closest greenstone belt north of the survey area, has 38 weed taxa recorded from surveys in the central and southern portion (Gibson & Lyons 2001; Thompson & Allen 2013). The Forrestania Greenstone Belt has a noticeable lack of cattle, whereas cattle are commonly seen at Bullfinch, and they are likely to contribute to the spread of weed taxa. There was only a single weed species, *Hypochaeris glabra*, common to this survey and Gibson's (2004a) southern Forrestania Greenstone Belt survey. All of the weed taxa recorded—*H. glabra*, *Pentaschistis airoides* subsp. *airoides*, *Rostraria cristata*, *Ursinia anthemoides* and *Vulpia myuros* forma *myuros*—are new records for the northern Forrestania Greenstone Belt; however, this is probably due to the lack of submission of specimens rather than to the novelty of the taxa to the area. The only weed taxon previously on record for the survey area was *Lysimachia arvensis*, which is also known from further south on the greenstone belt (Gibson 2004a).

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

Environmental correlates

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

The soil chemical parameters were highly intercorrelated, which has been documented in other greenstone belt studies in the Yilgarn Craton (Markey & Dillon 2008a, 2008b, 2009a, 2009b; Meissner & Caruso 2008a, 2008b, 2008c; Thompson & Sheehy 2011a, 2011b, 2011c). The positive relationship between Ca concentrations and other primary soil cations is not surprising given the characteristics of calcrete substrates. Calcrete accumulation has been allied with lower slopes and pediments (Anand et al. 1997) and calcretes are readily leached from the profile (Butt et al. 2000; Anand 2005). This is particularly evident in community type 7, where the soil chemical parameters indicated a strong presence of calcrete and the average concentrations of the soil cations were the highest of all communities. However, community type 8, which was characterised by low altitude and runoff (indicative of low surface gradients), had lower Ca concentrations. This may be indicative of variation in rates of weathering and different geologic sequences (i.e. ironstone or greenstone associations). Community type 8 had moderately high concentrations of both Mg and Fe and may represent an intergrade between underlying geologies (e.g. ironstone vs. greenstone). In comparison, community type 7 had the highest Mg concentration, indicative of the presence of greenstone, and the lowest Fe concentrations. This nutrient may have readily leached from the profile or originally been present in lower concentrations.

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

Conservation significance

The importance of improving the representation of greenstone belts in the conservation estate has been raised repeatedly over the years (Chapman & Newbey 1995; Gibson & Lyons 2001; Gibson 2004b), and particularly for the Forrestania Greenstone Belt (Henry-Hall 1990; Gibson 2004a). The only part of the Forrestania Greenstone Belt that is part of the conservation estate is the Lake Cronin Nature Reserve (a class 'A' nature reserve), which lies south of the survey-area boundary. However, the reserve does not represent any of the banded ironstone hills or laterite of the Forrestania Greenstone Belt (Gibson 2004a). Furthermore, recent papers have emphasised the greenstone belts, especially the banded ironstone formations, as hotspots for plant diversity and for the high beta-diversity associated with these landforms (Gibson et al. 2010; Gibson et al. 2012). The greenstone belt continues to be of interest for exploration and mining, with active and pending mining tenements covering much of the survey area. Expansion of the present reserve system in the greenstone belt remains an important imperative after more than two decades from the initial recommendation, particularly with regard to the newly discovered taxa.

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APPENDIX 1

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

Amaranthaceae
- *Ptilotus drummondii*
- *Ptilotus holosericeus*

Apiaceae
- *Daucus glochidiatus*
- *Platysace maxwellii*

Apocynaceae
- *Alyxia buxifolia*

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

Asparagaceae
- *Thysanotus manglesianus*
- *Thysanotus patersonii*

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

Boraginaceae
- *Halgania andromedifolia*

Campanulaceae
- *Wahlenbergia gracilenta*

Caryophyllaceae
- *Stellaria filiformis*

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

Celastraceae
- *Psammomoya choretroides*

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

Convolvulaceae
- *Wilsonia humilis*

Crassulaceae
- *Crassula colligata* subsp. *lamprosperma*

Cupressaceae
- *Callitris canescens*
- *Callitris preissii*

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

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

Droseraceae
- *Drosera browniana*
- *Drosera macrantha* subsp. *macrantha*

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

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

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

Acacia rendlei
Acacia sclerophylla var. *sclerophylla*
Acacia sp. narrow phyllode (BR Maslin 7831)
Acacia steedmanii subsp. *steedmanii*
Acacia sulcata var. *platyphylla*
Acacia tetraptera
Acacia viscifolia
Acacia yorkrakinensis subsp. *acrita*
Daviesia argillacea
Daviesia articulata
Daviesia benthamii subsp. *acanthoclona*
Daviesia pachyloma
Daviesia pachyphylla
Daviesia scoparia
Dillwynia divaricata
Eutaxia acanthoclada P3
Eutaxia nanophylla P3
Eutaxia neurocalyx
Gastrolobium melanocarpum
Gastrolobium spinosum
Gompholobium obcordatum
Jacksonia nematoclada
Labichea rossii P1
Leptosema daviesioides
Pultenaea aff. *arida*
Senna artemisioides subsp. *filifolia*
Senna artemisioides subsp. x *artemisioides*
Senna stowardii
Templetonia aculeata
Templetonia battii
Templetonia sulcata
Templetonia sulcata/smithiana

Goodeniaceae
Dampiera angulata subsp. *angulata*
Dampiera cf. *obliqua*
Goodenia dyeri
Goodenia pinifolia
Scaevola bursariifolia
Scaevola spinescens

Gyrostemonaceae
Codonocarpus cotinifolius

Haemodoraceae
Conostylis bealiana

Haloragaceae
Glischrocaryon flavescens

Hemerocallidaceae
Dianella revoluta var. *divaricata*

Lamiaceae
Hemigenia aff. *diplanthera*
Hemigenia westringioides
Microcorys sp. Forrestania (V English 2004) P4
Westringia cephalantha
Westringia cephalantha var. *cephalantha*
Westringia rigida

Lauraceae
Cassytha aurea var. *hirta*
Cassytha melantha
Cassytha nodiflora

Loganiaceae
Logania judithiana
Phyllangium sp.

Malvaceae
Keraudrenia cacaobrunnea subsp. *cacaobrunnea*
Lasiopetalum ferraricollinum
Lawrencia glomerata

Myrtaceae
Baeckea crispiflora
Baeckea elderiana
Baeckea grandibracteata
Baeckea sp. Parker Range (M Hislop & F Hort MH 2968) P3
Calothamnus quadrifidus subsp. *seminudus*
Calytrix sapphirina
Chamelaucium ciliatum
Chamelaucium pauciflorum subsp. *pauciflorum*
Cyathostemon sp. WA Thompson & J Allen 951
Eucalyptus burracoppinensis
Eucalyptus calycogona subsp. *calycogona*
Eucalyptus concinna
Eucalyptus cylindrocarpa
Eucalyptus eremophila
Eucalyptus extensa
Eucalyptus flocktoniae subsp. *flocktoniae*
Eucalyptus flocktoniae subsp. *hebes*
Eucalyptus horistes
Eucalyptus livida
Eucalyptus longicornis
Eucalyptus oleosa subsp. *oleosa*
Eucalyptus pileata
Eucalyptus polita
Eucalyptus rigidula
Eucalyptus salmonophloia
Eucalyptus salubris
Eucalyptus steedmanii R
Eucalyptus subangusta subsp. *subangusta*
Eucalyptus tenera
Eucalyptus tenuis
Eucalyptus urna
Eucalyptus yilgarnensis
Euryomyrtus maidenii
Leptospermum ?erubescens
Leptospermum roei
Melaleuca acuminata subsp. *acuminata*
Melaleuca adnata
Melaleuca calyptroides
Melaleuca carrii
Melaleuca cliffortioides
Melaleuca condylosa
Melaleuca cordata
Melaleuca cucullata
Melaleuca depauperata
Melaleuca eleuterostachya
Melaleuca hamata
Melaleuca johnsonii
Melaleuca lanceolata
Melaleuca lateriflora subsp. *lateriflora*
Melaleuca laxiflora
Melaleuca pauperiflora subsp. *fastigiata*
Melaleuca pauperiflora subsp. *pauperiflora*
Melaleuca phoidophylla
Melaleuca platycalyx
Melaleuca pungens
Melaleuca quadrifaria
Melaleuca scalena
Melaleuca teuthidoides
Micromyrtus erichsenii
Micromyrtus obovata
Rinzia carnosa
Rinzia sessilis
Thryptomene kochii

Appendix 1 (cont.)

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

Plantaginaceae
- *Plantago debilis*

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

Polygalaceae
- *Comesperma volubile*

Portulacaceae
- *Calandrinia calyptrata*
- *Calandrinia eremaea* s.l.

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

Pteridaceae
- *Cheilanthes sieberi* subsp. *sieberi*

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

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

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

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

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

Stylidiaceae
- *Stylidium involucratum*
- *Stylidium sejunctum* P2

Thymelaeaceae
- *Pimelea aeruginosa*
- *Pimelea suaveolens* subsp. *flava*

Violaceae
- *Hybanthus floribundus* subsp. *floribundus*

Zygophyllaceae
- *Zygophyllum glaucum*

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Flora and vegetation of greenstone formations of the Yilgarn Craton: southern Bullfinch Greenstone Belt

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ABSTRACT

The Bullfinch Greenstone Belt has long been recognised for its mineral wealth, yet comparatively little attention has been given to its floristic diversity. Fifty permanent quadrats were established in the southern portion of the greenstone belt, with all vascular flora and a suite of environmental parameters recorded. A total of 224 taxa were identified, representing 51 families and 125 genera. Favourable conditions during the survey contributed to a high presence of annuals, with 85 taxa recorded. Three taxa of conservation significance were recorded for the area, including *Tricoryne* sp. Wongan Hills (BH Smith 794), which represents a significant range extension (c. 230 km) and a potentially new taxon. Weeds were prevalent across the study area with 24 taxa identified, reflecting its long history of land use and disturbance. The six vegetation communities described from the survey had strong associations with edaphic factors. Although the southern Bullfinch Greenstone Belt has had a long history of land use, the area remains an important repository for floristic diversity. Future mineral exploration should ensure that these conservation values are retained.

Keywords: classification, Coolgardie, eastern goldfields, floristic diversity, ultramafics, vegetation patterns.

INTRODUCTION

The greenstone belts of the Yilgarn Craton have long been recognised for their mineral potential. The Bullfinch Greenstone Belt was one of the earliest locations identified for gold exploration, with the first payable gold east of Perth being discovered at Golden Valley in the southern part of the belt (Ralph 2007). The flora and vegetation of the area has been poorly documented, but recent surveys of the flora on banded ironstone ranges and allied greenstone belts have recorded high beta-diversity between the different terrain types (Gibson et al. 2007). This study is a continuation of the surveys on greenstone belts of the Yilgarn Craton that document the flora, plant communities and their associated environmental parameters (see Gibson et al. 2012).

STUDY SITE

The Bullfinch Greenstone Belt is situated in the central western area of the Coolgardie Bioregion, near the boundary with the Avon Wheatbelt Bioregion (Interim Biogeographic Regionalisation of Australia—IBRA; Thackway & Cresswell 1995). The greenstone belt extends c. 75 km north-north-west from the township of Bullfinch, approximately 35 km north-west of Southern Cross (Fig. 1). After approximately 20 km, the belt trends northwards to encompass the Highclere and Woongaring Hills. This study covers the southern extent of the Bullfinch Greenstone Belt south of Lake Deborah West and east of Lake Baladjie, an area of c. 20 km from north to south and c. 8–9 km from west to east. The latitudinal and longitudinal boundaries of the study area are roughly 30° 45" S, 31° 00" S and 118° 55" E, 119° 105" E, respectively. The land tenure for the greenstone belt, located within Yilgarn Shire, includes freehold land, the Golden Valley pastoral lease, unallocated crown land and crown reserve.

Land use history

Gold was first discovered in the Bullfinch area in 1887, with the townsite gazetted in 1910. Mining then occurred sporadically throughout the 1900s. At present, active mineral exploration leases are held over the Bullfinch Greenstone Belt, but no mines are active. The region supports several pastoral leases and farms (Chin & Smith 1983), with additional economic activity associated with resource exploration and extraction undertaken at the nearby Marda-Diemals Greenstone Belt.

In 1912, following the discovery of gold, government geologist HP Woodward undertook a reconnaissance of the Bullfinch Greenstone Belt and areas to the north (Chin & Smith 1983). Additional geological surveys and exploration identified economically viable deposits of iron ore in the Koolyanobbing area, with minor amounts of silver production only associated with gold extraction

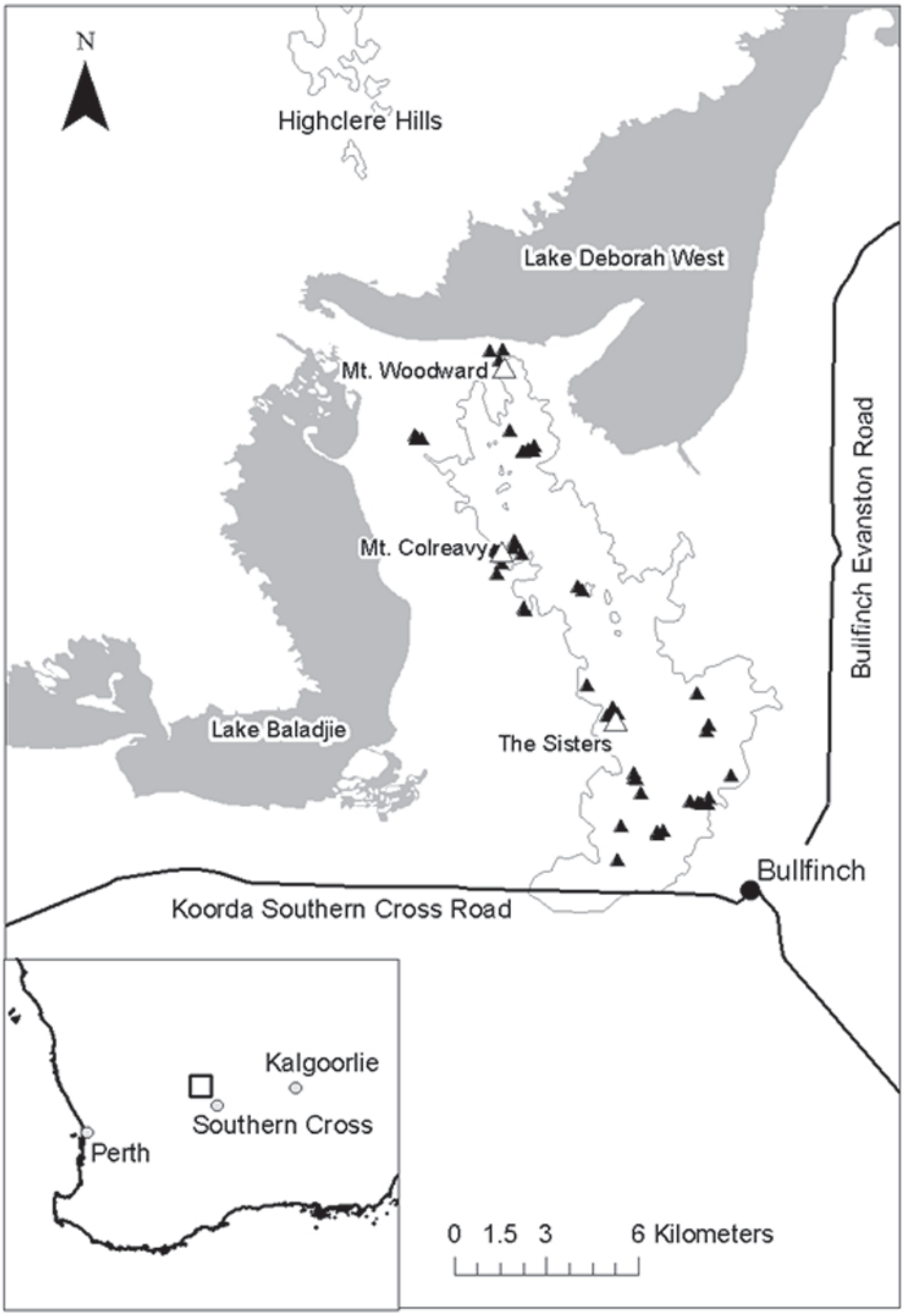


Figure 1. Map showing the location of the southern Bullfinch Greenstone Belt, with major landforms and landmarks indicated. The locations of the 50 permanent quadrats are marked by solid triangles (▲).

(Chin & Smith 1983). The presence of nickel and copper has been identified, but neither discovery has resulted in any production in the region.

Climate

Bullfinch sits in the central western portion of the Coolgardie Bioregion, which has a semi-arid climate with warm summers and mild winters. Rainfall events occur throughout the year, with most rain falling between May and August (Bureau of Meteorology 2010). Mean annual rainfall at Southern Cross (c. 35 km south-east of Bullfinch) is 294.5 mm, based on records from 1889 to 2007, with June and December having the highest (40.7 mm) and lowest (12.6 mm) average monthly rainfall, respectively. The average annual maximum is 25.5 °C and minimum is 10.7 °C, based on records between 1907 to 2007. The highest temperatures occur between December and March, with mean maximum temperatures exceeding

30 °C. The lowest daily minimum temperatures occur between May and September, where mean minimum temperatures are below 8 °C.

Geology

The geology of the Bullfinch Greenstone Belt has been mapped and described on the Jackson 1:250,000 geological sheet (Chin & Smith 1983). Greenstone locally refers to outcrops of ultramafics and mafics associated with Archaean meta-volcanic and meta-sedimentary rock sequences (Cole 1992). The Bullfinch area is characterised by low rock outcrops and lateritic duricrust, surrounded by undulating sandplains and alluvial valleys associated with a paleodrainage system (Chin & Smith 1983). The highest point in the survey area is Mt. Woodward (412 m), with the nearby salt lakes of Lake Baladjie and Lake Deborah West at c. 330 m above sea level.

The Bullfinch Greenstone Belt is part of the Archaean Yilgarn Craton, a tectonically stable region within the Pre-Cambrian Western Shield (Anand & Paine 2002), formed between 3000 and 2600 Ma (Myers 1993; Myers & Swagers 1997). Within the Yilgarn Craton, Bullfinch sits on the western boundary of the Southern Cross Domain (SCD) within the Youanmi Terrane (Cassidy et al. 2006).

The greenstone belts of the SCD trend primarily in a north-north-west direction, with Bullfinch having undergone powerful deformation to form a tightly folded structure (Griffin 1990). The Bullfinch Greenstone Belt is a typical greenstone formation, with sequences of mafic and sedimentary rocks over a lower succession of mafic and ultramafic rocks (Chin & Smith 1983; Griffin 1990). Within the southern portion of the Bullfinch Greenstone Belt, the dominant rock types are metamorphosed komatiitic basalt, metabasalt and metagabbro (Chin & Smith 1983). Isolated occurrences of talc schist, peridotite, metamorphosed conglomerate and quartz-muscovite schist are found within the study area (Chin & Smith 1983). The survey area also includes foliated granites on the eastern boundary of the greenstone. Quaternary colluvium deposits dominate the slopes and pediments adjacent to the main greenstone belt, which are then surrounded by aeolian and alluvial deposits associated with the salt lakes to the west (Lake Baladjie) and to the north (Lake Deborah West; Chin & Smith 1983).

Beard (1990) described the soils of the Coolgardie Bioregion as predominantly brown calcareous earths. Within the Bullfinch region, soils are typically shallow calcareous loams associated with rocky hills and brown calcareous earths on the slopes and adjacent pediments (Beard 1981). Natural red earths characterise areas that have undergone extensive weathering (Beard 1981).

Vegetation

The Bullfinch Greenstone Belt is part of the Coolgardie Botanical District within the South West Interzone (Beard 1990). The interzone represents the transitional boundary between the floristically-rich south-west and the desert communities of the interior. *Eucalyptus* woodlands are the predominant vegetation community; on calcareous substrates, eucalypt densities are reduced, coupled with increasing presence of the chenopod understorey (Beard 1990).

Beard (1981) mapped the southern Bullfinch Greenstone Belt as eucalypt woodland, bounded on the north by the salt lake, Lake Deborah West. The greenstone belt was described as the Yilgarn Hills, part of the Yilgarn Vegetation System; however, the northern portion of the Yilgarn Hills had greater affinity to the Highclere System to the north of Lake Deborah West (Beard 1980). The central portion of the greenstone-belt study area was described as mixed *Eucalyptus longicornis* and *E. lesoufeii* woodland with *E. salmonophloia* – *E. lesoufeii* woodlands to the northeast and *E. longicornis* – *E. salmonophloia* woodlands to the south-west (Beard 1981). Beard (1981) described the Highclere System as dominated by *E. longicornis* – *E. corrugata* woodlands on the hills with an *Atriplex* sp. understorey. Other elements of the vegetation system include the tree species *Casuarina pauper*, *Brachychiton gregorii*, *Callitris columellaris* and the shrubs *Acacia tetragonophylla*, *A. ramulosa* and *Santalum spicatum* (Beard 1980). Where the greenstone hills approach Lake Deborah West, the eucalypt woodland communities known to persist on the hills occur further downslope on the adjacent colluvium (Beard 1980). There are limited occurrences of ironstone ridges in the Yilgarn Hills, dominated by *A. quadrimarginea*, with the occasional specimen of *Casuarina cristata*, *B. gregorii* and *Pittosporum phylliraeoides*.

The eastern goldfields regional survey provided an overview of the vegetation in the Jackson–Kalgoorlie area. The adjacent Highclere Hills were described as supporting *Eucalyptus corrugata* woodlands on the stony upland sites, with *E. salmonophloia* and *E. salubris* woodlands downslope on the colluvial deposits (Newbey & Hnatiuk 1985). Less frequently encountered were *Acacia acuminata* and *A.* aff. *aneura* shrubland communities, found occasionally on rocky rises, and *E. longicornis* woodlands associated with more alkaline colluvial soils (Newbey & Hnatiuk 1985).

A detailed vegetation survey of the central Bullfinch Greenstone Belt, at Highclere Hills, recorded 217 native and 25 weed taxa (Gibson & Lyons 2001). Five dominant vegetation communities with two additional sub-groups were identified from the survey, each strongly influenced by edaphic factors. Characteristic of the Coolgardie Bioregion, *Eucalyptus* woodlands defined one of the community types, featuring *E. longicornis*, *E. salubris* and/or *E. corrugata* with a chenopod understorey (i.e. *Atriplex* sp., *Maireana* sp., *Scleroleana* sp.). Other vegetation communities included *Acacia acuminata* shrublands with *Casuarina pauper* and *A. tetragonophylla* and *Scaevola spinescens* associations. A single laterite community featured *Allocasuarina campestris*, *Baeckea elderiana* and *Grevillea paradoxa* (Gibson & Lyons 2001).

Broad-scale vegetation mapping (Beard 1980, 1981) and survey (Newbey & Hnatiuk 1985) have provided a regional context. The survey undertaken on the Highclere Hills represents the only detailed information on the flora and vegetation of the Bullfinch Greenstone Belt. This study aimed to record the floristic diversity, describe vegetation patterns and examine environmental parameters associated with the southern Bullfinch Greenstone Belt, between Lake Deborah West and the Bullfinch township. Our study addresses the deficiency of information on an area that has had over a century of mineral interests and exploration.

METHODS

In early September 2009, fifty 20 × 20 m permanent quadrats were established across the southern Bullfinch Greenstone Belt. The quadrats were environmentally stratified in order to represent the topographical, geological and geomorphological variation across the length and breadth of the belt. However, the sampling design was biased (non-random), due to access issues and the infrastructure present (i.e. water tanks). The sites were selected to capture the vegetation communities associated with the greenstone belt and its associated geologies. Landscape positions of the sites encompassed a broad topological sequence from hill crests downslope to the colluvial deposits. Methods used follow those of previous surveys on greenstone belts in the Yilgarn Craton (e.g. Markey & Dillon 2008a, 2008b; Meissner & Caruso 2008a, 2008b, 2008c). Quadrats were located in areas subject to minimal disturbance or modification, although the whole region has been the focus of both past mineral exploration and present-day pastoral activities. Thus, sites where evidence of heavy grazing, clearing or exploration-related disturbance were obvious were avoided.

The quadrats were marked by four steel fence droppers and their location recorded with a Garmin Map76 GPS. Photographs were taken at a set distance of 5 m from each corner. Site physical characteristics (landform, slope, aspect, litter and bare ground cover, size of coarse fragments, cover of surface rock fragments and bedrock, soil colour and texture) were recorded as a series of descriptive attributes and semi-quantitative scales, as defined by McDonald et al. (1998). Landform description was based on topographical position (crest, upper slope, mid slope, lower slope or flat) and landform element type (e.g. hillcrest, hillslope, breakaway; McDonald et al. 1998). Coarse fragments and rock outcrop data were recorded as specific geologies present and as part of a seven-point scale representing percent (%) cover. The seven cover classes were: zero % cover (0); <2% cover (1); 2–10% (2); 10–20% (3); 20–50% (4); 50–90% (5); >90% (6). Site disturbance was ranked between zero and three, with zero (0) representing no effective disturbance and three (3) being extensively cleared. Runoff was assigned to a scale of six classes (0 = no runoff, 1 = very slow, 2 = slow, 3 = moderately rapid, 4 = rapid, 5 = very rapid; McDonald et al. 1998).

Vegetation structure was determined by assigning the dominant taxa to the relevant stratum in the landscape, noting emergent taxa where appropriate, based on McDonald et al. (1998). All vascular plants were recorded from within the plot and assigned a cover class (D >70%, M 30–70%, S 10–30%, V <10%, I = isolated plants and L = isolated clumps). Material was collected for verification and vouchering at the Western Australian Herbarium (WA Herbarium). Additional specimens were collected adjacent to the plots, contributing to the overall species list for the survey area. Species were designated as 'weeds' based on the classification of the WA Herbarium, which classifies invasive species as those introduced or alien to the area (2010). Where sufficient representative plant material was available, it was lodged at the WA Herbarium. Nomenclature generally follows Florabase (Western Australian Herbarium 2010).

Soil chemical attributes were analysed for each quadrat. Soil was collected from 20 regularly-spaced intervals across the quadrat, bulked and sieved. The <2 mm fraction was analysed by a Inductively Coupled Plasma – Atomic Emission Spectrometer (ICP–AES) for B, Ca, Cd, Co, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, S and Zn using the Mehlich No. 3 procedure (Mehlich 1984). Soil pH was measured on 1:5 soil-water extracts in 0.01 M $CaCl_2$ (method S3, Rayment & Higginson 1992). Organic carbon content was measured using a modified Walkley–Black method (method 6A1) and the calculation of soil nitrogen (N) was based on a modified Kjeldahl digest (method S10, Rayment & Higginson 1992).

The classification and ordination analyses were undertaken on a presence/absence data matrix of the 87 perennial taxa that occurred at more than a single site, which is consistent with previous greenstone belt studies (Gibson 2004a, 2004b). The dissimilarity between sites was determined using the Bray–Curtis measure and the Resemblance routine in PRIMER v6 (Clarke & Gorley 2006). The Bray–Curtis measure is a widely-used assessment of ecological distance, which reflects differences in both relative abundance and compositional change (Legendre & Legendre 1998; Anderson & Robinson 2003), and provides quantitative output for similarity between samples (Faith et al. 1987). Using the Bray–Curtis similarity matrix, the site by species similarity matrix was classified based on the flexible unweighted pair-group mean average method (UPGMA, $\beta = -0.1$), using PATN v3.11 (Belbin 1989). The resulting dendrogram provided the basis for placing the taxa into ecological groups. A two-way table was created from the classification. The species–site similarity matrix was then subjected to Non-metric Multi-dimensional Scaling (NMS). An environmental data matrix that included soil chemical properties and site physical characteristics was created, which was then fitted to the NMS ordination using Spearman correlation values in Primer v6. The continuous environmental variables were normalised prior to fitting the environmental vectors.

The similarity percentages (SIMPER) analysis provided information on those species typically found within each community. The SIMPER routine in PRIMER determines those taxa that contribute the most to similarity within a community and dissimilarity amongst communities (Clarke & Warwick 2001). Those taxa contributing 10% or more to the similarity within each community type are reported. Where no individual species contribution reached the 10% threshold, taxa constituting 50% cumulative contribution were included. When ties occurred at the 50% level, all taxa in the tie were reported.

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

RESULTS

A total of 218 taxa were recorded in the permanent quadrats, representing 51 families and 125 genera. An additional six taxa were recorded from areas adjacent to the survey plots. The families with the highest number of taxa were: Asteraceae (47 taxa), Chenopodiaceae (20 taxa), Poaceae (16 taxa), Fabaceae (14 taxa) and Scrophulariaceae (nine taxa). At the level of genus, the greatest representation was within *Eremophila* (nine species), *Rhodanthe* (seven species), *Acacia* (six species), *Maireana* (five species, plus two hybrids) and *Ptilotus* (five species). The presence of weed taxa was notable during the survey, with 24 weed species recorded, accounting for 224 records.

Species richness within the survey plots varied considerably, ranging from five to 61 taxa. The mean species richness was 39.7 ± 14 SD. Representation of annuals was high, with 85 taxa. Eight taxa, including the *Maireana* hybrids, were combined into three species complexes for the analyses. The analyses excluded all annuals, singletons and indeterminate specimens, resulting in a matrix of 87 species × 50 sites.

Priority taxa

Three taxa of conservation significance were recorded during the survey (Table 1). Two of the species, *Caesia* sp. Ennuin (N Gibson & MN Lyons 2737) and *Austrostipa blackii*, were known from the Bullfinch Greenstone Belt north of the survey area. Only one collection of the undescribed *Caesia* sp. Ennuin (N Gibson & MN Lyons 2737) exists on record in the WA Herbarium. This survey identified a single individual of this priority-listed taxon, c. 10 km south of the known locality. The specimen is in good condition with flowers and may facilitate a formal taxonomic description of the species. *Austrostipa blackii* is a perennial grass known from 18 collections scattered in the Coolgardie, Avon Wheatbelt and Yalgoo Bioregions. The survey at Bullfinch identified three new populations of *A. blackii*.

Tricoryne sp. Wongan Hills (BH Smith 794) is a Priority 2 species, known from seven collections from the Avon Wheatbelt and Geraldton Sandplain Bioregions. Two specimens with strong resemblance to the *Tricoryne* sp. Wongan Hills (BH Smith 794) were collected from rocky sites c. 230 km from the nearest recorded population. Without a formal description of *Tricoryne* sp. Wongan Hills (BH Smith 794) available to ascertain the validity of the identification, the specimens from this survey were lodged as *Tricoryne* sp. Wongan Hills (BH Smith 794). Further clarification regarding the taxonomic identity of the Bullfinch collections is required, particularly with regard to the geographic disparity between collection sites, the smaller overall size of the Bullfinch specimens, and differing substrates on which the specimens have been found (G Keighery, pers. comm.).

Range extensions

Two range extensions were recorded during the survey, including the P2 *Tricoryne* sp. Wongan Hills (BH Smith 794) anomaly already mentioned. The second range extension was of the biennial herb *Cirsium vulgare*, a recognised weed taxon. *Cirsium vulgare* has been recorded through the south-west of Western Australia. The Bullfinch collection represents a c. 150 km range extension north-east of the nearest population in the Avon Wheatbelt.

Hybrids

Two hybrids were collected during the surveys on the northern Bullfinch Greenstone Belt. One of the hybrids, *Maireana georgei* × *Enchylaena tomentosa*, is recognised in the collection of the WA Herbarium. The second hybrid, *M. georgei* × *E. lanata*, has not been recorded in the WA Herbarium. However, there were eight collections of this hybrid confirmed by Chenopodiaceae taxonomist, Paul Wilson.

Floristic communities

Seven species groups (A–G) were identified, based on hierarchical clustering within the classification routine (Table 2). Species group E contained the most widespread taxa, with representation across all community types,

Table 1

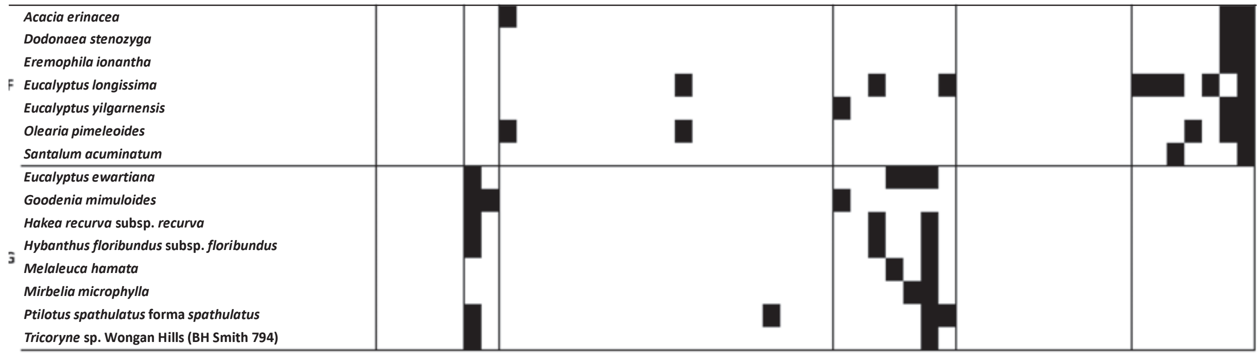
Priority taxa recorded from the southern Bullfinch Greenstone Belt. Bioregion abbreviations: COO = Coolgardie, YAL = Yalgoo, GS = Geraldton Sandplain, AW = Avon Wheatbelt, JF = Jarrah Forest.

Family	Taxon	Status for Bullfinch	Priority	Bioregion
Hemerocallidaceae	*Caesia* sp. Ennuin (N Gibson & MN Lyons 2737)	New record	P1	COO
Hemerocallidaceae	*Tricoryne* sp. Wongan Hills (BH Smith 794)	New record	P2	AW, GS, JF
Poaceae	*Austrostipa blackii*		P3	COO, YAL, AW

Table 2

Two-way table of community types (columns) and species groups (rows) for the Bullfinch Greenstone Belt. Each square represents the presence of a species in that survey quadrat within the particular community type.

Table 2 (cont.)



except one (community type 6). Using the clustering of samples and the SIMPROF routine, six community types were identified (Fig. 2). The dendrogram highlighted the relationship between community types, in particular, the separation of community type 6 is notable, as well as the close relationship between communities types 4 and 5. One pair of sites is discussed as community group 2; however, they were not analysed with the remaining community types. The cluster analysis identified them as a distinct group, but there were too few locations to warrant their inclusion in the analyses. The two-way table highlights the relationships between the site and species groups (Table 2). The NMS routine displays the interrelationship between sites, based on the resemblance matrix (2D stress = 0.15, 3D stress value = 0.11) with environmental vectors superimposed based on the line of best-fit in multi-dimensional space (Fig. 3). Strong correlation occurred between environmental vectors and community groups. Soil chemical parameters, soil pH, electrical conductivity, B, Ca, Mg and P exhibited the greatest correlation ($r_s \geq 0.7$).

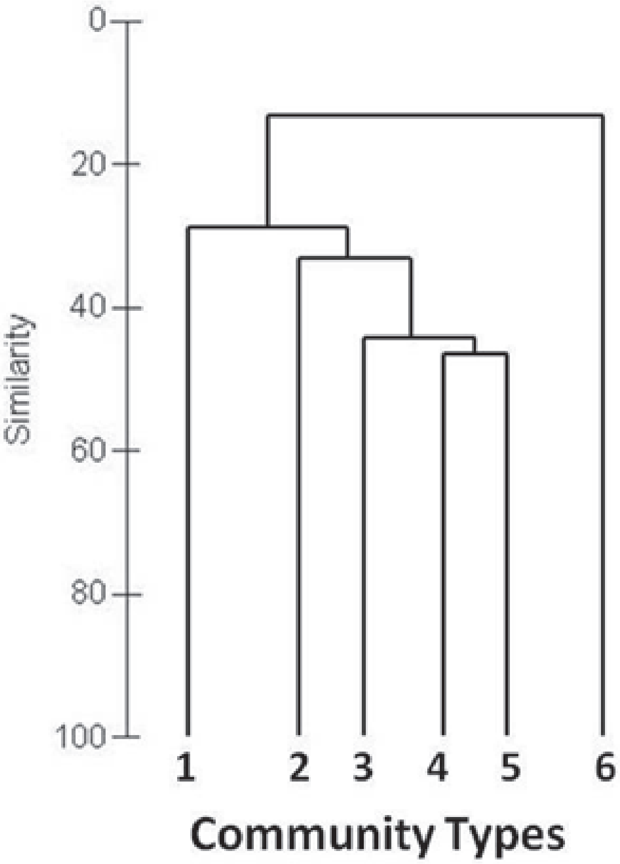


Figure 2. Summary dendrogram of community types for the southern Bullfinch Greenstone Belt. The six community types displayed in the dendrogram are derived from the classification analyses of the 87 taxa from 50 sites.

Community type 1 contained five quadrats, generally associated with lower topographical positions and gentle slopes. The exception was a single, mid-slope locality with a steep gradient. Overstorey species included *Eucalyptus corrugata* or *Acacia ramulosa* var. *ramulosa*. The understorey was dominated by *Dodonaea inaequifolia*, *Ptilotus obovatus*, *Solanum lasiophyllum* and chenopod shrubs, including *Atriplex vesicaria*, *Eriochiton sclerolaenoides*, *Maireana georgei* and *M. trichoptera*. This community type was allied with species groups A, C and D, with a complete absence of species from groups F and G (Table 2). Species richness was variable across sites, ranging from 28 to 46 taxa per quadrat (mean 36.2 ± 7.2 SD).

Soils from this community were neutral (pH 7.2–7.7) sandy clay loams. Ca concentrations were predominantly high and moderate to high concentrations of other major soil cations (K, Mg, Na) were recorded (Table 3). No exposed bedrock was present and coarse fragments were predominantly composed of basalt with mixed metasediments and calcrete. Cover of bare ground was high, with very sparse to sparse cover of leaf litter (4–15%).

Community type 2 was represented by a pair of lowland quadrats (BLFN 42 and 47) on gentle slopes. Community structure was dominated by open shrubland of *Acacia* sp. narrow phyllode (BR Maslin 7831), *A. tetragonophylla* and *Pittosporum angustifolium* over chenopod shrubs, including *Enchylaena* sp. and *M. trichoptera* over *Goodenia mimuloides* and *Austrostipa elegantissima*. The community was primarily associated with species groups A, D and G, with an absence of species from group B (Table 2). Species richness was 37 and 29

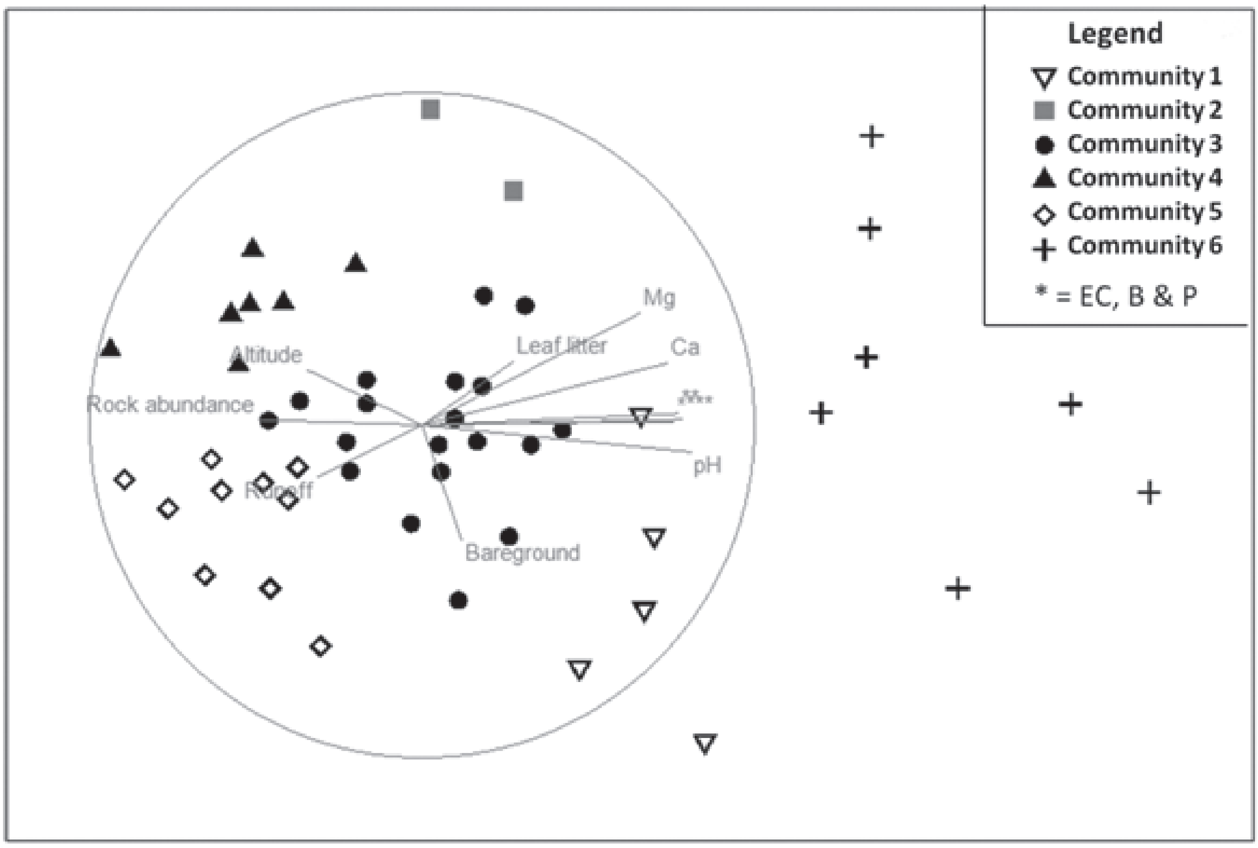


Figure 3. 2D graph of the first two axes of the NMS ordination (2D stress value = 0.15) of survey plots for the southern Bullfinch Greenstone Belt. Survey plots are separated by community groups overlain with environmental vectors, using the lines of best-fit in a multi-dimensional space. Vectors extending close to the edge of the circle indicate stronger correlation to those communities. The soil parameters (soil pH, electrical conductivity, Ca, Mg, B and P) that had the greatest correlation with community groups ($r_s \geq 0.7$) are shown. For comparison, the vectors of the top five site physical characteristics (abundance of coarse fragments and leaf litter, runoff, altitude and bare ground) are also shown. Data are a matrix of 87 perennial species from 50 survey sites.

taxa per quadrat, respectively; lower than the mean for all of the survey plots. Soils were acidic (pH 5.3) clay loam sands at BLFN 42 and mildly alkaline (pH 7.9) sandy clay loam at BLFN 47. Bare ground was prevalent with very sparse cover of leaf litter.

Community type 3 was the most widespread of all vegetation types, recorded within 19 quadrats. This was a predominantly woodland community found on upper slopes with moderate to steep gradients. Species richness was generally high (mean taxa per quadrat 49.1 ± 8.3 SD), ranging from 29 to 61 taxa per quadrat. Taxa were principally associated with species groups A, B and E, with minor representation in C and D (Table 2). Dominant overstorey species varied, but included *Eucalyptus ewartiana* and *Brachychiton gregorii.* A group of sites within this community type were more typical of shrubland communities and lacked dominant tree species; however, further surveys are required to clarify their status as a potential sub-type or separate community. Other key taxa included *Acacia tetragonophylla*, *Dodonaea inaequifolia*, *Enchylaena* sp., *Ptilotus obovatus*, and *Scaevola spinescens* over *Goodenia berardiana* and *Sida* sp. dark green fruits (S van Leeuwen 2260).

Soils were sandy loam to sandy clay loam, varying from acidic to mildly alkaline (pH 5–7.7). Coarse fragments were very abundant across all sites, with the majority of sites also having exposed bedrock. Regolith composition was primarily ironstone (some banded) and metabasalt. Leaf litter was sparse to moderate, with a high proportion of bare ground present. Ca concentrations were comparatively high at most of the plots (Table 3). Other soil cation concentrations were concomitantly high, except for Na, which had moderate concentrations compared with other community types.

Community type 4 was a group of mallee shrubland sites with highly acidic soils (pH 5.1–5.6), found on gentle gradients across a range of topographical positions. Species richness was high, ranging from 41 to 53 taxa per quadrat (mean 46.9 ± 4.3 SD); taxa were predominantly associated with species groups A, E and G (Table 2). There was a complete absence of taxa from group B. The dominant mallee species was *Eucalyptus ewartiana*. Other eucalypts included *E. longissima* and *E. yilgarnensis*. Typical shrub taxa included *Acacia* sp. narrow phyllode (BR Maslin 7831), *Dodonaea inaequifolia* and *Enchylaena* sp. Other typical taxa included the geophyte *Cheilanthes*

Table 3

Summary statistics for environmental variables, separated by community type, for the southern Bullfinch Greenstone Belt. Mean values with standard deviation are listed for community types with greater than a single locality recorded. Differences were determined using Kruskal–Wallis non-parametric analysis of variance. Only community types with >2 representative quadrats were included in the analyses. Significance values are indicated by * ($p < 0.05$ = *; $p < 0.01$ = **; $p < 0.001$ = ***; $p < 0.0001$ = ****) and $^{+}$ equates to no significant difference of means; post-hoc differences were set at $\alpha = 0.05$. Units of measurements for the parameters are: soil chemicals = mg/kg; abundance of fragments and outcrop abundance = categorical maximum (0 = 0%, 1 = <2%, 2 = 2–10%, 3 = >10–20%, 4 = >20–50%, 5 = >50–90%, 6 = >90%); topographical position: 1 = crest, 2 = upper slope, 3 = mid-slope, 4 = lower slope, 5 = flat; species richness = number of taxa per quadrat.

	Community Types					
Soil Parameters	**1**	**2**	**3**	**4**	**5**	**6**
B****	1.36 ± 0.78 ab	1.0 ± 0.78	1.3 ± 0.7 ab	0.4 ± 0.2 c	0.6 ± 0.1 bc	4.8 ± 1.8 a
Ca****	3340.0 ± 1636.5 ab	3600.0 ± 2687	2838.9 ± 1786.1 ab	1247.1 ± 349.5 a	1069.0 ± 226.5 a	5500.0 ± 0.0 b
Cd*	0.019 ± 0.013 ab	0.015 ± 0.007	0.040 ± 0.06 a	0.017 ± 0.008 ab	0.011 ± 0.008 b	0.016 ± 0.008 ab
Co****	3.1 ± 1.3 ab	3.7 ± 3.8	3.3 ± 1.9 a	5.6 ± 1.5 a	4.7 ± 1.1 a	0.5 ± 0.2 b
Cu*	3.9 ± 1.2 ab	4.5 ± 0.8	7.3 ± 4.8 a	4.9 ± 2.2 ab	4.7 ± 2.5 ab	2.7 ± 1.3 b
EC****	29.2 ± 23.7 a	9.0 ± 4.2	13.3 ± 6.6 ab	5.7 ± 2.4 bc	4.5 ± 1.4 c	23.6 ± 10.4 a
Fe***	45.8 ± 9.1 ab	46.5 ± 31.8	58.3 ± 16.3 bc	74.6 ± 12.2 c	59.2 ± 7.4 bc	37.9 ± 6.0 a
K**	442.0 ± 81.7 a	370.0 ± 99.0	390.0 ± 80.1 a	328.6 ± 67.7 ab	286.0 ± 51.7 b	438.6 ± 83.6 ab
Mg***	492.0 ± 97.8 ab	620.0 ± 240.4	481.1 ± 290.6 a	407.1 ± 250.2 a	247.0 ± 57.0 a	975.7 ± 169.3 b
Mn***	194.0 ± 49.3 a	154.5 ± 78.5	166.1 ± 81.3 a	187.1 ± 43.5 a	211.0 ± 40.7 a	63.0 ± 20.7 b
N (total)**	0.10 ± 0.05 ab	0.11 ± 0.02	0.14 ± 0.06 ab	0.12 ± 0.04 ab	0.09 ± 0.02 a	0.22 ± 0.07 b
Na**	147.6 ± 165.1 a	29.5 ± 2.1	31.2 ± 16.3 b	24.6 ± 9.7 b	26.9 ± 12.2 b	89.6 ± 62.8 ab
Ni***	3.0 ± 1.9 ab	9.0 ± 9.9	6.0 ± 9.2 ab	8.8 ± 5.8 a	1.1 ± 0.3 b	1.7 ± 0.8 b
Organic C (%)**	1.1 ± 0.6 ab	1.2 ± 0.4	1.5 ± 0.7 ab	1.4 ± 0.6 ab	0.9 ± 0.2 a	2.9 ± 0.9 b
P****	8.4 ± 1.1 ab	7.0 ± 5.7	9.3 ± 5.3 ab	4.1 ± 0.7 bc	3.8 ± 0.9 c	27.3 ± 15.0 a
pH****	7.4 ± 0.3 ab	6.6 ± 1.8	6.7 ± 0.9 b	5.3 ± 0.2 c	5.7 ± 0.3 bc	7.9 ± 0.1 a
S***	13.2 ± 11.9 ab	10.0 ± 0.0	9.4 ± 3.9 a	10.0 ± 5.3 ab	5.7 ± 2.5 a	43.4 ± 25.0 b
Zn^{NS}	2.2 ± 0.2	1.2 ± 0.4	3.0 ± 1.6	1.9 ± 0.4	3.5 ± 2.0	2.0 ± 1.1
Site Physical Parameters						
Altitude (m)**	349.0 ± 12.7 a	367.0 ± 8.5	382.0 ± 15.0 b	373.1 ± 8.5	388.5 ± 25.0 b	380.0 ± 14.8 ab
Bare ground (%)*$^{+}$	96.8 ± 1.3	96.5 ± 0.7	95.3 ± 1.5	94.4 ± 1.6	96.4 ± 1.3	95.0 ± 1.8
Abundance-fragments*$^{+}$	3.8 ± 1.8	4.0 ± 1.4	5.6 ± 0.6	4.9 ± 1.5	5.8 ± 0.6	4.9 ± 0.4
Leaf litter (%)**	8.4 ± 4.4 a	8.0 ± 2.8	9.3 ± 4.3 a	13.0 ± 6.5 ab	9.1 ± 4.2 a	31.1 ± 12.1 b
Topographical position*	4.4 ± 0.9 a	4.0 ± 0.0	2.3 ± 1.0 b	3.1 ± 1.3 ab	2.3 ± 1.1 ab	2.7 ± 1.4 ab
Outcrop abundance*$^{+}$	0.0 ± 0.0	0.0 ± 0.0	1.3 ± 1.3	0.4 ± 0.8	1.3 ± 0.9	0.4 ± 0.8
Runoff***	1.3 ± 0.9 a	1.3 ± 0.4	2.8 ± 0.6 b	1.8 ± 0.9 ab	2.8 ± 0.9 ab	1.7 ± 0.8 ab
Species Richness	36.2 ± 7.2	33.0 ± 5.7	48.6 ± 8.0	46.9 ± 4.3	40.9 ± 6.0	11.6 ± 5.5
Number of quadrats:	**5**	**2**	**19**	**7**	**10**	**7**

adiantoides and the climbers *Drosera macrantha* subsp. *macrantha* and *Thysanotus manglesianus*.

Soils were sandy clay loams. The abundance of coarse fragments was variable, with limited surface exposure of bedrock. Rock fragments were primarily composed of basalt with mixed metasediments. Leaf litter cover was generally low (3–20%; Table 3).

Community type 5 corresponded to *Allocasuarina* woodlands, typical of mid to upper slopes in the northern portion of the study area. Taxa were predominantly associated with species groups D and E (Table 2). Species richness was high, with 33 to 51 taxa per quadrat (mean 40.9 ± 6 SD). The dominant canopy species was typically *A. dielsiana*, with an understorey of *Acacia* sp. narrow phyllode (BR Maslin 7831), *Eremophila clarkei*, *Ptilotus obovatus* and *Solanum lasiophyllum* over *Goodenia berardiana* and *Sida* sp. dark green fruits (S van Leeuwen 2260), along with the climber *T. speckii*.

Soils were mildly to strongly acidic (pH 5.3–6.4) sandy clay loams. The abundance of coarse fragments was high, with exposed bedrock found at most sites. Basalt was the primary rock present, with some calcrete present, as indicated by moderate Ca concentrations (Table 3). Leaf litter was generally very sparse (3–15%).

Community type 6 was a heterogeneous group of *Eucalyptus* spp. woodland sites that were species-poor (mean taxa per quadrat 11.6 ± 5.5 SD). Predominantly found in the southern part of the survey area, the community was associated with species groups A and F, with a near absence of the ubiquitous taxa of group E and no species from group G (Table 2). The community was primarily *E. longissima* woodlands over chenopod shrubs, particularly *Atriplex nummularia* and *Maireana trichoptera*.

The sites were not associated with any particular topographical position, but were characterised by sandy loam to sandy clay loam and moderately alkaline soils (pH 7.8–8). Coarse fragments were abundant, up to 60 cm in size, but presence of exposed bedrock was limited. Relative to other communities at Bullfinch, the soils had high concentrations of Ca, moderate to high concentrations of organic carbon and low to moderate Fe content (Table 3).

Environmental variables

The southern Bullfinch Greenstone Belt was characterised by low hills and subtle topographic variation. Variation in altitude for the survey sites ranged from 330 to 413 m. The soils collected were skeletal to shallow in depth and typically brown and red brown sandy loams and sandy clay loams. The abundance of coarse rock fragments was high at most survey sites, with an average cover category of 5.18, representing 50–90% cover (Table 3). The presence of exposed bedrock was variable, with 26 sites having no surface bedrock. Where present, bedrock was identified as basalt, ironstone or undifferentiated greenstone. The majority of sites had a high proportion of bare ground (mean 95.5% ± 1.6 SD) and sparse leaf litter present (mean 12.7% ± 9.7 SD).

Soil pH varied from 5 to 8, with a mean of 6.5 ± 1.1 SD. Nearly half of the sites had soils that were acidic to strongly acidic; the remaining plots were evenly distributed between having neutral or alkaline soils. Those survey plots with alkaline soils (pH >7.5) also had the highest Ca concentration (Ca ≥ 4000 mg kg^{-1}) and high Mg content (Mg >450 mg kg^{-1}).

Strong intercorrelations existed amongst soil parameters (Table 4). Soil pH, electrical conductivity, organic carbon and the following soil chemical properties (B, Ca, K, Mg, N, Na, P and S) were positively intercorrelated ($p < 0.05$). All were negatively correlated with Fe ($p < 0.05$), except organic carbon, Mg and N ($p > 0.05$) and Co ($p < 0.05$). The strongest correlation was between organic carbon and N ($r_s = 0.97$, $p < 0.0001$). Species richness was positively correlated with Co, Cu, Fe, Mn, Ni and negatively correlated with soil pH, B, Ca, Mg, Na and P ($p < 0.05$).

Environmental attributes were examined for correlative relationships. Strong positive correlations existed between slope and runoff ($r_s = 0.77$, $p < 0.0001$). Positive inter-correlations were detected between altitude, abundance of coarse fragments and exposed bedrock, maximum rock fragment size and runoff ($p < 0.05$); all were negatively correlated with topographical position (i.e. 1 = crest to 5 = outwash; $p < 0.05$). Topographical position was positively correlated with disturbance ($r_s = 0.34$, $p < 0.05$), suggesting that disturbance was occurring more frequently on the lower slopes.

The Kruskal–Wallis analysis of variance determined whether significant differences in environmental variables occurred between community groups; community type 2 was excluded from the analyses due to paucity of representative sites (Table 3). Community type 6 was distinguished by having distinctly high or low means for many of the soil chemical parameters, with the highest mean value for B, Ca, Mg, N, S, organic carbon and soil pH and the lowest mean value for Co, Cu, Fe and Mn. In particular, concentrations of Co, Cu, Fe, Mg and Mn and soil pH were significantly different between community type 6 and community type 3. Concentrations of B, Ca, Co, Fe, Mg, Mn and P, soil pH and electrical conductivity were significantly different between community types 4 and 5 and community type 6. Significant differences in site physical parameters were more marked between community types 1 and 3 (altitude, topographical position and runoff). Percent cover of leaf litter exhibited patterns more similar to soil chemical parameters, with community type 6 having the highest mean value, which was significantly different from communities types 1, 3 and 5.

DISCUSSION

No systematic surveys of the flora or vegetation have been carried out in the southern Bullfinch Greenstone Belt, with only the central portion of the greenstone belt previously receiving attention by Gibson and Lyons (2001). In total, 218 taxa were identified during the survey, which was lower than the 242 taxa identified by Gibson and Lyons (2001), but comparable to other flora surveys of the

Table 4

Spearman rank correlation coefficients for select soil parameters and species richness. The upper value for each correlation is the correlation coefficient and the lower value represents significance at $p < 0.05$. Bold values represent highly significant correlations at $p < 0.0001$. Where no lower value is reported, the relationship is not significant ($p > 0.05$).

	B	CA	CO	CU	EC	FE	K	MG	MN	N	NA	NI	ORG C	P	pH	S
CA	**0.7916**															
	0															
CO	**-0.7128**	-0.512														
	0	0.0002														
CU	-0.0902	0.056	0.395													
			0.0048													
EC	**0.7445**	**0.7502**	**-0.5685**	-0.0715												
	0	**0**	**0**													
FE	**-0.6259**	-0.5226	**0.6545**	0.2139	-0.4597											
	0	0.0001	**0**		0.0009											
K	**0.6508**	**0.668**	-0.3381	0.2006	**0.6774**	-0.4117										
	0	**0**	0.0167		**0**	0.0032										
MG	**0.5902**	**0.8202**	-0.3356	0.0017	**0.5625**	-0.1715	0.4178									
	0	**0**	0.0176		**0**		0.0027									
MN	**-0.5791**	**-0.5611**	**0.6678**	0.2237	-0.4066	0.2449	-0.2743	**-0.6438**								
	0	**0**	**0**		0.0036			**0**								
N	**0.6503**	**0.6341**	-0.4196	-0.0037	0.5333	-0.1269	0.5114	**0.6496**	**-0.6331**							
	0	**0**	0.0026		0.0001		0.0002	**0**	**0**							
NA	0.4294	0.487	-0.3332	-0.2422	**0.6499**	-0.3998	0.4637	0.3881	-0.1077	0.3619						
	0.002	0.0004	0.0185		**0**	0.0043	0.0008	0.0056		0.0102						
NI	-0.2143	0.0914	0.4289	0.2148	0.0408	**0.5496**	0.125	0.3333	0.0083	0.1281	-0.0674					
			0.0021			**0**		0.0184								
ORG C	**0.6516**	**0.5963**	-0.4577	-0.1002	0.5184	-0.1152	0.4629	**0.6174**	**-0.6314**	**0.9699**	0.3646	0.1383				
	0	**0**	0.0009		0.0001		0.0008	**0**	**0**	**0**	0.0096					
P	**0.8219**	**0.6129**	**-0.8039**	-0.2021	**0.748**	**-0.5521**	**0.5599**	0.4499	**-0.625**	**0.5751**	0.4298	-0.2143	**0.6018**			
	0	**0**	**0**		**0**	**0**	**0**	0.0012	**0**	**0**	0.002		**0**			
pH	**0.8262**	**0.8627**	**-0.6231**	-0.0159	**0.7133**	**-0.6913**	**0.5774**	**0.6546**	-0.512	0.3853	0.424	-0.2082	0.3337	**0.6612**		
	0	**0**	**0**		**0**	**0**	**0**	**0**	0.0002	0.006	0.0023		0.0183	**0**		
S	**0.6322**	**0.5494**	**-0.5662**	-0.1924	**0.6539**	-0.3292	**0.5523**	0.4553	-0.4854	**0.7883**	0.4925	-0.0292	**0.7966**	**0.6886**	0.3861	
	0	**0**	**0**		**0**	0.02	**0**	0.001	0.0004	**0**	0.0003		**0**	**0**	0.0059	
RICHNESS	-0.3064	-0.3021	0.4977	0.346	-0.149	**0.5667**	-0.0417	-0.314	0.2866	-0.0588	-0.3771	0.3804	-0.0827	-0.2916	-0.4068	-0.2264
	0.0309	0.0333	0.0003	0.0142		**0**		0.0268	0.0439		0.0073	0.0067		0.0403	0.0036	

greenstone belts within the Yilgarn Craton (e.g. Markey & Dillon 2008a, 2008b; Meissner & Caruso 2008a, 2008b, 2008c). The high representation of annuals (85 taxa) identified during the survey was probably associated with above average precipitation in the months preceding the survey. During the three months prior to the survey (June–August 2009), 129.8 mm of rain was recorded, whereas the mean rainfall for this period is 110.5 mm (Bureau of Meteorology 2010).

The survey recorded three priority taxa. The Highclere Hills survey only recorded two priority taxa—*Tricoryne* sp. Morawa (GJ Keighery & N Gibson 6759) and *Caesia* sp. Ennuin (N Gibson & MN Lyons 2737)—one of which, *Caesia* sp. Ennuin (N Gibson & MN Lyons 2737), was recorded during this survey. The *Tricoryne* sp. Wongan Hills (BH Smith 794) collected at Bullfinch requires further clarification, due to the differing substrate and geographic disparity when compared with the other collections. A formal taxonomic description may elucidate the identity of the collection. Considering the disjunct distribution and conservation status (P2), care should be taken to preserve the population of *Tricoryne* sp. Wongan Hills (BH Smith 794) in the Bullfinch Greenstone Belt.

The presence of weeds reflects the long history of disturbance in the area, as it was one of the earliest areas to be mined in the Goldfields region. There were 24 weed taxa recorded during the survey, which is comparable to the 25 weed taxa recorded at Highclere Hills (Gibson & Lyons 2001). However, there was an overlap of only 11 taxa. The Highclere Hills had a notable dominance of weed taxa from the Poaceae family (eight species), whereas Bullfinch had more weed taxa from the Asteraceae family (6) and only five Poaceae taxa. *Carrichtera annua* (Ward's weed), known to inhabit disturbed areas (Weber 2003) was the most dominant weed taxon, with records from 32 quadrats.

There were overlaps in taxa within species groups between the Highclere Hills study and this one. This was expected, as Highclere Hills is a continuation of the Bullfinch Greenstone Belt north of Lake Deborah West. For example, species group A and the Highclere Hills' species group G, which were associated with neutral to alkaline sites, have seven shared taxa. Common taxa within the species groups shared between surveys included *Atriplex nummularia*, *Austrostipa trichophylla*, *Eremophila oppositifolia*, *Eucalyptus corrugata*, *Exocarpos aphyllus*, *Maireana trichoptera* and *Sclerolaena diacantha*. Species group E contained a similar suite of species to the Highclere Hills' species group C: both groups were characterised by rather ubiquitous taxa. In particular, *Acacia tetragonophylla*, *Dianella revoluta* var. *divaricata*, *Eremophila serrulata*, *Prostanthera althoferi* subsp. *althoferi*, *Ptilotus obovatus*, *Scaevola spinescens* and *Solanum lasiophyllum* were shared taxa within the species groups. Species group F and Highclere Hills' species group H shared three taxa from the mid to upper stratum, including *Dodonaea stenozyga*, *Eucalyptus yilgarnensis* and *Santalum acuminatum*.

Specific community types were not directly analogous between this survey and the Highclere Hills survey (Gibson & Lyons 2001). Community type 6 in this study may be a species-poor variation of Highclere Hills' community type 1, both eucalypt woodland communities with chenopod species present in the understorey (e.g. *Atriplex* spp., *Maireana trichoptera* and *Sclerolaena diacantha*). Additional placement of survey quadrats within the Bullfinch Greenstone Belt may resolve the variation in community types, in particular differences that may be linked to geographic gradients or degree of weathering along the belt.

Environmental correlates

Soils were predominantly moderately acidic sandy loams and sandy clay loams. The sites with higher soil pH were associated with high Ca concentrations, suggesting the presence of calcrete. The soils were less acidic than in other greenstone belt areas in the Yilgarn Craton, which were characterised by highly acidic soils (Thompson & Sheehy 2011a, 2011b, 2011c), indicative of heavily weathered regolith (Slattery et al. 1999). However, vegetation communities were characterised by similar soil pH patterns (i.e. the division of acidic and alkaline sites) and affinities for specific geologies seen at Highclere Hills (i.e. ironstone vs. ultramafics; Gibson & Lyons 2001).

Weathering of the regolith influences the concentration of trace elements in the soils. Lower slopes and adjacent outwash areas are enriched by the movement of mobile elements from the upland regions (Ben-Shahar 1990). In particular, calcrete accumulation has been allied with lower slopes and pediments (Anand et al. 1997). However, this relationship was less evident within the Bullfinch Greenstone Belt, possibly related to the more gentle topographic gradients across survey sites. Relatively high Ca concentrations were recorded within community types 1 and 2, which had the two lowest mean altitudes and corresponding topographical positions across community types. However, community type 6 had the highest concentrations of Ca, S and organic carbon. The disparity in Ca concentration relative to topographical position may be indicative of different rates of weathering, as studies have shown that sulphides and carbonates are readily leached from the profile (Butt et al. 2000; Anand 2005). Furthermore, community type 6 had relatively low Fe concentrations, another element indicative of weathered soils and underlying bedrock (Gray & Murphy 2002).

Environmental parameters were important to the delineation of community types, with soil chemical parameters highly correlated with community groupings. Other studies of the flora and vegetation of the greenstone belts of the Yilgarn Craton have documented extensively the relationship between plant communities and environmental parameters, especially topographical position and edaphic factors (Markey & Dillon 2008a, 2008b; Meissner & Caruso 2008a, 2008b, 2008c; Thompson & Sheehy 2011a, 2011b, 2011c). In the Highclere Hills portion of the Bullfinch Greenstone Belt, vegetation patterns were predominantly influenced by soil parameters, rather than topographical position (Gibson & Lyons 2001). The relationship was generally similar for the southern part of the Bullfinch Greenstone Belt. In this study, the strong correlation between Mg concentrations and community types was not surprising, given the presence of mafic rocks in the greenstone belt. Soils within community types were also characterised by relatively consistent pH values.

Some plant communities, however, were strongly allied to topographical position. In particular, community type 1, which was typical of footslopes and adjacent pediments, occupied topographical postions significantly different to those where community type 3, a predominantly upland vegetation association, was found. The difference between communities types 1 (low) and 3 (high) were the same for runoff, which is related to slope and is often linked to topographical position. The reduced influence of topographical position on vegetation communities compared with other greenstone belt studies may be related to the more subdued topography of the Bullfinch Greenstone Belt (Gibson & Lyons 2001). Other greenstone belt studies in the Yilgarn Craton have focused on the banded ironstone formations (BIF), which are often ranges and outcropping with significant topographical gradients. Another consideration is the underlying geologic sequences and variation in weathering confounding the relationship of topographical position and vegetation communities; our soil samples and site physical parameters do not provide a complete substrate/geologic profile.

Conservation significance

Greenstone belts are poorly represented in the conservation estate and this has been highlighted over the years with respect to both flora and fauna values (Henry-Hall 1990; Chapman & Newbey 1995). Recent papers (e.g. Gibson et al. 2010; Gibson et al. 2012) have reiterated the importance of the plant species richness within the greenstone belts of the Yilgarn Craton, in particular the banded ironstone formations and the high beta-diversity (species turnover) between these areas. The long history of exploration, mining and pastoral use is evident in the landscape. In particular, it was observed repeatedly that where exploration and mining had occurred, there was a noticeable lack of rehabilitation. A history of poor environmental controls has left significant scars on the landscape. Establishment of quadrats was limited in many areas due to drilling (both pads and equipment) and existing mining and pastoral infrastructure on some of the hills. The prevalence of *Carrichtera annua* and other weed taxa at many sites during the survey reflects the high level of landscape disturbance. Overall, the southern portion of the Bullfinch Greenstone Belt does not represent the same repository of conservation taxa recorded elsewhere in the Yilgarn Craton (e.g. Markey & Dillon 2008b; Meissner & Caruso 2008a). However, the survey has identified the second population of an undescribed priority taxon record from the earlier assessment by Gibson and Lyons (2001), and a significant range extension of another undescribed priority taxon, which may be a new species. The areas containing these species should be protected from further degradation.

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APPENDIX 1

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

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

Amaranthaceae
- *Ptilotus exaltatus*
- *Ptilotus gaudichaudii* var. *parviflorus*
- *Ptilotus holosericeus*
- *Ptilotus obovatus*
- *Ptilotus spathulatus* forma *spathulatus*

Apiaceae
- *Daucus glochidiatus*

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

Araliaceae
- *Hydrocotyle pilifera* var. *glabrata*
- *Trachymene ornata*

Asparagaceae
- *Arthropodium curvipes*
- *Arthropodium dyeri*
- *Thysanotus manglesianus*
- *Thysanotus speckii*

Aspleniaceae
- *Pleurosorus rutifolius*

Asteraceae
- *Actinobole uliginosum*
- **Arctotheca calendula*
- *Asteridea athrixioides*
- *Blennospora drummondii*
- *Brachyscome ciliaris*
- *Brachyscome ciliocarpa*
- *Brachyscome lineariloba*
- *Brachyscome perpusilla* var. *tenella*
- *Calotis hispidula*
- *Cephalipterum drummondii*
- *Ceratogyne obionoides*
- *Chthonocephalus pseudevax*
- **Cirsium vulgare*
- *Erymophyllum ramosum* subsp. *ramosum*
- *Hyalosperma demissum*
- *Hyalosperma glutinosum* subsp. *glutinosum*
- *Hyalosperma zacchaeus*
- **Hypochaeris glabra*
- *Isoetopsis graminifolia*
- *Lawrencella rosea*
- *Lemooria burkittii*
- *Leucochrysum fitzgibbonii*
- *Millotia myosotidifolia*
- *Millotia perpusilla*
- **Monoculus monstrosus*
- *Olearia muelleri*
- *Olearia pimeleoides*
- *Podolepis canescens*
- *Podolepis capillaris*
- *Podolepis lessonii*
- *Podotheca angustifolia*
- *Podotheca gnaphalioides*
- *Rhodanthe haigii*
- *Rhodanthe laevis*
- *Rhodanthe manglesii*
- *Rhodanthe oppositifolia* subsp. *oppositifolia*
- *Rhodanthe pygmaea*
- *Rhodanthe rubella*
- *Rhodanthe stricta*
- *Schoenia cassiniana*
- *Senecio glossanthus*
- *Senecio pinnatifolius*
- **Sonchus oleraceus*
- *Trichanthodium skirrophorum*
- *Triptilodiscus pygmaeus*
- **Ursinia anthemoides*
- *Waitzia acuminata* var. *acuminata*

Boraginaceae
- *Cynoglossum* sp. Inland Ranges (CA Gardner 14499)
- *Omphalolappula concava*

Brassicaceae
- **Brassica tournefortii*
- **Carrichtera annua*
- *Lepidium oxytrichum*
- *Menkea australis*
- *Menkea sphaerocarpa*
- **Sisymbrium orientale*
- *Stenopetalum filifolium*

Campanulaceae
- *Wahlenbergia gracilenta*

Caryophyllaceae
- **Silene nocturna*
- *Stellaria filiformis*

Casuarinaceae
- *Allocasuarina dielsiana*

Chenopodiaceae
- *Atriplex nummularia*
- *Atriplex paludosa* subsp. *baudinii*
- *Atriplex vesicaria*
- *Chenopodium curvispicatum*
- *Einadia nutans* subsp. *eremaea*
- *Enchylaena lanata*
- *Enchylaena tomentosa* var. *tomentosa*
- *Eriochiton sclerolaenoides*
- *Maireana georgei*
- *Maireana georgei* x *Enchylaena tomentosa*
- *Maireana georgei* x *Enchylaena lanata*
- *Maireana planifolia*
- *Maireana tomentosa*
- *Maireana trichoptera*
- *Maireana triptera*
- *Rhagodia drummondii*
- *Salsola australis*
- *Sclerolaena diacantha*
- *Sclerolaena obliquicuspis*

Colchicaceae
- *Wurmbea tenella*

Convolvulaceae
- **Cuscuta planiflora*

Crassulaceae
Crassula colorata var. *acuminata*

Cyperaceae
Schoenus nanus

Droseraceae
Drosera macrantha subsp. *macrantha*

Fabaceae
Acacia erinacea
Acacia jennerae
Acacia ligulata
Acacia ramulosa var. *ramulosa*
Acacia sp. narrow phyllode (BR Maslin 7831)
Acacia tetragonophylla
Isotropis juncea
**Medicago minima*
Mirbelia microphylla
Senna artemisioides subsp. *filifolia*
Senna charlesiana
Senna stowardii
Swainsona sp.

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

Goodeniaceae
Goodenia berardiana
Goodenia mimuloides
Goodenia occidentalis
Scaevola spinescens
Velleia rosea

Haloragaceae
Haloragis sp.

Hemerocallidaceae
Caesia occidentalis
Caesia sp. Ennuin (N Gibson & MN Lyons 2737) P1
Dianella revoluta var. *divaricata*
Tricoryne sp. Wongan Hills (BH Smith 794) P2

Hypoxidaceae
Hypoxis glabella var. *glabella*

Juncaginaceae
Triglochin sp. A Flora of Australia (GJ Keighery 2477)

Lamiaceae
Prostanthera althoferi subsp. *althoferi*

Loganiaceae
Phyllangium sulcatum

Malvaceae
Abutilon cryptopetalum
Abutilon oxycarpum
Brachychiton gregorii
Sida calyxhymenia
Sida petrophila
Sida sp. dark green fruits (S van Leeuwen 2260)
Sida sp. golden calyces glabrous (HN Foote 32)

Myrtaceae
Eucalyptus corrugata
Eucalyptus ewartiana
Eucalyptus longissima
Eucalyptus salmonophloia
Eucalyptus yilgarnensis
Melaleuca hamata
Melaleuca lanceolata
Melaleuca pauperiflora subsp. *fastigiata*

Orchidaceae
Diuris pulchella
Prasophyllum gracile
Pterostylis aff. *spathulata*
Pterostylis mutica
Pterostylis sp. inland (AC Beauglehole 11880)

Orobanchaceae
**Parentucellia latifolia*

Pittosporaceae
Bursaria occidentalis
Pittosporum angustifolium

Plantaginaceae
Plantago debilis

Poaceae
Aristida contorta
Austrodanthonia caespitosa
Austrostipa blackii P3
Austrostipa elegantissima
Austrostipa nitida
Austrostipa scabra
Austrostipa tenuifolia
Austrostipa trichophylla
Austrostipa variabilis
**Avellinia michelii*
Bromus arenarius
**Bromus rubens*
Elymus scaber
**Hordeum leporinum*
**Pentaschistis airoides* subsp. *airoides*
**Vulpia myuros* forma *myuros*

Polygalaceae
Comesperma integerrimum

Polygonaceae
**Acetosa vesicaria*

Portulacaceae
Calandrinia calyptrata
Calandrinia eremaea s.l.

Proteaceae
Hakea recurva subsp. recurva

Pteridaceae
Cheilanthes adiantoides
Cheilanthes lasiophylla
Cheilanthes sieberi subsp. *sieberi*

Rhamnaceae
Trymalium myrtillus subsp. *myrtillus*

Rubiaceae
**Galium spurium*

Rutaceae
Philotheca brucei subsp. *brucei*

Santalaceae
Exocarpos aphyllus
Santalum acuminatum
Santalum spicatum

Sapindaceae
Dodonaea inaequifolia
Dodonaea stenozyga
Dodonaea viscosa subsp. *angustissima*

Appendix 1 (cont.)

Scrophulariaceae

Eremophila alternifolia
Eremophila clarkei
Eremophila decipiens subsp. *decipiens*
Eremophila interstans subsp. *interstans*
Eremophila ionantha
Eremophila miniata
Eremophila oppositifolia subsp. *angustifolia*
Eremophila scoparia
Eremophila serrulata

Solanaceae

Nicotiana occidentalis subsp. *obliqua*
Solanum lasiophyllum
Solanum orbiculatum subsp. *orbiculatum*
Solanum petrophilum

Thymelaeaceae

Pimelea microcephala subsp. *microcephala*

Urticaceae

Parietaria cardiostegia

Violaceae

Hybanthus floribundus subsp. *floribundus*

Zygophyllaceae

Zygophyllum eremaeum
Zygophyllum ovatum

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Flora and vegetation of greenstone formations of the Yilgarn Craton: south-west Ravensthorpe Greenstone Belt

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ABSTRACT

A quadrat-based survey of the flora of the south-west region of the Ravensthorpe Greenstone Belt identified 321 taxa, including six taxa of conservation significance and three weed species. All of the conservation-listed taxa were known to the area. Range extensions were recorded for three taxa and additional collections of two *Austrostipa* species currently under taxonomic description were made. Six community types were derived from statistical classification of the 50 quadrats. These community types were similar to those described from other parts of the Ravensthorpe Greenstone Belt. As with the other greenstone belts of the Yilgarn Craton, soil chemical parameters and site physical characteristics were influential in delineating community types. Only a small portion of the study area is in the conservation estate; mining and exploration pressures remain the primary threat to this species-rich area.

Keywords: classification, Esperance Plains, Fitzgerald Biosphere, floristic diversity, ultramafics, vegetation communities

INTRODUCTION

Recent surveys of the flora and vegetation of the Yilgarn Craton have identified patterns of high beta-diversity between banded ironstone ranges and associated greenstone belts (Gibson et al. 2007). The greenstone belts of the Yilgarn Craton have long been of interest for pastoral settlement and resource exploration. The south-west region of the Ravensthorpe Greenstone Belt has received attention for its mineral deposits, yet scant attention in terms of systematic description of its flora and vegetation, despite being part of the UNESCO Fitzgerald Biosphere Reserve. This study is part of a survey effort to document the flora, vegetation communities and associated environmental parameters of the greenstone belts in the Yilgarn Craton (see Gibson et al. 2012).

STUDY SITE

The south-western region of the Ravensthorpe Greenstone Belt is situated in the centre of the Esperance Plains Bioregion (IBRA; Thackway & Cresswell 1995). The belt begins c. 25 km south of the South Coast Highway near the West River, trending north-north-east toward Ravensthorpe township (Fig. 1). The greenstone belt covers c. 45 km from north to south and c. 20 km west to east. The latitudinal and longitudinal boundaries of the target area of the Ravensthorpe Greenstone Belt are roughly 33° 30' S, 33° 50' S and 119° 45' E, 120° 05' E, respectively. The land tenure for the greenstone belt, located within the Ravensthorpe Shire, includes freehold, unallocated crown land and crown land, including the Fitzgerald River National Park, Cocanarup Timber Reserve and Crown Reserve 12324 (recreation).

Land use history

The Ravensthorpe area was first surveyed in 1848, with the Dunn brothers taking up land in 1868 at Cocanarup. Following the discovery of gold in Annabel Creek, development occurred in association with gold and copper mines. Ravensthorpe was the state's main copper-producing area until the closure of major operations in 1971 (Thom et al. 1977). Mineral exploration and mining has continued sporadically in the Ravensthorpe area, with particular interest in deposits of gold, copper, nickel and tantalum. At present, the Galaxy Resources Ltd operation is focused on tantalum extraction north of Ravensthorpe, and Tectonic Resources has two operations centred on gold, copper, lead and zinc, primarily south of Ravensthorpe. A nickel mine operation in the Ravensthorpe Range, which was placed in 'care and maintenance' in 2009, has been acquired by First Quantum, with annual production estimated to be between 28,000–39,000 tonnes per annum (First Quantum 2010). In addition to the mineral interest, the area is farmed by a mixture of free- and lease-hold sheep

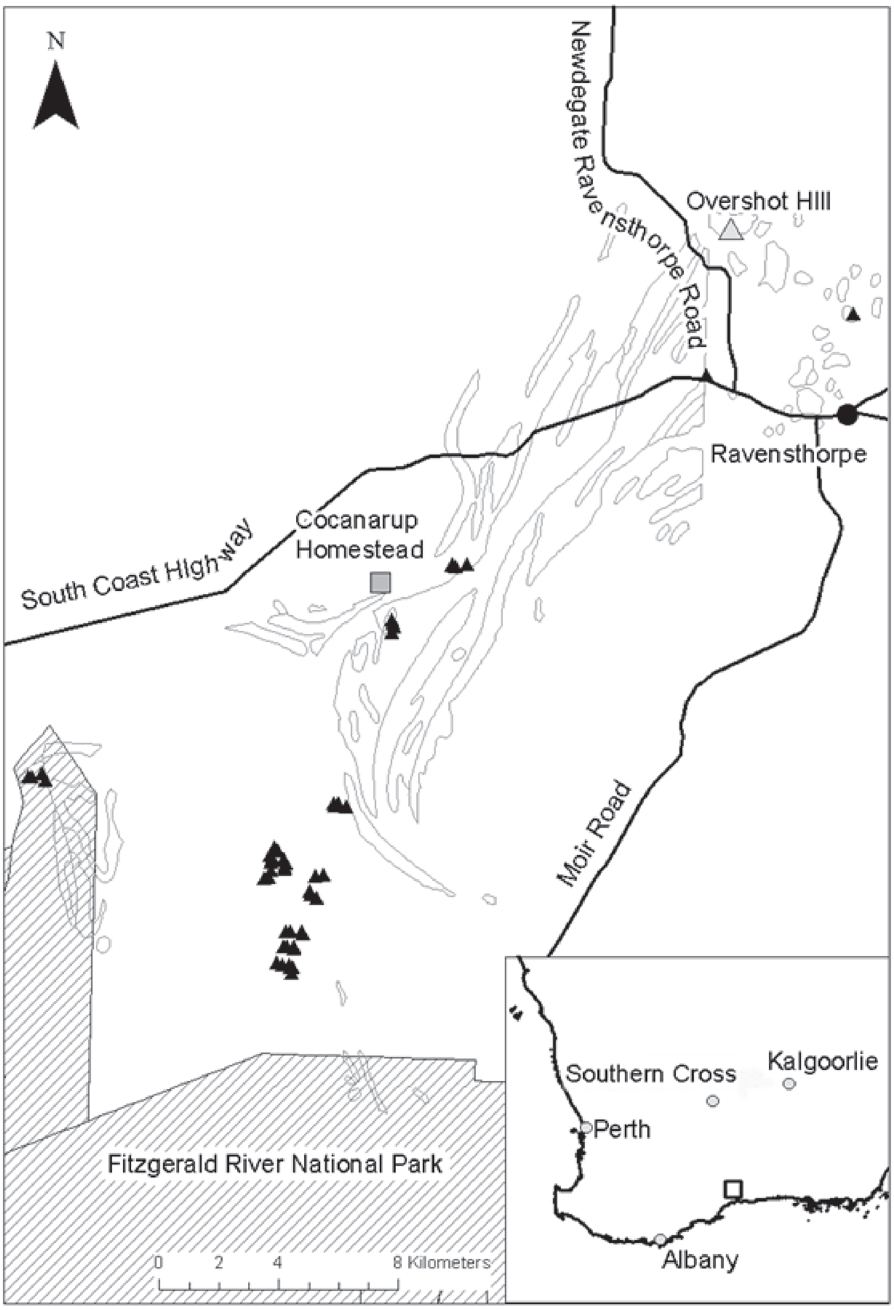

Figure 1. Map showing the location of the south-west region of the Ravensthorpe Greenstone Belt survey area, with major landforms and landmarks indicated. The locations of the 50 permanent quadrats are marked by solid triangles (▲).

and cereal producers. Fitzgerald River National Park sits in the south-west of the study area. The park and study area are within the UNESCO Fitzgerald River Biosphere Reserve. The area is recognised internationally as a biodiversity hotspot that is biologically rich in both flora and fauna (Myers et al. 2000).

Climate

The south-west region of the Ravensthorpe Greenstone Belt sits in the central portion of the Esperance Plains Bioregion, which has a temperate Mediterranean climate with warm to hot summers and mild winters. Rain falls throughout the year, with a slight increase in average monthly rainfall between May and September (mean >40 mm per month; Bureau of Meteorology 2010). Average annual rainfall at Ravensthorpe township (c. 10 km north-east of the survey area) is 425.1 mm (based on records from 1901 to 2010), with the months of July and December having the highest and lowest mean monthly rainfall, respectively. The mean annual maximum and mean minimum temperatures recorded between 1962 and 2010 are 22.7 °C and 10.4 °C, respectively. The warmest months are from November through to March, with average maximum daily temperatures above 25 °C. The lowest daily minimum temperatures occur between May and October, where mean daily minimum temperatures are below 10 °C. Temperatures below zero are an infrequent occurrence.

Geology

The south-west region of the Ravensthorpe Greenstone Belt has been mapped and described on the Newdegate (Thom et al. 1984) and Ravensthorpe (Thom et al. 1977) 1:250,000 geological sheets and straddles the 1:100,000 Cocanarup and Ravensthorpe map sheets (Witt 1994, 1995). This region of the greenstone belt is characterised by relatively low relief, and is surrounded by low granite hills. The dominant feature in the landscape is the Ravensthorpe Range, a north-west trending band of hills that rises c. 400 m above sea level, north-east of the Ravensthorpe township (Thom et al. 1984).

The Ravensthorpe Greenstone Belt, part of the Yilgarn Craton, occurs at the southern extent of the Southern Cross Domain within the Youanmi Terrane (Cassidy et al. 2006). The Archaean-aged Yilgarn Craton is an example of the intact, tectonically stable crusts that occur in the central portion of the Pre-Cambrian Western Shield of Australia (Anand & Paine 2002). The craton contains a series of greenstone belts within vast areas of granitoid and gneiss, believed to have formed between 3000 Ma and 2600 Ma (Myers 1993; Myers & Swagers 1997). Greenstone refers to the surface expression of ultramafic and mafics associated with Archaean meta-volcanic and meta-sedimentary rock sequences in Western Australia, occurring as outcrops or ranges (Cole 1992).

The majority of the Ravensthorpe Greenstone Belt is composed of tonalite and volcanic associations with the western edge dominated by strongly deformed meta-sedimentary rocks (Witt 1997). The principal geologic units of the study area belong to Archaean Annabelle volcanics (metamorphosed mafics to intermediate tuffs), Manyutup tonalite (metamorphosed tonalite and quartz diorite complex) and gneissic granitoids (Witt 1994). Other geologic components include amphibolites, garnetiferous mixed schist and banded quartz-amphibole-plagioclase rock, which constitute the western edge of the greenstone belt (Witt 1994).

The soils of the Esperance Plains Bioregion are typically clay and ironstone gravels overlain by sands (Beard 1990). Where valleys have been carved in the area, the yellow-mottled soils are generally neutral to alkaline (Beard 1990). The soils of the Ravensthorpe Range have been described as shallow calcareous loams on the greenstone uplands, with cracking clays found further downslope and on the adjacent plains (Beard 1981).

Vegetation

The Ravensthorpe Greenstone Belt occurs within the Eyre Botanical District in the South West Botanical Province (Beard 1990). The greenstone belt, particularly the Ravensthorpe Range, is known for its high biodiversity values and is recognised for being floristically rich (Chapman & Newbey 1995a; Craig et al. 2008; Kern et al. 2008). Vegetation surveys and mapping have occurred across the greenstone belt and survey area, principally focusing on the Fitzgerald River National Park (Alpin & Newbey 1990; Chapman & Newbey 1995b) and the Ravensthorpe Range (Chapman & Newbey 1995a; Craig et al. 2008; Kern et al. 2008; Markey et al. 2012).

The area is dominated by scrub- and mallee-heath sandplains, characterised by the presence of *Eucalyptus pleurocarpa* (formerly *E. tetragona*; Beard 1990). Beard (1981) mapped the south-west portion of the Ravensthorpe Greenstone Belt as predominantly *E. nutans* mallee on greenstone, with pockets of *E. loxophleba* and *E. occidentalis* woodlands and *E. reduncа* scrub in the south. The western boundary of the study area, encompassing some of the Fitzgerald River National Park, is chiefly mallee and mallee-heath.

The Ravensthorpe Greenstone Belt belongs to the Ravensthope Vegetation System (Beard 1981). Vegetation associations tend to change with changes in topography and soil depth. Recent surveys have focused on the flora and vegetation of the Ravensthorpe Range (Craig et al. 2008; Kern et al. 2008; Markey et al. 2012), a narrow range of hills with subdued relief occupying much of the north-east area of the greenstone belt. The Ravensthorpe Range is dominated by thicket communities on the uplands, including *E. preissiana* and *E. lehmannii* with *Banksia heliantha* (formerly *Dryandra quercifolia*; Beard 1981). Mallee communities tend to be found further downslope, with *E. loxophleba* and *E. salmonophloia* woodlands occurring on the deeper valley soils (Beard 1981).

Following detailed vegetation mapping (1:10,000), Craig et al. (2008) identified 70 vegetation units associated with the Ravensthorpe Range between Mt. Short and Kundip. Two-hundred permanent vegetation quadrats were established on the Ravensthorpe Range in 2007, and 627 taxa representing 59 families were recorded (Kern et al. 2008). Recently, Markey et al. (2012) analysed the Kern et al. (2008) survey data in conjunction with additional survey quadrats from the Ravensthorpe Range and described 21 community types, predominantly influenced by topographical position, substrate and altitude. Dominant families containing the 698 taxa identified during the survey included Myrtaceae, Fabaceae, Proteaceae and Cyperaceae, with 45 taxa of conservation significance recorded (6 Declared Rare Flora and 39 priority-listed species; Markey et al. 2012).

No systematic surveys have examined the floristic diversity of the south-west Ravensthorpe Greenstone Belt, with prior flora and vegetation surveys focused on the Ravensthorpe Range. This study aimed to alleviate the gap in information on the flora and vegetation of the south-western region of the Ravensthorpe Greenstone Belt. The timing was particularly important as interest in the mineral-rich belt has not dissipated in recent decades. The objective of the study was to record the floristic diversity, describe vegetation patterns and examine environmental correlates associated with this region.

METHODS

Between 21 October and 2 November 2009, fifty 20 × 20 m permanent quadrats were established across the south-west region of the Ravensthorpe Greenstone Belt. The greenstone belt was sampled using an environmentally stratified, biased (non-random) strategy: bias occurred due to various limitations in sampling capacity, including access restrictions, human settlement and associated clearing, and recent wildfire through the central survey area. Quadrats were located to represent the topographical, geological and geomorphological variation across the length and breadth of the range, which also allowed the capture of associated vegetation communities. The methods used followed those of previous surveys on greenstone belts in the Yilgarn Craton (e.g. Markey & Dillon 2008a, 2008b; Meissner & Caruso 2008a, 2008b, 2008c). The landscape positions of the sites encompassed a broad topological sequence from hill crests downslope to the colluvial deposits. Quadrats were located in areas that had minimal disturbance or modification following burning or from pastoral agriculture. Thus, sites where there was evidence of disturbance were avoided (e.g. heavy grazing, fire scars, clearing or exploration-related activities). Much of the north-north-eastern portion of the defined survey area is cleared and the central-western portion had been burnt in a wildfire (<2 years) prior to the survey; therefore, fewer quadrats were located in these areas.

The quadrats were marked by four steel fence droppers and their location recorded using a Garmin Map76 GPS. Photographs were taken at a set distance of 5 m from each corner. Site physical characteristics (landform, slope, aspect, litter and bare ground cover, size of coarse fragments, cover of surface rock fragments and bedrock, soil colour and texture) were recorded as a series of descriptive attributes and semi-quantitative scales, as defined by McDonald et al. (1998). Landform description was based on topographical position (crest, upper slope, mid-slope, lower slope or flat) and landform element type (e.g. hillcrest, hillslope, breakaway; McDonald et al. 1998). Coarse fragments and rock outcrop data were recorded as specific geologies and as part of a seven-class scale representing percent (%) cover. The seven cover classes were: zero % cover (0); <2% cover (1); 2–10% (2); 10–20% (3); 20–50% (4); 50–90% (5); >90% (6). Site disturbance was ranked between zero and three, with zero (0) representing no effective disturbance and three (3) being extensively cleared. Runoff was assigned to a scale of six classes (0 = no runoff, 1 = very slow, 2 = slow, 3 = moderately rapid, 4 = rapid, 5 = very rapid; McDonald et al. 1998).

Vegetation structure was determined by assigning the dominant taxa to each stratum found in the landscape, noting emergent taxa where appropriate, based on McDonald et al. (1998). All vascular plants were recorded from within the plot and assigned a cover class (D >70%, M 30–70%, S 10–30%, V<10%, I = isolated plants and L = isolated clumps); material was collected for verification and vouchering at the Western Australian Herbarium (WA Herbarium). Additional specimens were collected adjacent to the plots, contributing to the overall species list for the range. When sufficient representative plant material was available, it was lodged at the WA Herbarium. Nomenclature generally follows Florabase (Western Australian Herbarium 2010). For this study, 'weed' refers to an invasive species, recognised as introduced or alien to the area, in accordance with the WA Herbarium.

Soil chemical attributes were analysed for each quadrat. Soil was collected from 20 regularly-spaced intervals across the quadrat, bulked and sieved. The <2 mm fraction was analysed by an Inductively Coupled Plasma – Atomic Emission Spectrometer (ICP–AES) for B, Ca, Cd, Co, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, S and Zn using the Mehlich No. 3 procedure (Mehlich 1984). Soil pH was measured on 1:5 soil-water extracts in 0.01 M $CaCl_2$ (method S3; Rayment & Higginson 1992). Organic carbon content was determined using a modified Walkley–Black method (method 6A1) and calculation of soil nitrogen (N) was based on a modified Kjeldahl digest (method S10; Rayment & Higginson 1992).

The classification and ordination analyses were undertaken on a presence/absence data matrix of 195 perennial taxa occurring in more than a single quadrat, which was consistent with previous greenstone belt studies (Gibson et al. 2012). The dissimilarity between quadrats was determined using the Bray–Curtis measure and the Resemblance routine in PRIMER v6 (Clarke & Gorley 2006). The Bray–Curtis measure is a widely-used assessment of ecological distance, which reflects differences in compositional change (Legendre & Legendre 1998; Anderson & Robinson 2003), providing quantitative output for similarity between samples (Faith et al. 1987).Using the Bray–Curtis similarity matrix, the quadrats were classified based on the flexible unweighted pair-group mean average method (UPGMA, $\beta = -0.1$), using PATN v3.11 (Belbin 1989). The resulting dendrogram provided the basis for grouping of taxa into ecological groups. A two-way table was created based on the classification. Non-metric Multi-dimensional Scaling (NMS) was performed on the species–site similarity matrix, and stress values for both the 2D and 3D ordination were determined. An environmental data matrix that included soil chemical properties and site physical characteristics was created. The continuous variables in the environmental matrix were normalised prior to fitting environmental vectors to the NMS ordination. The environmental vectors are lines of 'best-fit' in multi-dimensional space, with stronger correlations corresponding to those lines extending closer to the edge of the circle (see Fig. 3).

The similarity percentages (SIMPER) analyses provided information on those species typically found within each community. The SIMPER routine in PRIMER determines those taxa contributing the greatest similarity within a community and dissimilarity amongst communities (Clarke & Warwick 2001). Those taxa contributing 10% or more to the similarity within each community type were initially selected. However, given the high species richness of the area, this was not applicable for most groups. Therefore, taxa that contributed to a cumulative 50% similarity between community types were included. Where individual species contributions were tied at the 50% level, all taxa in the tie were reported.

The relationships between environmental variables were examined using the nonparametric Spearman's rank correlation routine in Statistix 7.1 (Analytical Software, Tallahassee, Florida). The environmental variables were subjected to Kruskal–Wallis nonparametric one-way analysis of variance and post-hoc significance testing of means at $\alpha = 0.05$ (Sokal & Rolf 1995), using the community types determined by the site dendrogram.

RESULTS

Summary information

A total of 313 taxa were collected from within the quadrats in the south-west Ravensthorpe Greenstone Belt and an additional eight taxa were identified from areas adjacent to the quadrats (Appendix 1). There were 49 families represented, principally Myrtaceae (62 taxa), Fabaceae (39), Cyperaceae (30), Proteaceae (22) and Poaceae (14). There were 131 genera recorded, with *Eucalyptus* (22 species), *Acacia* (20 species), *Lepidosperma* (19 species) and *Melaleuca* (17 species) having the highest representation. Five weed species (Table 1), representing 9 collections, were identified. All weed species, except *Pentatschistis airoides* subsp. *airoides*, were known to the Ravensthorpe area. No new taxa were identified during the survey.

Table 1

Weed taxa recorded during the survey of the south-west region of the Ravensthorpe Greenstone Belt.

Family	Taxon	No. Records
Asparagaceae	*Asparagus asparagoides*	1
Malvaceae	*Malva parviflora*	1
Poaceae	*Ehrharta longiflora*	2
Poaceae	*Pentaschistis airoides* subsp. *airoides*	3
Primulaceae	*Lysimachia arvensis*	2

Species richness varied from 10 to 53 species per quadrat, with a mean species richness of 28.7 ± 9.1 SD. The majority of the taxa recorded were perennials, with only 14 annuals identified. Twenty taxa were amalgamated into nine species complexes during analyses. This occurred for taxa where a lack of sufficient material (i.e. flowering or fruiting specimens) prevented identification to subspecies level and for *Senna artemisioides* integrades. The final species matrix used in the classification and ordination routines consisted of 190 species × 50 sites. All annuals, singletons and specimens unidentifiable below generic level were removed from the data matrix prior to the analyses.

Priority taxa

Six taxa of conservation significance, represented in 16 populations, were identified during the survey (Table 2). All priority-listed taxa recorded were known to occur in the Ravensthorpe area. Two undescribed taxa of interest, *Austrostipa* sp. Carlingup Road (S Kern & R Jasper LCH18459) and *A.* sp. Ravensthorpe Range (A Markey & J Allen 6261), described below, have been classified Priority 1 (P1). A single collection of the former was made and 10 populations of the latter were recorded. Fifteen collections of *Lepidosperma diurnum* (formerly P1) were made during the survey. *L. diurnum* is widespread in the Ravensthorpe region and has been delisted, based on recommendations (Barrett el al. 2009). Only isolated individuals were collected of the following priority taxa: *Cassinia arcuata* (P2), *Eucalyptus desmondensis* (P4) and *Melaleuca penicula* (P4). Two collections were made of *Acacia bifaria* (P3).

Range extensions

Range extensions were recorded for three taxa collected during the survey. A single collection of *A. brumalis* represented a c. 100 km range extension to the south-east of its current distribution. *Acacia brumalis* occurs as a shrub or tree and is predominantly known from the Avon Wheatbelt Bioregion; this is the first record for the Esperance Plains Bioregion. A slight range extension eastward (c. 40 km) was recorded for *Schoenus* sp. Cape Riche Cushion (GJ Keighery 9922), a small perennial sedge. A single collection of *M. sparsiflora* was made

Table 2

Priority taxa recorded from the south-west region of the Ravensthorpe Greenstone Belt. Bioregion abbreviations: COO = Coolgardie, MAL = Mallee, ESP = Esperance Plains.

Family	Taxon	Priority Status	Distribution
Poaceae	*Austrostipa* sp. Carlingup Road	P1	ESP, MAL, COO
Poaceae	*Austrostipa* sp. Ravensthorpe Range	P1	ESP, MAL
Asteraceae	*Cassinia arcuata*	P2	ESP, MAL
Fabaceae	*Acacia bifaria*	P3	ESP
Myrtaceae	*Eucalyptus desmondensis*	P4	ESP
Myrtaceae	*Melaleuca penicula*	P4	ESP, MAL

opportunistically from outside of the survey quadrat boundaries. This record represents a small range extension of c. 50 km. The shrub is principally known from the Mallee Bioregion, north of the survey area.

Taxa of interest

Two species of *Austrostipa* that were collected during the survey are of taxonomic interest, as they represented new taxa currently undergoing formal description. *Austrostipa* sp. Carlingup Road (S Kern & R Jasper LCH18459) and *Austrostipa* sp. Ravensthorpe Range (A Markey & J Allen 6261) were initially collected from the Ravensthorpe Range area (north-west of this survey effort), with a single collection of each lodged at the WA Herbarium. The survey efforts in the south-west Ravensthorpe Greenstone Belt resulted in a single additional collection of *Austrostipa* sp. Carlingup Road (S Kern & R Jasper LCH18459) and four new populations of *Austrostipa* sp. Ravensthorpe Range (A Markey & J Allen 6261). Both taxa are currently listed as Priority 1.

Floristic communities

Hierarchical clustering separated the taxa into 13 species groups (A–M). Species group B was associated with more neutral to alkaline soils and group E contained the most ubiquitous taxa, with representation across all sites. Species group H was associated with more acidic soils. Six broad community types were defined from the site dendrogram (Fig. 2). The dendrogram highlighted the close relationship between particular communities as well as less well-defined community types with low representation of quadrats. Community types were characterised by similarity in species groups (Table 3) as well as similarity in edaphic factors such as soil pH and soil cation concentrations (Ca, K, Mg, Na; Table 4). However, separation of community types was not distinctly along gradients of soil pH (acidic vs. alkaline) or soil cation concentrations. Community types 2 and 4 were characterised by highly acidic soils with relatively low cation concentrations compared with the community types on more moderately acidic to neutral soils, but had low numbers of representative quadrats (i.e. 2–4 quadrats). This is a reflection of the limitations of the survey sampling and not necessarily a representation of the extent of these community types within the greenstone belt. By comparison, community types 1, 3 and 5a had more moderately acidic to neutral soils, with comparatively higher soil cation concentrations.

The NMS output (2D stress = 0.16, 3D stress = 0.12) displays the relationship between the sites, based on the resemblance matrix with environmental vectors overlain (Fig. 3). Vectors extending close to the edge of the circle indicate stronger correlation to those communities. The environmental vectors overlain on the NMS ordination highlight the influence of edaphic factors on vegetation communities, suggesting a greater influence on community composition than site physical characteristics such as position in the landscape.

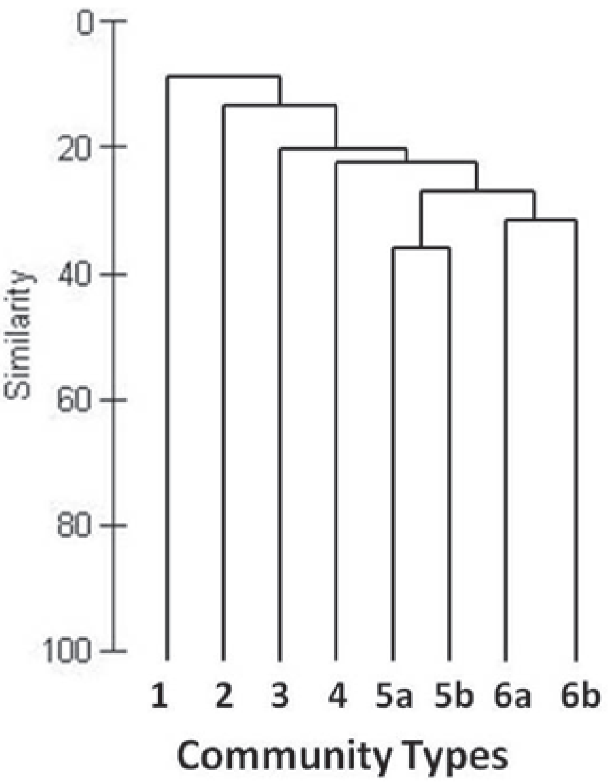

Figure 2. Summary dendrogram of community types for the Ravensthorpe Greenstone Belt. The six community types displayed in the dendrogram are derived from the classification analyses of the 195 taxa from 50 sites.

One pair of sites (SWRV 23 and 49) are discussed below as a community type (community type 4), despite only being recorded within two quadrats. Further regional survey will potentially clarify the status of these sites as a distinct community type.

Community type 1 was identified from ten quadrats with moderate species richness (14–28 taxa per quadrat, mean 23.2 ± 2.7 SD). They were *Eucalyptus* woodland sites, with either *E. myriadena* or *E. salmonophloia* as the dominant eucalypt species. A single quadrat with low species richness was included as the taxa recorded fitted the pattern of species grouping and other site physical characteristics. Although the survey area was not characterised by significant gradients, community type 1 contained sites classified predominantly as upland, with variable slopes. Taxa were principally from species groups A, B and E; no representative taxa were recorded from groups F–J and L–M (Table 3). Typical taxa of this community included the shrubs *Dodonaea ptarmicaefolia*, *Enchylaena tomentosa* var. *tomentosa*, *Eremophila decipiens* subsp. *decipiens*, *Rhagodia crassifolia*, *Senna artemisioides* subsp. *filifolia* and the grass *Austrostipa* sp. Ravensthorpe Range (A Markey & J Allen 6261).

Soils were principally red-brown slightly acidic to alkaline (pH 5.1–7.8) sandy clay loams. Ca concentrations were high, particularly in the alkaline soils (Table 4). Other soil cation concentrations were also high (K, Mg, Na).

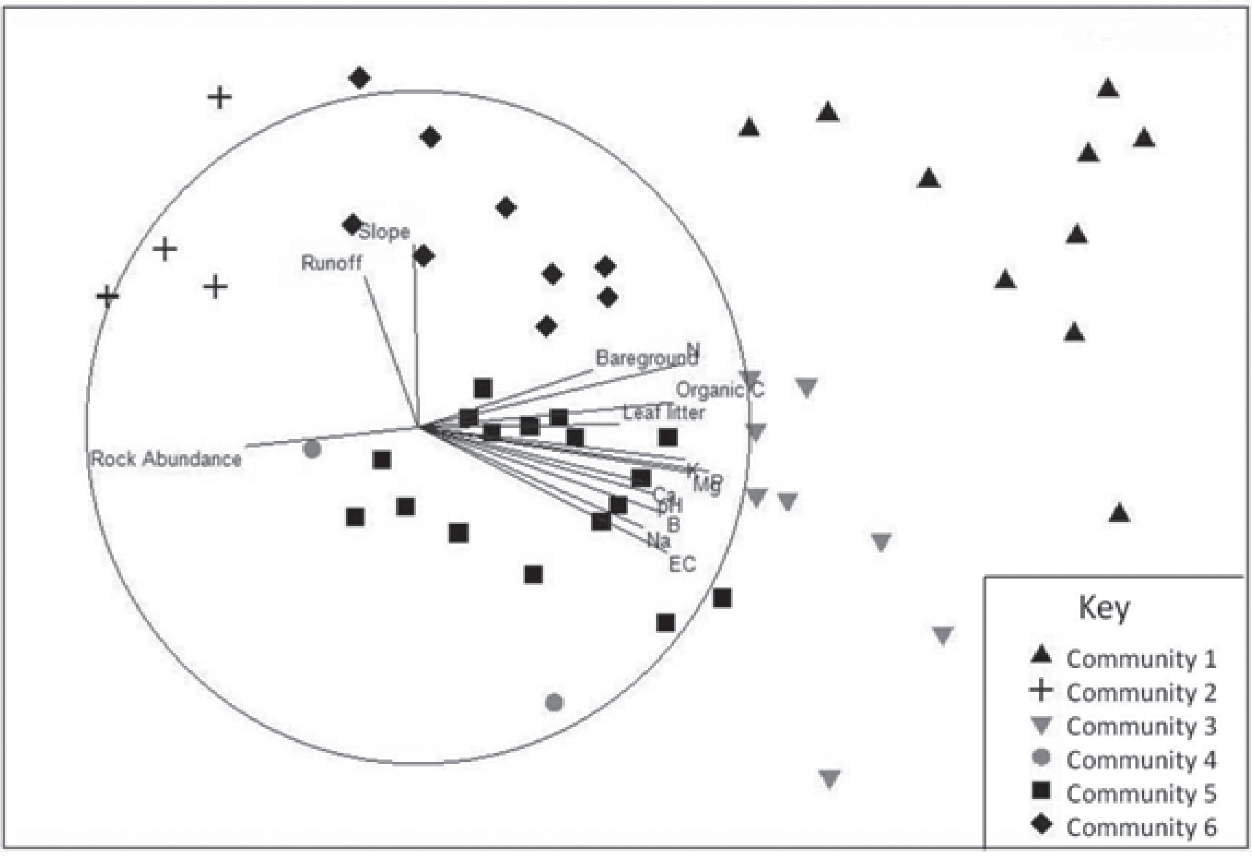

Figure 3. 2D graph of the first two axes of the NMS ordination (stress value = 0.16) of survey quadrats from the Ravensthorpe Greenstone Belt. Data are a matrix of 195 perennial species from 50 survey sites. Survey quadrats are presented as community groups overlain with environmental vectors; the closer the line of 'best-fit' approaches the circle boundary, the stronger the correlation. The soil parameters (soil pH, electrical conductivity, organic C, B, Ca, K, Mg, Na and P) that had the strongest correlation ($r_s \geq 0.7$) using Spearman rank correlation coefficient are shown. For comparison, the top five site physical characteristic vectors are shown (abundance of coarse fragments, leaf litter, runoff, slope and bare ground).

Organic carbon concentrations were relatively high for the survey area. Coarse rock fragments, leaf litter and bare ground were generally abundant.

Community type 2 was a group of species-rich quadrats (23–43 taxa per quadrat, mean 35.7 ± 9 SD) on moderate slopes. Taxa were principally allied with species groups E, H, I and J. Sites were typically mallee *Eucalyptus pleurocarpa* with a rich shrub layer including *Acacia mimica* var. *angusta*, *Calothamnus quadrifidus* subsp. *quadrifidus*, *Calytrix leschenaultia*, *Daviesia pachyphylla*, *Hakea verrucosa*, *Leptospermum spinescens*, *Leucopogon cuneifolius*, *Melaleuca villosisepala*, *Petrophile seminuda*, *Platysace deflexa*, plus *Conostylis argentea* and *Mesomelaena stygia* subsp. *stygia* (Table 3).

Soils were strongly acidic (pH 4.5–5.3) yellow-brown loamy sands or sandy loams. Cation concentrations were low, with Ca concentrations concomitantly low in the quadrats with more acidic soil (Table 4). Coarse rock fragments were very abundant, predominantly medium gravel-sized quartzite and mixed metasediment with minimal surface exposure of any bedrock.

Community type 3 consisted of quadrats characterised by heterogeneous topography, gentle to moderate slopes and variable species richness (10–39 taxa per quadrat, mean 21.2 ± 9.8 SD). Taxa were principally allied with species groups B and E, with minimal representation in group D and no representative taxa from groups F–J (Table 3). Typical taxa were *Eucalyptus extensa*, *E. oleosa* subsp. *corvina* with *Melaleuca cucullata* over *Acacia glaucoptera* and the *Senna artemisioides* subsp. × *artemisioides* group.

Soils were mildly acidic to alkaline (pH 6.2–7.8) sandy loams and sandy clay loams. Soil cation concentrations were high, with higher concentrations associated with higher soil pH (Table 4). High Na values were recorded at sites with correspondingly high electrical conductivity (EC) values. Coarse rock fragments were moderate to abundant in cover, with minimal exposed bedrock recorded.

Community type 4 was recorded within a pair of quadrats in open mallee shrubland, particularly distinguished by their soil characteristics. Soils were highly acidic (pH 4.3–4.7) orange-brown sandy clay loams and loamy sands. Species richness was 21 and 42 taxa per quadrat. Taxa were associated with species groups E, H, L and M (Table 3). Typical taxa of these sites were *E. pluricaulis* subsp. *pluricaulis* and *E. suggrandis* subsp.

Table 3

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


E
Exocarpos sparteus
Gahnia ancistrophylla
Gastrolobium musaceum
Gastrolobium tetragonophyllum
Goodenia concinna
Grevillea oligantha
Grevillea pectinata
Hakea verrucosa
Hibbertia exasperata
Hybanthus floribundus subsp. adpressus
Lepidosperma diurnum
Lepidosperma sp. A2 Inland Flat (G.J. Keighery 7000)
Lepidosperma sp. Bandalup Scabrid
Lepidosperma sp. Ravensthorpe (G.F. Craig 5188)
Melaleuca cliffortioides
Melaleuca cucullata
Melaleuca glaberrima
Melaleuca lateriflora subsp. lateriflora
Melaleuca pomphostoma
Melaleuca scalena
Melaleuca torquata
Santalum acuminatum
Senna artemisioides subsp. x artemisioides complex
Stylidium albomontis
Templetonia neglecta
Templetonia retusa
Thysanotus patersonii
Wilsonia humilis
F
Austrostipa hemipogon
Boronia inconspicua
Goodenia scapigera subsp. scapigera
Lasiopetalum compactum
Leptospermum erubescens
G
Acacia gonophylla
Acacia pravifolia
Acrotriche cordata
Cassytha glabella
Coopernookia strophiolata
Cryptandra nutans
Eucalyptus leptocalyx
Gahnia aristata
Lasiopetalum rosmarinifolium
Lepidosperma sp. Saltbush Hill (K.R. Newbey 4118)
Logania stenophylla
Marianthus microphyllus
Microcorys glabra
Siegfriedia darwinioides
Spyridium cordatum
H
Acacia mimica var. angusta
Amphipogon turbinatus
Astroloma serratifolium
Calytrix leschenaultii
Conostylis argentea
Daviesia pachyphylla
Eucalyptus pleurocarpa
Hakea lissocarpha
Hibbertia gracilipes
Kunzea affinis
Lepidosperma sp. Clathrate
Lepidosperma sp. Tibialate
Leucopogon cuneifolius
Leucopogon lloydiorum
Leucopogon sp. Newdegate (M. Hislop 3585)
Lysinema pentapetalum
Melaleuca hamata
Melaleuca villosisepala
Mesomelaena stygia subsp. stygia
Olax benthamiana
Petrophile seminuda
I
Lepidosperma sp. Mt Short
Lepidosperma sp. Shoemaker Levy
J
Allocasuarina microstachya
Banksia nivea subsp. nivea
Chamelaucium ciliatum
Eucalyptus perangusta
Hakea incrassata
Hakea laurina
Lepidosperma carphoides
Leptospermum oligandrum
Leptospermum spinescens
Lomandra mucronata
Melaleuca hamulosa
Melaleuca pentagona var. pentagona
Platysace deflexa
Schoenus subflavus
Synaphea interioris
Verticordia chrysantha

Table 3 (cont.)

K	*Acacia saligna* subsp. *lindleyi*		■						■
	Astus tetragonus							■	
	Baeckea crispiflora		■					■	■
	Choretrum glomeratum var. *glomeratum*			■					■
	Eucalyptus occidentalis		■						■
	Guichenotia micrantha							■	■
	Kunzea strigosa							■	■
	Phyllanthus calycinus								■
	Pimelea brachyphylla						■	■	■
	Spartochloa scirpoidea	■						■	■
L	*Acrotriche ramiflora*						■		
	Eucalyptus densa subsp. *improcera*				■		■		
	Eucalyptus uncinata				■		■		
	Grevillea dolichopoda						■	■	■
	Kunzea cincinnata						■	■	
	Leucopogon hamulosus						■	■	
	Leucopogon obtusatus		■				■		
	Melaleuca rigidifolia		■		■		■		
	Melaleuca uncinata						■	■	
	Neurachne alopecuroidea		■	■	■		■	■	
	Rinzia communis						■		
	Stylidium involucratum						■	■	
M	*Eucalyptus suggrandis* subsp. *suggrandis*				■				
	Lepidosperma sp. Mt Benson				■			■	
	Lomandra effusa			■	■				
	Tetraria sp. Mt Madden (C.D. Turley 40 BP/897)				■		■		

suggrandis over *Melaleuca hamata*, *Daviesia incrassata* subsp. *incrassata*, *Dianella revoluta* var. *revoluta* and *Gastrolobium musaceum* with *Lepidosperma* sp. A2 Inland Flat (GJ Keighery 7000), *Lepidosperma* sp. Ravensthorpe (GF Craig 5188) and the parasitic climber *Cassytha melantha*.

The plots primarily had low soil cation concentrations, and one plot had very high electrical conductivity and Na concentrations (Table 4). Coarse rock fragments were highly abundant on the surface, predominantly weathered ironstone and laterite with undifferentiated greenstone of large gravel size.

Community type 5 was recorded in a group of quadrats in mallee woodland with relatively high species richness (23–53 taxa per quadrat, mean 34.7 ± 7.8 SD). The community was dominated by *E. flocktoniae* subsp. *flocktoniae* and *E. phenax* subsp. *phenax*, with a typical understorey of *Acacia glaucoptera*, *A. ingrata*, *Boronia inornata* subsp. *inornata* and *Dodonaea* sp. (Table 3). Two sub-types are discussed, as species associations outside of the ubiquitous group E diverged strongly. Sites typically had high abundance of rock fragments and variable amounts of exposed bedrock (Table 4).

Community type 5a was characterised by the aforementioned taxa and *Grevillea pectinata*. Taxa were allied with species groups B, D and F, with no representatives from groups I–M. Soils were more alkaline (pH 5.8–7.8) and typically red-brown sandy loams and sandy clay loams with relatively higher soil cation concentrations.

Taxa in community type 5b also included the mallee *E. proxima*, understorey shrubs *Daviesia benthamii* subsp. *benthamii*, *Hakea verrucosa*, *Hibbertia exasperata*, *Melaleuca lateriflora* subsp. *lateriflora* and the sedge *Gahnia ancistrophylla*. Taxa were allied with species groups G, H, I and L. Soils were typically strongly acidic to slightly alkaline (pH 4.9–7.6) light brown sandy clay loams and sandy loam. Soil cation concentrations, organic carbon content and electrical conductivity values were generally lower than those recorded in type 5a.

Community type 6 was characterised by quadrats containing *Allocasuarina campestris* with *Dodonaea pinifolia* and *Hakea verrucosa*. Soils were typically sandy clay loams with a high cover of coarse rock fragments and some exposed bedrock at the surface. Two sub-types are discussed, as site characteristics and taxa associations diverged outside of the ubiquitous species group E.

Community type 6a was characterised by strongly acidic yellow-brown sandy loam soils (pH 5.3–5.4; Table 4). Additional species fidelity included groups H, K and L, with a noticeable absence of taxa from groups A–D, F and G (Table 3). Typical taxa included *A. campestris*, with additional shrubs of *Calothamnus quadrifidus* subsp. *quadrifidus* and *Grevillea dolichopoda* and the tussock grass *Spartochloa scirpoidea*. Soils had lower cation concentrations, particularly Ca, than community type 6b.

Community type 6b had moderately acidic (pH 5.5–6.7) red-brown sandy clay loam soils (Table 4). Typical taxa included *A. campestris*, with *Exocarpos aphyllus* and *Santalum acuminatum* over *Hibbertia exasperata*, with *Gahnia ancistrophylla* and *Lepidosperma diurnum*. Taxa were principally allied with species group B, H and K, with no representative taxa from groups A, J, L and M (Table 3).

Environmental variables

Survey quadrats were located on altitudes ranging from 111 to 273 m above sea level (mean 182.6 ± 36.5 SD; Table 4). The predominant soil textures were sandy loam and sandy clay loams, with only eight sites characterised by loamy sands, loams or clay loams. All sites had coarse fragments present, with a mean surface cover score of 4.6, which corresponded to 20–50% cover. Surface bedrock was recorded in over half of the quadrats, with 21 quadrats having no outcrops. The sites typically had a high

Table 4

Summary statistics for environmental variables, separated by community type, for the south-west Ravensthorpe Greenstone Belt. Mean values with standard deviation are listed for community types recorded in more than one quadrat. Differences were determined using Kruskal–Wallis nonparametric one-way analysis of variance. Significance values are indicated by * ($p < 0.05$ = *, $p < 0.01$ = **, $p < 0.001$ = ***, $p < 0.0001$ = ****) and $^{+}$ indicates no significant difference of means. Post-hoc differences were set at $\alpha = 0.05$. Units of measurements for the parameters are: soil chemicals = mg/kg; abundance of fragments and outcrop abundance = categorical maximum (0 = 0%, 1 = <2%, 2 = 2–10%, 3 = >10–20 %, 4 = >20–50 %, 5 = >50–90 %, 6 = >90%); topographical position: 1 = crest, 2 = upper slope, 3 = mid-slope, 4 = lower slope, 5 = flat; species richness = number of taxa/quadrat.

	Community Types					
Soil Parameters	**1**	**2**	**3**	**4**	**5**	**6**
B***	1.5 ± 0.9 [a]	0.1 ± 0.1 [b]	2.0 ± 1.4 [a]	0.6 ± 0.0 [ab]	0.5 ± 0.6 [ab]	0.3 ± 0.6 [b]
Ca***	3300.0 ± 1298.7 [a]	365.0 ± 157.8 [b]	4412.5 ± 1840.4 [a]	375.0 ± 134.4 [ab]	2435.9 ± 1963.6 [ab]	1785.6 ± 1278.4 [ab]
Cd[NS]	0.006 ± 0.002	0.005 ± 0.00	0.005 ± 0.00	0.005 ± 0.00	0.005 ± 0.00	0.013 ± 0.025
Co***	2.2 ± 1.3 [ac]	0.1 ± 0.1 [b]	1.5 ± 1.3 [abc]	0.6 ± 0.3 [abc]	0.8 ± 0.5 [bd]	1.8 ± 1.4 [acd]
Cu***	4.5 ± 2.8 [a]	0.2 ± 0.2 [b]	4.1 ± 1.2 [a]	1.6 ± 0.1 [ab]	2.3 ± 1.7 [ab]	3.1 ± 3.2 [ab]
EC***	17.0 ± 5.5 [a]	2.0 ± 0.8 [b]	20.9 ± 10.9 [a]	72.0 ± 96.2 [ab]	11.2 ± 7.5 [ab]	4.9 ± 1.8 [b]
Fe*$^{+}$	92.2 ± 39.6	111.5 ± 42.8	80.8 ± 25.6	120.0 ± 14.1	116.5 ± 38.4	140.1 ± 40.5
K***	351.0 ± 113.8 [ac]	71.8 ± 24.7 [b]	433.8 ± 131.3 [a]	140.5 ± 84.1 [abc]	190.8 ± 131.2 [bc]	188.9 ± 88.8 [abc]
Mg***	932.0 ± 233.5 [a]	66.8 ± 31.2 [b]	935.0 ± 305.6 [a]	350.0 ± 183.9 [ab]	553.5 ± 312.9 [ab]	438.9 ± 271.9 [ab]
Mn*$^{+}$	76.1 ± 29.3	27.3 ± 24.2	88.8 ± 58.9	8.0 ± 1.7	49.6 ± 47.4	83.4 ± 64.9
N (Total)****	0.26 ± 0.07 [a]	0.05 ± 0.02 [b]	0.15 ± 0.06 [ab]	0.08 ± 0.03 [ab]	0.10 ± 0.04 [b]	0.11 ± 0.03 [b]
Na***	168.3 ± 89.2 [ac]	11.8 ± 2.8 [b]	246.4 ± 129.3 [a]	582.5 ± 731.9 [ab]	99.2 ± 55.2 [ab]	64.6 ± 46.3 [bc]
Ni***	4.9 ± 3.5 [a]	0.2 ± 0.1 [b]	2.5 ± 0.7 [ac]	1.2 ± 0.6 [abc]	1.6 ± 1.9 [bc]	3.4 ± 3.8 [abc]
Organic C (%)***	3.6 ± 0.7 [a]	0.8 ± 0.3 [c]	2.6 ± 1.1 [ab]	2.0 ± 1.0 [abc]	1.8 ± 0.7 [bc]	1.9 ± 0.6 [bc]
P****	5.7 ± 1.6 [a]	1.1 ± 0.6 [b]	5.3 ± 3.1 [ac]	2.5 ± 2.1 [abc]	2.5 ± 1.3 [bc]	1.2 ± 0.8 [b]
pH***	6.9 ± 0.9 [ac]	5.0 ± 0.3 [b]	7.2 ± 0.6 [a]	4.5 ± 0.3 [bc]	6.4 ± 1.0 [abc]	6.0 ± 0.6 [abc]
S**	13.0 ± 5.9 [a]	3.3 ± 1.9 [b]	15.5 ± 10.9 [ab]	82.5 ± 109.6 [ab]	8.1 ± 5.8 [ab]	5.7 ± 1.7 [ab]
Zn**	3.0 ± 1.0 [a]	0.5 ± 0.3 [b]	1.6 ± 0.5 [ab]	1.3 ± 0.1 [ab]	1.9 ± 1.2 [ab]	2.3 ± 1.7 [ab]
Site Physical Parameters						
Altitude (m)*	194.8 ± 31.4 [ab]	225.8 ± 19.8 [a]	178.1 ± 40.6 [ab]	202.0 ± 80.6 [ab]	178.1 ± 31.8 [ab]	158.1 ± 26.3 [b]
Bare ground (%)*$^{+}$	94.0 ± 2.2	91.0 ± 1.2	94.5 ± 1.4	90.0 ± 7.1	90.9 ± 3.7	92.2 ± 3.2
Abundance fragments***	3.7 ± 0.9 [ab]	4.8 ± 0.5 [ab]	3.6 ± 0.9 [a]	5.5 ± 0.7 [ab]	5.1 ± 0.6 [b]	5.0 ± 0.5 [ab]
Leaf litter (%)**	55.0 ± 27.0 [a]	9.0 ± 2.6 [c]	42.9 ± 21.0 [ab]	25.0 ± 14.1 [abc]	19.4 ± 13.2 [bc]	20.2 ± 14.5 [abc]
Topographical position[NS]	2.5 ± 1.0	3.3 ± 0.5	2.8 ± 1.6	1.5 ± 0.7	2.6 ± 1.1	2.6 ± 0.9
Outcrop abundance[NS]	0.7 ± 0.8	0.3 ± 0.5	0.5 ± 0.8	1.0 ± 1.4	1.2 ± 1.0	1.2 ± 0.8
Slope*$^{+}$	5.6 ± 3.8	4.4 ± 1.3	2.7 ± 1.2	2.0 ± 1.4	3.3 ± 2.0	6.2 ± 3.6
Species Richness	23.2 ± 4.7	35.8 ± 9.0	21.3 ± 9.9	31.5 ± 14.8	34.7 ± 7.8	26.4 ± 5.2
Number of quadrats:	10	4	8	2	17	9

Table 5

Spearman rank correlation coefficients for select soil parameters and species richness for the south-west Ravensthorpe Greenstone Belt. The upper value for each correlation is the correlation coefficient and the lower value represents significance at $p < 0.05$. Bold values represent highly significant correlations at $p < 0.0001$. Where no lower value is reported, the relationship is not significant ($p > 0.05$).

	B	CA	CO	CU	EC	FE	K	MG	MN	N	NA	NI	ORG C	P	pH	S
CA	**0.7773**															
	0															
CO	0.3107	0.4478														
	0.0284	0.0012														
CU	**0.5595**	**0.7093**	**0.6587**													
	0	**0**	**0**													
EC	**0.8376**	**0.7955**	0.3293	0.5106												
	0	**0**	0.0199	0.0002												
FE	-0.6054	-0.5822	-0.0865	-0.5055	-0.4912											
	0	0		0.0002	0.0003											
K	**0.8309**	**0.8861**	0.5096	**0.7661**	**0.7906**	-0.5935										
	0	**0**	0.0002	**0**	**0**	0										
MG	**0.8794**	**0.9054**	0.5244	**0.68**	**0.8802**	-0.5381	**0.9099**									
	0	**0**	0.0001	**0**	**0**	0.0001	**0**									
MN	0.3375	0.5396	**0.7255**	**0.603**	0.3212	-0.1429	**0.5703**	0.49								
	0.0169	0.0001	**0**	**0**	0.0233		**0**	0.0004								
N	**0.6934**	**0.7286**	**0.5657**	**0.6165**	**0.7091**	-0.434	**0.8024**	**0.797**	0.5326							
	0	**0**	**0**	**0**	**0**	0.0018	**0**	**0**	0.0001							
NA	**0.746**	**0.6637**	0.2764	0.4857	**0.848**	-0.5473	**0.7197**	**0.7794**	0.211	**0.6018**						
	0	**0**		0.0004	**0**	0.0001	**0**	**0**		**0**						
NI	**0.5607**	**0.6527**	**0.8295**	**0.6081**	**0.5637**	-0.2243	**0.6695**	**0.7302**	**0.6066**	**0.6898**	0.4873					
	0	**0**	**0**	**0**	**0**		**0**	**0**	**0**	**0**	0.0004					
ORG C	**0.7249**	**0.7209**	0.5052	**0.5896**	**0.7794**	-0.4101	**0.7816**	**0.797**	0.4674	**0.9373**	**0.713**	**0.671**				
	0	**0**	0.0002	**0**	**0**	0.0033	**0**	**0**	0.0007	**0**	**0**	**0**				
P	**0.6843**	**0.5921**	0.4609	0.506	**0.733**	-0.472	**0.7069**	**0.7365**	0.4493	**0.6976**	**0.6187**	0.5237	**0.6846**			
	0	**0**	0.0009	0.0002	**0**	0.0006	**0**	**0**	0.0012	**0**	**0**	0.0001	**0**			
pH	0.7647	0.8919	0.4508	0.5539	0.7478	-0.4869	**0.7819**	**0.8645**	0.5101	**0.6305**	**0.558**	**0.5859**	**0.5755**	**0.6216**		
	0	0	0.0011	0	0	0.0004	**0**	**0**	0.0002	**0**	**0**	**0**	**0**	**0**		
S	0.8193	0.7377	0.3158	0.5775	0.8831	-0.4256	**0.8066**	**0.8332**	0.3824	**0.7618**	**0.6932**	0.5357	**0.8132**	**0.6485**	**0.6243**	
	0	0	0.0259	0	0	0.0022	**0**	**0**	0.0064	**0**	**0**	0.0001	**0**	**0**	**0**	
ZN	0.3131	0.4051	0.4693	0.3444	0.332	-0.068	0.3267	0.4375	0.2766	0.4596	0.3716	0.4787	0.4806	0.2982	0.3539	0.2828
	0.0272	0.0038	0.0007	0.0147	0.0189		0.021	0.0016		0.0009	0.0082	0.0005	0.0005	0.0358	0.0121	0.0469
RICHNESS	**-0.5627**	-0.4451	-0.1737	-0.341	-0.5471	0.3002	**-0.6009**	-0.5443	-0.2562	-0.5733	-0.4453	-0.308	**-0.5492**	-0.4825	-0.4573	-0.5928
	0	0.0013		0.0158	0.0001	0.0345	**0**	0.0001		0	0.0013	0.03	**0**	0.0005	0.0009	0

proportion of bare ground (mean 92.3% ± 3.3 SD) and sparse to moderate leaf litter (29.8% ± 23.2 SD).

Soils ranged from very strongly acidic (pH 4.3) to mildly alkaline (pH 7.8). Mean soil pH was 6.4 ± 1 SD, with an equal number of sites characterised as slightly to moderately acidic (pH 5.6–6.5, 18 sites) or neutral to moderately alkaline (pH 6.6–7.8, 18 sites; Bruce & Rayment 1982). Typical of greenstone belt soils, soil cation concentrations (Ca, K, Mg, Na) were predominantly moderate to high.

Significant intercorrelations occurred between environmental variables (Table 5). Soil pH, electrical conductivity, organic carbon and the elements B, Ca, Cu, K, Mg, N, Na, Ni, P and S were all positively intercorrelated ($p < 0.01$). These strongly intercorrelated soil parameters were negatively correlated with species richness and Fe ($p < 0.05$), except for Ni, which was not significantly correlated with Fe ($p > 0.05$). Species richness was negatively correlated with disturbance and percentage leaf litter ($p < 0.05$) but positively correlated with the abundance of surface coarse fragments ($p < 0.01$). Site physical parameters exhibited fewer significant correlations with any other environmental parameters than the soil chemical characteristics. Bare ground was positively correlated ($p < 0.05$) with the same large group of intercorrelated soil chemical characteristics (soil pH, electrical conductivity, organic carbon, B, Ca, Cu, K, Mg, N, Na, Ni, P and S), but negatively correlated with Fe ($p < 0.05$). Slope and runoff were highly positively correlated ($r_s = 0.78$, $p < 0.0001$).

Kruskal–Wallis one-way analysis of variance revealed significant differences between community groups for the site physical and chemical characteristics. (Table 4). Community types 1 and 3 had significantly higher mean values than community type 2 for many of the soil parameters, including soil pH, electrical conductivity, organic carbon, B, Ca, Cu, K, Na, Ni and P. Community type 1 also had significantly higher mean values of N, P and organic carbon than both community types 5 and 6. Community type 4 had the lowest mean soil pH values, which were significantly different from community type 3. For site physical parameters, there were significant differences of means for altitude (community type 6 found at lower altitudes on average than community type 2), abundance of coarse fragments (community type 5 had higher cover than community type 3) and percentage cover of leaf litter (community type 1 had greater cover than community types 2 and 5; community type 3 greater cover than community type 2).

DISCUSSION

Flora and vegetation communities

The 321 taxa recorded from this survey (313 from within quadrats) represent a markedly lower total than previously recorded in the Ravensthorpe Greenstone Belt. Flora and vegetation surveys on the northern Ravensthorpe Greenstone Belt, encompassing the Ravensthorpe Range, recorded 698 taxa from within and adjacent to 266 quadrats (Kern et al. 2008; Markey et al. 2012). The significant difference in the number of taxa recorded is attributed to the variation in surveying effort. This survey was based on collecting within 50 quadrats and adjacent areas, while the WA Herbarium holds over 1300 records for the broader survey polygon. This is to be expected for an area that corresponds to the eastern region of the Fitzgerald Biosphere Reserve, a UNESCO-recognised hotspot for biodiversity.

Previous surveys of the flora of the Ravensthorpe Greenstone Belt have identified at least 56 taxa of conservation significance, including six declared as rare taxa (Craig et al. 2008; Kern et al. 2008; Markey et al. 2012). This survey of the south-western region of the greenstone belt recorded six priority-listed taxa and no Declared Rare Flora (DRF). All of the priority-listed taxa were known to the Ravensthorpe area. There are five Priority Ecological Communities (all Priority 1) currently recognised in the Ravensthorpe Greenstone Belt (see Markey et al. 2012), all of which are associated with the Ravensthorpe Range and were not recorded during this survey.

Community types described from this study were comparable with the communities recognised by Craig et al. (2008) and Markey et al. (2012). Overlapping suites of species have been observed between surveys and provided guidance as to where the species groups in the south-west portion of the belt fit within the more well-defined vegetation communities of the northern and eastern areas of the Ravensthorpe Greenstone Belt (see Craig et al. 2008; Markey et al. 2012). However, further sampling and meta-analysis of the data are required to clarify the status of the broad community types described from this study. Analogous communities are addressed below, referring primarily to Markey et al. (2012), as their study incorporated the corresponding mapping codes of Craig et al. (2008).

Community type 1 contained a similar suite of understorey species to Markey et al.'s (2012) community type 1 (lowland *Eucalyptus flocktoniae* – *E. phenax* – *E. calycogona* woodlands), particularly the presence of chenopod shrubs; however, the prevalent eucalypt was *E. salmonophloia*, which was described in Markey et al.'s community type 2 (*E. salmonophloia* woodlands on lower hillslopes). Similarly, community type 2 corresponded with two community types from Markey et al. (2012): both lateritic *E. pleurocarpa* mallee shrubland communities, separated by geographic extent (northern vs. southern) and the suite of other eucalypt species present. As community type 2 was only represented by four quadrats, with no additional eucalypt species present and the understorey species from both of Markey et al.'s communities, no further interpretation is possible without additional survey and analysis. Community type 3 was closely matched to that of Markey et al.'s (2012) *Eucalyptus oleosa* subsp. *corvina* tall open mallee shrubland and open forest, with similar species composition including *E. oleosa* subsp. *corvina*, *E.*

extensa, *Acacia glaucoptera* and *Senna artemisioides* subsp. x *artemisioides*.

Community type 4 contained taxa similar to Markey et al.'s (2012) community type 20, defined as *Eucalyptus uncinata*, *E. incrassata*, *E.* spp. mallee shrublands. Markey et al. (2012) noted that *E. pluricaulis* subsp. *pluricaulis* and *E. suggrandis* subsp. *suggrandis* occurred in the south-eastern portion of the Raventhorpe Range and a north-to-south species gradation may exist within this community. The pair of sites from this study may represent the southern gradation of this eucalypt mallee shrubland community. Craig et al. (2008) and Markey et al. (2012) both recognised the *E. flocktoniae* – *E. phenax* mallee woodlands, which are analogous to community type 5 from this study. Community type 6 was similar to Markey et al.'s (2012) community type 21 (*E. desmondensis* – *Allocasuarina* spp. tall mallee shrubland), recorded in the southern part of the range, which would be at similar latitudes as this survey. Both communities shared the dominant taxa of *A. campestris* and *Melaleuca hamata*.

Environmental correlates

The south-west Ravensthorpe Greenstone Belt was characterised primarily by sandy clay loam and sandy loam soils with varying soil pH, typical of the greenstone belts of the Yilgarn Craton. The locations where low soil pH values were recorded are indicative of extensive weathering (Slattery et al. 1999). This has been widely documented in the greenstone belts throughout the Yilgarn Craton (Markey & Dillon 2008a, 2008b; Meissner & Caruso 2008a, 2008b, 2008c; Thompson & Sheehy 2011a, 2011b, 2011c), although it is more pronounced across the greenstone belts further north. Ca concentrations are closely linked with soil pH, with more alkaline values typically associated with lowland communities (Anand et al. 1997), as lower slopes and adjacent areas are enriched by the movement of mobile elements from the upland regions (Ben-Shahar 1990) This pattern holds true in the survey area, the one exception being that the highest Ca concentrations were recorded across varying, but subtle, topographical gradients. This inconsistency in Ca concentrations relative to topographical position may be indicative of different rates of weathering, as studies have shown that sulphides and carbonates are readily leached from the profile (Butt et al. 2000; Anand 2005). The prevalence of high Mg concentrations was expected, given the presence of mafic and ultra-mafic rocks within the greenstone belt.

Variations in vegetation community types were related to environmental parameters, particularly soil chemistry. The link between vegetation patterns and soil parameters has been widely documented on greenstone belts in the Yilgarn Craton (Gibson 2004b; Markey & Dillon 2008a, 2008b, 2009; Meissner & Caruso 2008a, 2008b, 2008c; Meissner et al. 2009a, 2009b, 2009c) and within the Ravensthorpe Greenstone Belt (Craig et al. 2008; Kern et al. 2008; Markey et al. 2012). The strongest correlations were between the community types and the soil chemical characteristics of soil pH, electrical conductivity, and concentrations of organic carbon, B, Ca, K, Mg, Na and P. In particular, communities types 1 and 3 had significantly higher mean values for many of the soil parameters compared with community type 2, which was characterised by low soil pH and cation concentrations (Ca, K, Mg and Na). The strong relationship between soil chemical parameters was likely due to rates of weathering and the variable underlying geology, as weathering of the regolith influences the concentration of trace elements in the soils.

Previous greenstone belt studies have found that distinct vegetation associations are found at particular topographical positions in the landscape (i.e. gradients from crests to colluvial footslopes and outwash; Gibson 2004b; Gibson & Lyons 2001; Markey & Dillon 2008a, 2008b; Meissner & Caruso 2008a, 2008b, 2008c), especially in the Ravensthorpe Range (Markey et al. 2012). However, much of the topographical gradient in the south-west region of the Ravensthorpe Greenstone Belt is subtle. There were significant differences between community types with respect to altitude but not topographical position. Community type 2 was recorded at the highest mean altitude, which was only significantly different from the lowest mean altitude recorded for community type 6. The NMS ordination highlighted that environmental site characteristics were influencing community groups. However, edaphic factors were more strongly correlated with the ordination, suggesting they had a greater influence on community composition than position in the landscape. Higher concentration of some soil cations (e.g. Ca, K, Mg) have been linked with lowland communities (Thompson & Sheehy 2011c). There were some correlations between communities and environmental variables seen in the south-west Ravensthorpe Greenstone Belt, with community types 1 and 3 having the highest values for the soil cations and covering a range of topographical positions, but all in areas with gentle to moderate slopes. Another consideration is the complex underlying geologic sequences and variation in weathering confounding the relationship between topographical position and vegetation communities: our soil samples and site physical parameters do not provide a complete substrate or geologic profile. Stronger associations with topographical position are more likely to occur with significant topographical gradients, as was found in many of the banded ironstone formations (BIF) and associated ranges that constitute significant elements of many greenstone belts in the Yilgarn Craton.

Conservation significance

The poor representation of greenstone belts in the conservation estate has been long recognised (Henry-Hall 1990; Chapman & Newbey 1995a) and highlighted in other greenstone belt flora surveys in the Yilgarn Craton, particularly with respect to the BIF ranges (Gibson 2004a, 2004b; Gibson et al. 1997; Gibson & Lyons 2001; Markey & Dillon 2008a, 2008b; Meissner & Caruso 2008a, 2008b, 2008c; Thompson & Sheehy 2011a, 2011b, 2011c). Recent papers (e.g. Gibson et al. 2010; Gibson et al. 2012) have reiterated the urgency for adequate conservation of greenstone belts, particularly because of the lack of conservation status over the main portion of the Ravensthorpe Range (Markey et al. 2012). These areas are hotspots of plant species richness, with high beta-diversity (species turnover) between greenstone belts within the Yilgarn Craton.

A small portion of the far south-west region of the greenstone belt survey area is held within the conservation estate as part of the Fitzgerald River National Park, and the middle area is part of the Cocanarup Timber Reserve (Fig. 1). Much of the northern portion of the study area is freehold and used for agricultural and pastoral purposes. This study highlights the high species richness and diverse substrates of this region and suggests the need for further systematic survey of the flora in the south-west portion of the Ravensthorpe Greenstone Belt. The scope of this study was limited in scale, as large areas of the belt were recovering from fire. Therefore, further surveying of the area is required, which may provide further detailed description of the diversity and associated communities. This is particularly important, given the continuing mineral interest in the area, with both live and pending mining tenements held over the study area.

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APPENDIX 1

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

Aizoaceae
- *Carpobrotus* sp.
- *Disphyma crassifolium*

Amaranthaceae
- *Ptilotus holosericeus*

Apiaceae
- *Daucus glochidiatus*
- *Platysace deflexa*

Apocynaceae
- *Alyxia buxifolia*

Asparagaceae
- **Asparagus asparagoides*
- *Chamaexeros serra*
- *Lomandra collina*
- *Lomandra effusa*
- *Lomandra micrantha* subsp. *teretifolia*
- *Lomandra mucronata*
- *Thysanotus patersonii*

Asteraceae
- *Argentipallium niveum*
- *Asteridea athrixioides*
- *Calotis hispidula*
- *Cassinia arcuata* P2
- *Lagenophora huegelii*
- *Olearia imbricata*
- *Olearia muelleri*
- *Ozothamnus lepidophyllus*
- *Podolepis rugata*
- *Senecio quadridentatus*
- *Vittadinia cervicularis*
- *Vittadinia gracilis*
- *Waitzia acuminata* var. *acuminata*

Boraginaceae
- *Halgania anagalloides* var. Southern (AE Orchard 1609)
- *Halgania andromedifolia*

Casuarinaceae
- *Allocasuarina campestris*
- *Allocasuarina huegeliana*
- *Allocasuarina humilis*
- *Allocasuarina microstachya*

Celastraceae
- *Stackhousia monogyna*

Chenopodiaceae
- *Atriplex semibaccata*
- *Chenopodium desertorum* subsp. *microphyllum*
- *Enchylaena tomentosa* var. *tomentosa*
- *Maireana erioclada*
- *Maireana marginata*
- *Maireana suaedifolia*
- *Rhagodia crassifolia*
- *Rhagodia preissii*
- *Rhagodia preissii* subsp. *preissii*
- *Sclerolaena diacantha*

Convolvulaceae
- *Wilsonia humilis*

Crassulaceae
- *Crassula colorata* var. *colorata*

Cupressaceae
- *Callitris drummondii*

Cyperaceae
- *Gahnia ancistrophylla*
- *Gahnia aristata*
- *Gahnia drummondii*
- *Lepidosperma* aff. *diurnum*
- *Lepidosperma* aff. *fimbriatum*
- *Lepidosperma* aff. *pruinosum*
- *Lepidosperma carphoides*
- *Lepidosperma diurnum*
- *Lepidosperma fimbriatum*
- *Lepidosperma gahnioides*
- *Lepidosperma* sp. A2 Inland Flat (GJ Keighery 7000)
- *Lepidosperma* sp. Bandalup Scabrid (N Evelegh 10798)
- *Lepidosperma* sp. Carracarrup Creek (S Kern, R Jasper, D Brassington LCH 16738)
- *Lepidosperma* sp. Clathrate
- *Lepidosperma* sp. K Boorabbin (KL Wilson 2579)
- *Lepidosperma* sp. Mt Benson
- *Lepidosperma* sp. Mt Chester (S Kern et al. LCH 16596)
- *Lepidosperma* sp. Mt Short (S Kern et al. LCH 17510)
- *Lepidosperma* sp. Ravensthorpe (GF Craig 5188)
- *Lepidosperma* sp. Saltbush Hill (KR Newbey 4118)
- *Lepidosperma* sp. Shoemaker Levy (L Ang & O Davies 10815)
- *Lepidosperma* sp. Tibialate
- *Mesomelaena stygia* subsp. *stygia*
- *Schoenus breviculmis*
- *Schoenus brevisetis*
- *Schoenus racemosus*
- *Schoenus* sp. Cape Riche Cushion (GJ Keighery 9922)
- *Schoenus subflavus* subsp. hispid culms (KR Newbey 8278)
- *Schoenus subflavus* subsp. subflavus
- *Tetraria* sp. Mt Madden (CD Turley 40 BP/897)

Dilleniaceae
- *Hibbertia exasperata*
- *Hibbertia gracilipes*
- *Hibbertia recurvifolia*

Ericaceae
- *Acrotriche cordata*
- *Acrotriche ramiflora*
- *Astroloma epacridis*
- *Astroloma serratifolium*
- *Leucopogon concinnus*
- *Leucopogon cuneifolius*
- *Leucopogon hamulosus*
- *Leucopogon lloydiorum*
- *Leucopogon obtusatus*
- *Leucopogon* sp. Newdegate (M Hislop 3585)
- *Leucopogon tamminensis* var. *australis*
- *Lysinema pentapetalum*
- *Styphelia pulchella*

Euphorbiaceae
- *Beyeria lechenaultii*
- *Stachystemon virgatus*

Fabaceae
- *Acacia acuminata*
- *Acacia bifaria* P3

Acacia binata
Acacia brumalis
Acacia chrysella
Acacia cyclops
Acacia erinacea
Acacia glaucoptera
Acacia gonophylla
Acacia harveyi
Acacia ingrata
Acacia lachnophylla
Acacia microbotrya
Acacia mimica var. *angusta*
Acacia pravifolia
Acacia saligna subsp. *lindleyi*
Acacia sp. narrow phyllode (BR Maslin 7831)
Acacia sulcata var. *planoconvexa*
Acacia sulcata var. *platyphylla*
Acacia tetanophylla
Daviesia anceps
Daviesia benthamii subsp. *benthamii*
Daviesia incrassata subsp. *incrassata*
Daviesia nematophylla
Daviesia pachyphylla
Eutaxia cuneata
Gastrolobium musaceum
Gastrolobium tetragonophyllum
Gompholobium confertum
Mirbelia ramulosa
Pultenaea rotundifolia
Senna artemisioides subsp. *filifolia*
Senna artemisioides subsp. x *artemisioides*
Senna artemisioides subsp. x *artemisioides* x *filifolia*
Senna sp. Pallinup River (JW Green 4847)
Templetonia aculeata
Templetonia battii
Templetonia neglecta
Templetonia retusa

Goodeniaceae
Coopernookia strophiolata
Dampiera angulata subsp. *angulata*
Goodenia affinis
Goodenia concinna
Goodenia laevis subsp. *humifusa*
Goodenia scapigera subsp. *scapigera*
Goodenia tripartita

Haemodoraceae
Conostylis argentea

Haloragaceae
Glischrocaryon aureum
Glischrocaryon flavescens

Hemerocallidaceae
Dianella brevicaulis
Dianella revoluta var. *revoluta*

Lamiaceae
Microcorys glabra
Teucrium sessiliflorum
Westringia dampieri

Lauraceae
Cassytha glabella
Cassytha melantha

Linaceae
Linum marginale

Loganiaceae
Logania stenophylla
Phyllangium divergens

Malvaceae
Alyogyne wrayae
Guichenotia ledifolia
Guichenotia micrantha
Lasiopetalum compactum
Lasiopetalum rosmarinifolium
**Malva parviflora*
Thomasia foliosa

Myrtaceae
Astus tetragonus
Baeckea corynophylla
Baeckea crispiflora
Baeckea preissiana
Beaufortia micrantha var. *micrantha*
Callistemon phoeniceus
Calothamnus quadrifidus subsp. *quadrifidus*
Calytrix aff. *leschenaultii*
Calytrix leschenaultii
Chamelaucium ciliatum
Eucalyptus brachycalyx
Eucalyptus calycogona subsp. *calycogona*
Eucalyptus cernua
Eucalyptus densa subsp. *improcera*
Eucalyptus desmondensis P4
Eucalyptus extensa
Eucalyptus flocktoniae subsp. *flocktoniae*
Eucalyptus leptocalyx
Eucalyptus myriadena
Eucalyptus myriadena subsp. *myriadena*
Eucalyptus occidentalis
Eucalyptus oleosa subsp. *corvina*
Eucalyptus perangusta
Eucalyptus phaenophylla subsp. *phaenophylla*
Eucalyptus phenax subsp. *phenax*
Eucalyptus pleurocarpa
Eucalyptus pluricaulis subsp. *pluricaulis*
Eucalyptus proxima
Eucalyptus redunca
Eucalyptus salmonophloia
Eucalyptus suggrandis subsp. *suggrandis*
Eucalyptus uncinata
Kunzea affinis
Kunzea cincinnata
Kunzea jucunda
Kunzea micrantha
Kunzea preissiana
Kunzea strigosa
Leptospermum erubescens
Leptospermum nitens
Leptospermum oligandrum
Leptospermum spinescens
Melaleuca acuminata subsp. *acuminata*
Melaleuca cliffortioides
Melaleuca cucullata
Melaleuca glaberrima
Melaleuca hamata
Melaleuca hamulosa
Melaleuca lateriflora subsp. *lateriflora*
Melaleuca penicula P4
Melaleuca pentagona var. *pentagona*
Melaleuca pomphostoma
Melaleuca rigidifolia

Appendix 1 (cont.)

Melaleuca scalena
Melaleuca sparsiflora
Melaleuca torquata
Melaleuca uncinata
Melaleuca undulata
Melaleuca villosisepala
Rinzia communis
Verticordia acerosa var. *preissii*
Verticordia chrysantha

Olacaceae
Olax benthamiana

Orchidaceae
Pterostylis aff. *spathulata*
Pterostylis platypus ms

Oxalidaceae
Oxalis perennans

Phyllanthaceae
Phyllanthus calycinus

Pittosporaceae
Billardiera coriacea
Cheiranthera brevifolia
Cheiranthera filifolia
Marianthus bicolor
Marianthus microphyllus

Plantaginaceae
Plantago hispida

Poaceae
Amphipogon turbinatus
Austrodanthonia setacea
Austrostipa acrociliata
Austrostipa elegantissima
Austrostipa hemipogon
Austrostipa pycnostachya
Austrostipa sp. Carlingup Road (S Kern & R Jasper LCH18459) P1
Austrostipa sp. Ravensthorpe Range (A Markey & J Allen 6261) P1
Austrostipa trichophylla
Austrostipa variabilis
**Ehrharta longiflora*
Neurachne alopecuroidea
**Pentaschistis airoides* subsp. *airoides*
Spartochloa scirpoidea

Polygalaceae
Comesperma integerrimum
Comesperma polygaloides
Comesperma scoparium

Polygonaceae
Muehlenbeckia adpressa

Portulacaceae
Calandrinia eremaea s.l.

Primulaceae
**Lysimachia arvensis*

Proteaceae
Banksia cirsioides
Banksia nivea subsp. *nivea*
Grevillea concinna subsp. *lemanniana*
Grevillea dolichopoda
Grevillea huegelii
Grevillea oligantha
Grevillea patentiloba subsp. *patentiloba*
Grevillea pectinata
Grevillea rigida subsp. *distans*
Grevillea teretifolia
Hakea commutata
Hakea incrassata
Hakea laurina
Hakea lissocarpha
Hakea marginata
Hakea nitida
Hakea pandanicarpa subsp. *crassifolia*
Hakea verrucosa
Isopogon sp. Fitzgerald River (DB Foreman 813)
Persoonia striata
Petrophile seminuda
Synaphea interioris

Restionaceae
Desmocladus asper
Lepidobolus preissianus

Rhamnaceae
Cryptandra nutans
Cryptandra pungens
Pomaderris paniculosa subsp. *paniculosa*
Siegfriedia darwinioides
Spyridium cordatum
Trymalium elachophyllum

Rutaceae
Boronia inconspicua
Boronia inornata subsp. *inornata*
Boronia scabra subsp. *scabra*
Boronia subsessilis
Microcybe albiflora
Philotheca gardneri subsp. *gardneri*

Santalaceae
Choretrum glomeratum var. *glomeratum*
Exocarpos aphyllus
Exocarpos sparteus
Santalum acuminatum
Santalum spicatum

Sapindaceae
Dodonaea concinna
Dodonaea pinifolia
Dodonaea ptarmicaefolia

Scrophulariaceae
Eremophila decipiens subsp. *decipiens*
Glycocystis beckeri

Stylidiaceae
Stylidium albomontis
Stylidium involucratum
Stylidium piliferum

Thymelaeaceae
Pimelea brachyphylla
Pimelea erecta

Violaceae
Hybanthus floribundus subsp. *adpressus*

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

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ABSTRACT

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

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

INTRODUCTION

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

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

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

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

Geology

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

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

Climate

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

Vegetation

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

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

METHODS

The methods used in this survey follow the standard procedures used in previous vegetation surveys of other ironstone and greenstone ranges in Western Australia (e.g. Markey & Dillon 2008; Meissner & Caruso 2008). Fifty 20 × 20 m quadrats were established on the stony crests and slopes of the greenstone ranges of Credo Station during the spring of August and September 2011 (Fig. 1). Quadrats were located to cover the broader geographical and geomorphological variation found within the study area. The quadrats were placed stratigraphically across the hills in a toposequence, from crests to footslopes and plains, in the least disturbed vegetation available in the area sampled, avoiding areas heavily grazed or cleared. Each quadrat was permanently marked with four steel fence droppers and their positions determined using a Garmin GPSMAP 60CSx. All vascular plants within the quadrat were recorded and collected for later identification at the Western Australian Herbarium.

Data on topographical position, disturbance, abundance, size and shape of coarse fragments on the surface, the abundance of rock outcrops (defined as the cover of exposed bedrock), cover of leaf litter and bare ground were recorded following McDonald et al. (1990). Additionally, growth form, height and cover were recorded for dominant taxa in each stratum (tallest, mid and lower). The qualitative data were used to describe the plant communities following McDonald et al. (1990). Nomenclature follows Western Australian Herbarium (1998–).

Twenty soil samples were collected from four evenly spaced locations on five parallel transects, separated by 5 m, across the quadrat. The upper 10 cm of the soil profile within each quadrat was sampled. The samples were bulked and the <2 mm fraction was analysed for Al, B, Ca, Cd, Co, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, S and Zn using an Inductively Coupled Plasma – Atomic Emission Spectrometer (ICP–AES). Electrical conductivity (EC), organic carbon, total nitrogen and pH were determined using the methods described in Meissner and Wright (2010).

Quadrats were classified on the basis of similarity in species composition, using perennial species only and excluding singletons. This was done to remove any temporal variations in the abundance of annuals that may confound comparisons with other greenstone and banded ironstone ranges (Markey & Dillon 2008; Meissner & Caruso 2008). Species were classified into species groups according to their occurrence within the same quadrats. The quadrat and species' classifications were undertaken using the Bray–Curtis coefficient followed by hierarchical clustering (using group-average linking), using PRIMER v6 software (Clarke & Gorley 2006). Quadrat classification was followed by similarity profile (SIMPROF) testing to determine the significance of internal group structures using permutation testing (Clarke & Gorley 2006). Community group circumscription closely followed SIMPROF results. Indicator species for community groups were determined following De Cáceres et al. (2010) using 'indicspecies' in the R language (De Cáceres & Legendre 2009).

Following the classification, the quadrats were ordinated using non-metric multidimensional scaling (MDS), a nonparametric approach that is not based upon the assumptions of linearity, or presumption of any underlying model of species' response gradients (Clarke & Gorley 2006).

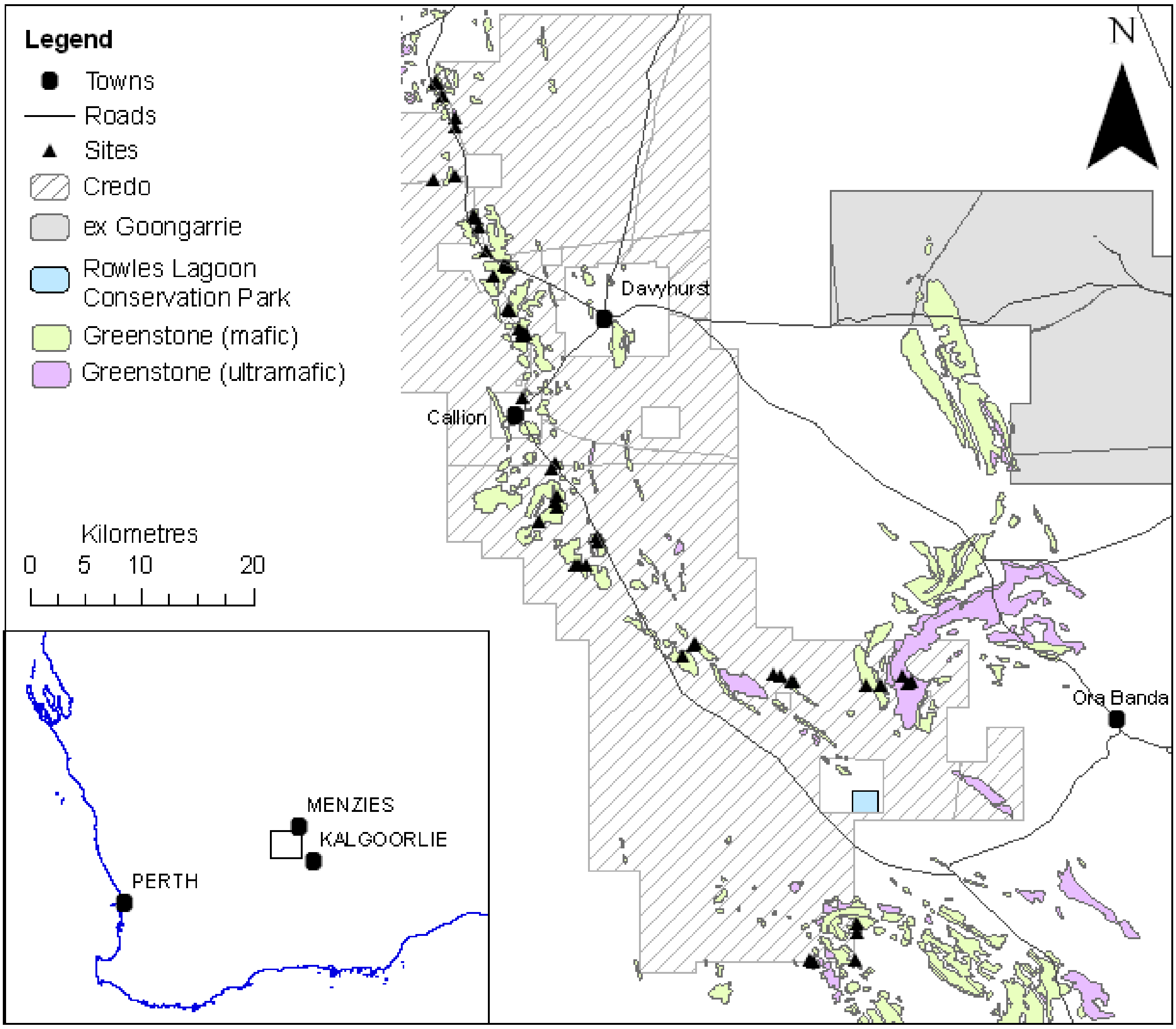


Figure 1. Location of the 50 quadrats (▲) established on the greenstone ranges on Credo Station (hashed areas) within the Coolgardie IBRA Bioregion. The Archaean mafic and ultramafic geology are shown in green and purple respectively.

To determine the environmental variables that best explained the community pattern, the BEST analysis using the BIOENV algorithm in PRIMER v6 (Clarke & Gorley 2006) was undertaken on a Euclidean distance resemblance matrix based on normalised environmental data. Prior to normalisation, EC, sodium and nickel were transformed using log(x +1). The BEST routine selects environmental variables that best explain the community pattern, by maximising a rank correlation between their respective resemblance matrices (Clarke & Warwick 2001). In the BIOENV algorithm, all permutations of the environmental variables were tried and the five best variables selected. The normalised environmental variables were then fitted to the MDS ordination and Pearson rank correlation values ($r > 0.6$) calculated to determine linear correlations between the variables and the vegetation communities.

RESULTS

Flora

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

Priority flora

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

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

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

Plant communities

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

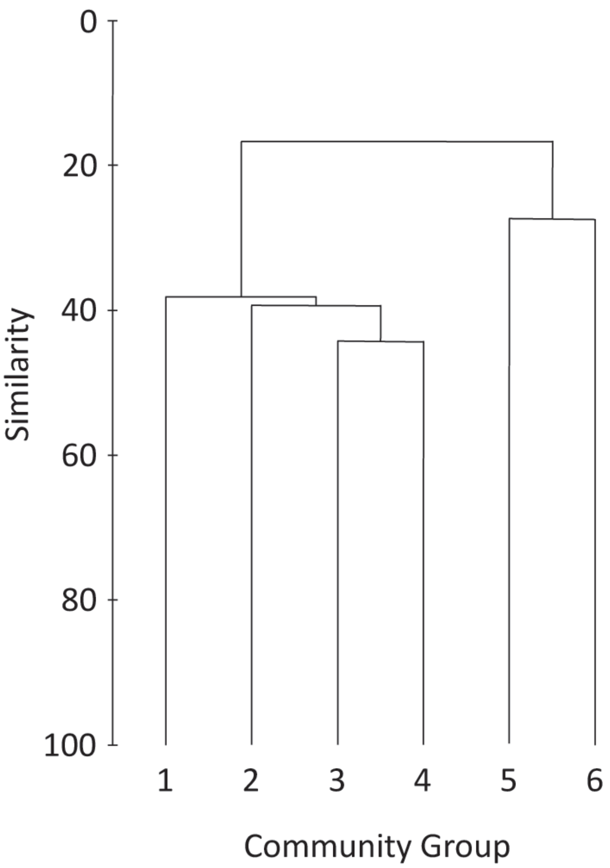


Figure 2. Dendogram of the classification of the 50 quadrats established on Credo Station into six community groups.

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

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

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

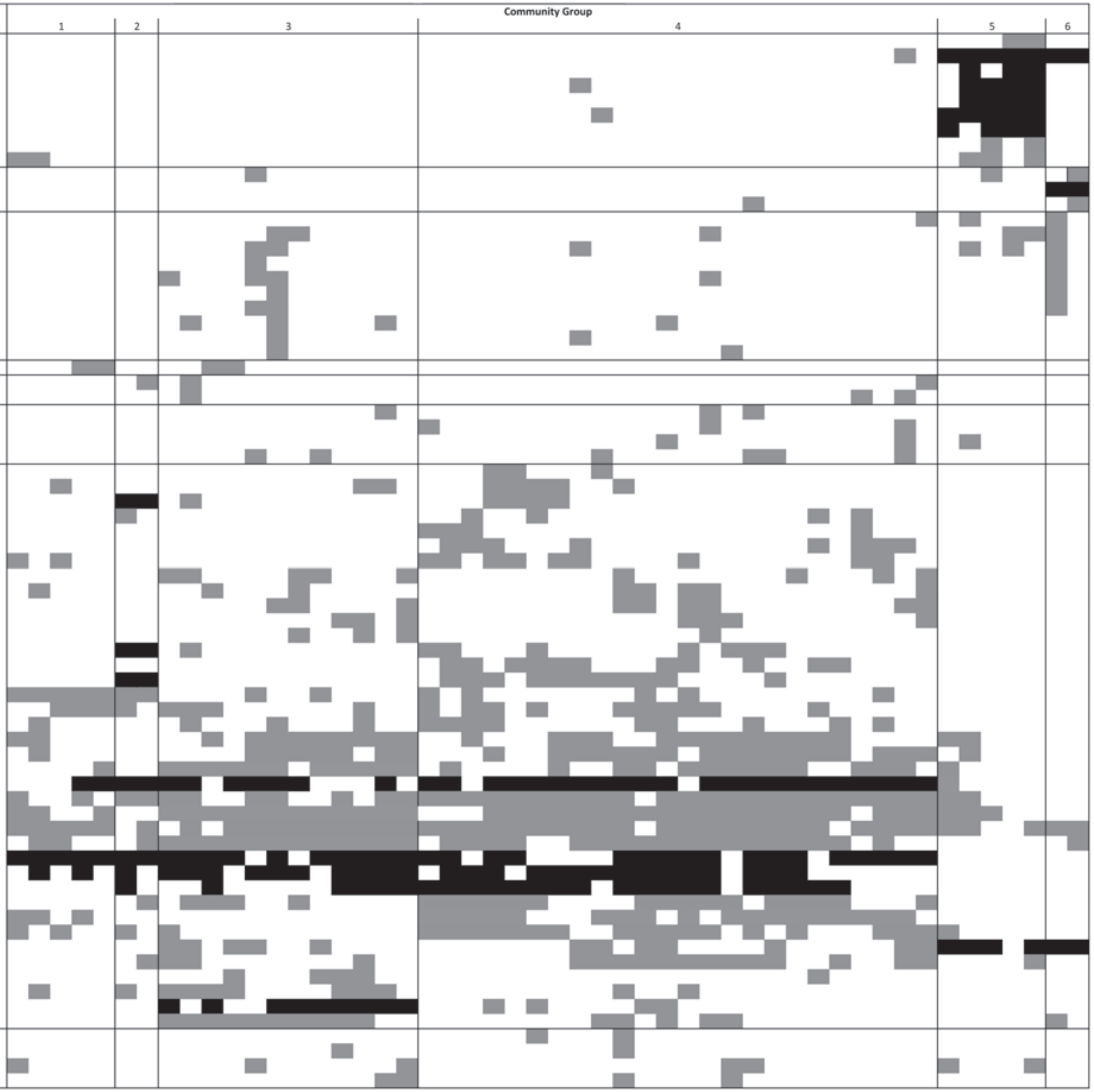
Community 4 was characterised as open forests to open woodlands of *Eucalyptus* spp. (*E. clelandii*, *E. celastroides* subsp. *celastroides*, *E. griffithsii*) and the occasional *Casuarina pauper*, over shrublands to sparse shrublands of *Eremophila* spp. (*E. oldfieldii* subsp. *angustifolia*, *E.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

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

Table 1

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

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



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

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

Environmental correlates

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

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

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

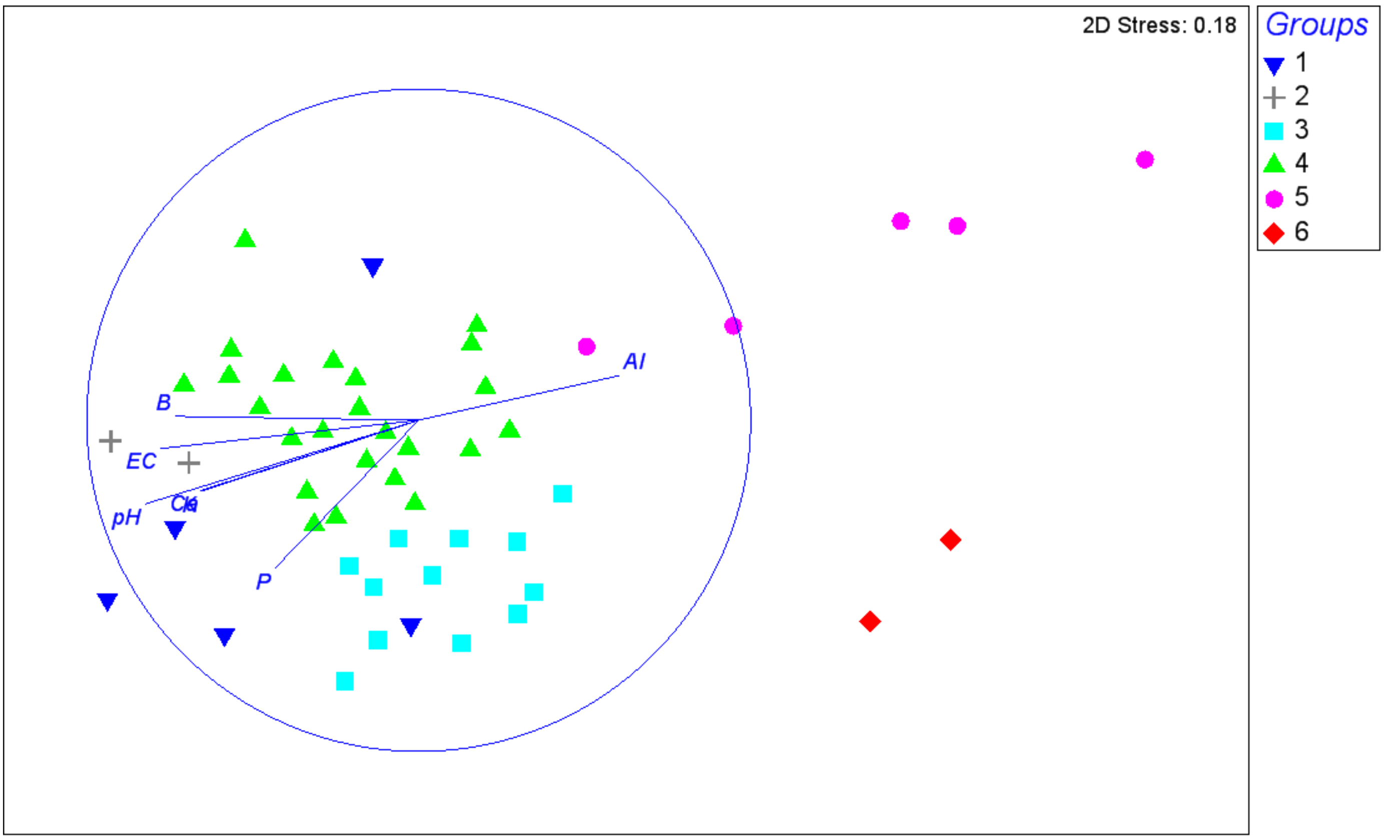


Figure 3. Two dimensional ordination of the 50 quadrats established on Credo Station. The six communities, as defined by the classification, are shown with the seven environmental variables correlated with the MDS using Pearson rank correlation (r > 0.6). The lines represent the seven environmental variables,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

Table 2

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

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

Table 3

Mean values for site attributes by plant community type: aspect (degrees); slope (degrees); morphology type (1 – crest, 2 – mid slope, 3 – lower slope, 4 – simple slope); land form (1 – hill crest, 2 – hill slope); disturbance (0 – no effective disturbance, 1 – no effective disturbance except grazing by hoofed animals); maximum size of coarse fragments (CF Max; 1 – fine gravely to 6 – boulders); coarse fragment (CF) abundance (0 – no coarse fragments to 6 – very abundant coarse fragments); rock outcrop (RO) abundance (0 – no bedrock exposed to 4 – very rocky); runoff (0 – no runoff to 4 – rapid); soil depth (1 – skeletal, 2 – shallow, 3 – deep). Differences between ranks tested using Kruskal–Wallis nonparametric analysis of variance. Standard error in parentheses (n = number of quadrats).

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

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

DISCUSSION

Flora

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

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

Plant communities

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

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

Conservation

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

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APPENDIX 1

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

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

Apiaceae
- *Daucus glochidiatus*

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

Araliaceae
- *Trachymene cyanopetala*
- *Trachymene ornata*

Asparagaceae
- *Thysanotus manglesianus*
- *Thysanotus speckii*

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

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

Campanulaceae
- *Wahlenbergia gracilenta*

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

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

Centrolepidaceae
- *Centrolepis cephaloformis*

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

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

Cyperaceae
- *Schoenus nanus*

Droseraceae
- *Drosera macrantha* subsp. *macrantha*

Euphorbiaceae
- *Euphorbia drummondii* subsp. *drummondii*

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

Geraniaceae
- *Erodium aureum*
- *Erodium cygnorum*

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

Haloragaceae
- *Haloragis trigonocarpa*

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

Loganiaceae
- *Phyllangium sulcatum*

Loranthaceae
- *Amyema miquelii*

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

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

Phyllanthaceae
- *Poranthera leiosperma*
- *Poranthera microphylla*

Pittosporaceae
- *Pittosporum angustifolium*

Plantaginaceae
- *Plantago debilis*

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

Polygalaceae
- *Comesperma integerrimum*

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

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

Pteridaceae
- *Cheilanthes adiantoides*
- *Cheilanthes sieberi* subsp. *sieberi*

Rhamnaceae
- *Cryptandra aridicola*

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

Santalaceae
- *Exocarpos aphyllus*
- *Santalum acuminatum*
- *Santalum spicatum*

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

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

Solanaceae
- *Solanum lasiophyllum*
- *Solanum nummularium*

Thymelaeaceae
- *Pimelea microcephala* subsp. *microcephala*

Violaceae
- *Hybanthus floribundus* subsp. *curvifolius*

Zygophyllaceae
- *Zygophyllum eichleri*
- *Zygophyllum ovatum*

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Wader numbers and distribution on Eighty Mile Beach, north-west Australia: baseline counts for the period 1981–2003

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ABSTRACT

This paper analyses ground counts and aerial surveys of high-tide wader roosts conducted over the 23-year period from 1981 to 2003, at Eighty Mile Beach, north-west Australia. It provides a baseline data set with which later count data can be compared. Over the study period, Eighty Mile Beach held a maximum of around 470,000 waders in any given year. This represented around 20% of the total number of migratory waders visiting Australia each year and around 6% of the total East Asian – Australasian Flyway migratory wader population. The most numerous species were great knot (169,000), bar-tailed godwit (110,000), greater sand plover (65,000) and oriental plover (58,000). Distribution of waders along the beach was not uniform, with up to 85% occurring in the section between 25 km and 80 km south of Cape Missiessy where, at peak, numbers averaged 7000 per kilometre of shore; however, distributions for some species diverged from this pattern. Count data showed that waders arrived in north-west Australia over an extended period from July to October. The majority of these birds remained at Eighty Mile Beach throughout the nonbreeding season (austral summer) although some smaller waders used Eighty Mile Beach as a staging point. Most adult birds left on northward migration in March–April of the following year. The number of (mainly) immature birds remaining at Eighty Mile Beach over the May–July period was equivalent to 9% of the peak spring/summer population. The counts also showed that Eighty Mile Beach, especially the southern half, is important for resident wader species. Threats to its ecological integrity are identified and the introduction of enhanced long-term protection measures recommended to ensure that key sections of Eighty Mile Beach are managed for the benefit of the internationally significant numbers of waders occurring there.

Keywords: conservation, counts, Eighty Mile Beach, north-west Australia, shorebirds, waders.

INTRODUCTION

Eighty Mile Beach, which is actually 140 miles (220 km) long, lies on the north-west Australian coast between Broome and Port Hedland (Fig. 1). Tidal ranges along this coast are high, and intertidal areas extensive. During the austral summer these invertebrate-rich intertidal areas support large numbers of waders, mostly northern hemisphere migrants. Eighty Mile Beach's importance to migratory waders was first noted as recently as 1962 by Marshall and Drysdale (1962) and confirmed in 1980 by Simon Bennett (pers. comm.), who reported huge concentrations of wading birds, including many great knot (*Calidris tenuirostris*), then considered a globally uncommon species.

This information was timely, as it came at the start of a Royal Australasian Ornithologists Union (RAOU) project aimed at conducting, between 1981 and 1985, a complete wader population census across Australia. As

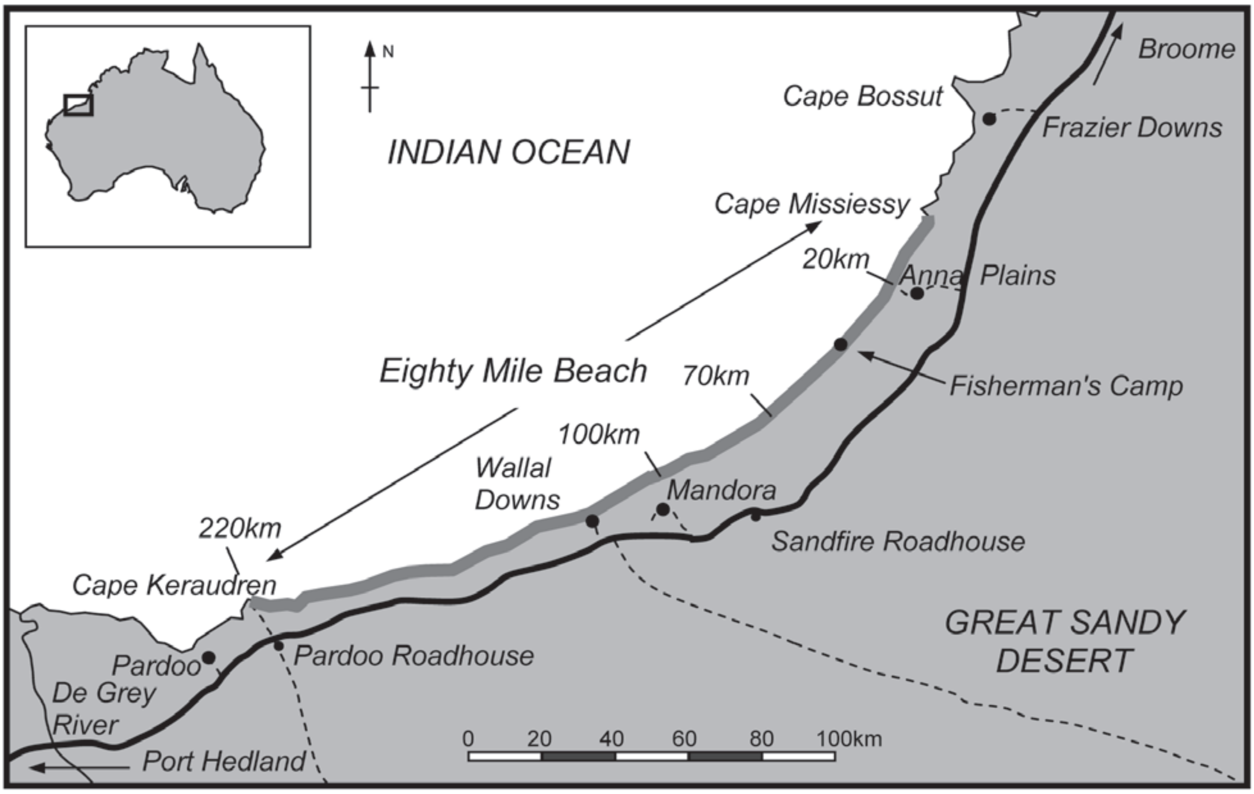

Figure 1. Map of Eighty Mile Beach showing the distances from Cape Missiessy south to Cape Keraudren.

part of this effort, the Australasian Wader Studies Group (AWSG) undertook a special expedition to north-west Australia during late August and early September 1981. An aerial survey and brief ground visit confirmed the presence of large numbers of waders on Eighty Mile Beach, particularly its northern sections. Since 1981, aerial surveys and/or ground counts of waders and terns have been undertaken there almost every year. Difficulties associated with surveying the entire length of Eighty Mile Beach meant that most counts covered only those sections of beach known to support good numbers of migratory waders.

Data generated from aerial and ground counts between 1981 and 1986 provided the basis for the population estimates for Eighty Mile Beach (and Australia as a whole) derived by Lane (1987). Based on these estimates, Watkins (1993) ranked Eighty Mile Beach as the top site in Australia as far as total wader numbers were concerned, and the third most important in terms of the number of different wader species that had populations above the internationally significant (15 species) and the nationally significant (19 species) levels: for 11 species (10 migrant, one resident) Eighty Mile Beach held the highest concentrations in Australia. These rankings made it highly desirable that early wader population estimates be verified. Also, by the mid-1990s populations of several wader species were in decline elsewhere in Australia and it was desirable to know if trends were similar on Eighty Mile Beach. Therefore, a complete ground count was attempted in October 1998 and a similar, follow-up, count was undertaken in November 2001. The first complete count during the austral winter was conducted in July 2003.

This paper presents findings from an analysis of count data obtained at Eighty Mile Beach during the period up until 2003; particular importance is attached to data from the 1998 and 2001 complete counts. Results obtained during counts subsequent to 2003 have not been included since pressures on wader habitats in the Asia–Pacific Flyway have increased markedly recently, particularly in the Yellow Sea area (Barter 2003; Milton et al. 2003; van de Kam et al. 2010). Restricting the analysis to data from the 1981–2003 period, when disturbances to wader habitat in the flyway were less severe, enabled a reference data set for this period to be established. Having such baseline data available will be valuable when assessments are made of the nature, magnitude and causes of more recent and future changes in wader numbers, distributions and migration patterns.

The specific objectives of the work described in this paper were:

a) To determine the total numbers of waders and number of wader species using Eighty Mile Beach, and to establish how patterns of use vary seasonally.
b) To determine patterns of arrival for each species.
c) To establish how waders in general, and individual species in particular, are distributed along Eighty Mile Beach.
d) To identify key conservation sites and issues for Eighty Mile Beach.

METHODS

Site Description

Eighty Mile Beach extends south-west from Cape Missiessy (19° 02' S, 121° 32' E) to Cape Keraudren (20° 00' S, 119° 48' E; Fig. 1). For most of its length the beach consists of an extensive intertidal area and sandy beach, backed by sand dunes, which give way inland to narrow coastal plains. The daily tidal range varies from about 2 m on neap tides to 10 m during spring tides. At spring low tide the tidal flats adjoining the beach vary from 1.5 to >4 km in width and the maximum exposed area of mud and sandflats is about 60,000 ha (Pearson et al. 2005a).

Along the southern part of the beach, south of Wallal, there are occasional small rocky outcrops and, in the segment 160–165 km from Cape Missiessy, a low rocky cliff abuts the mudflats. No mangroves are present along the beach except for a few scattered bushes, 1 m high, in the small creek where the Mandora Marsh drains to the sea (CALM 2003).

The area experiences a semi-arid monsoonal climate, with a short wet season from late December to early March (Pearson et al. 2005a). Mean annual rainfall at Mandora Station, located midway along Eighty Mile Beach, is 341 mm (Wade & Hickey 2008); however, because the region regularly experiences cyclones, the amount and seasonality of rainfall events varies greatly (CALM 2003). Mean monthly maximum temperatures range from 28 °C in July to 36 °C in December (Wade & Hickey 2008).

Sediments are predominantly calcareous rather than siliceous in nature and become sandier towards the southern end of the beach (Pearson et al. 2005a). Sediment grain sizes are not uniform across the intertidal areas: the coarsest sediments are found at the highest intertidal level and finer sizes near the low-water mark (Honkoop et al. 2006; Wade & Hickey 2008). Benthic organisms on which waders feed are concentrated along the northern half of Eighty Mile Beach, right across the intertidal areas. The structure of benthic assemblages across intertidal areas is related to distribution of sediment sizes; however, unexpectedly large differences in benthic species composition are found between areas of comparable sediment characteristics at different localities along Eighty Mile Beach. It is speculated that these differences are caused by the cyclones that periodically disrupt intertidal sediments and their associated benthic fauna (Honkoop et al. 2006; Wade & Hickey 2008).

Counts from the air

For both air and ground counts, counting was practical only when waders were driven off tidal flats by the rising tide and concentrated in roosting flocks along the sandy beaches. Counting was made easier by the tendency of flocks to roost on damp substrates along the tide edge. During aerial counts, a light aircraft was flown along the beach at heights under 200 ft (60 m). This ensured that all flocks flushed, enabling observers in the plane to identify the more distinctive species present. Flock sizes were estimated independently by two experienced observers while a third passenger recorded their observations. Such counts provided information on the total numbers and distribution patterns of waders present but complementary ground counts were needed to acquire detailed information on the numbers of each species.

Counts on the ground

Ground counts were undertaken by teams of three to four observers driving along the beach in 4WD vehicles. For counting purposes, Eighty Mile Beach was divided into 5-km-long segments, denoted by their distance from Cape Missiessy (e.g. 0–5 km, 5–10 km, etc.). Each counting team was assigned a sector comprising two or more segments and counts were undertaken simultaneously during a 3–4 hour period during high tide. The procedure involved driving along the beach, stopping at strategic points to observe and record the numbers of different waders present. The number of birds in each 5-km segment was recorded separately. Along densely populated stretches of beach a counting team could only cover two segments in the 3–4 hours available. Where few roosting flocks were present, up to 20 km (or even 30 km on one sector) could be covered in the same timeframe. For the complete counts made in October 1998 and November 2001, six teams were required on each of the two days over which counts took place. Only four teams were needed on each day of the July 2003 count.

At Eighty Mile Beach, experience has shown that low (almost neap) tides, rather than spring high tides, are most suitable for counting waders in high-tide roosts along the tide edge. There are no tide gauges on the beach but field observations have shown that tide time and height is predicted reasonably well by published tide predictions from Roebuck Bay. The most appropriate tidal range for wader counts was 6.8 to 7.6 m. (The appropriate tidal range has been given as 6 to 6.8 m in several previous publications, e.g. Rogers [2005], but since then the National Tide Centre has raised the regional tide datum by 0.86 m.) Under these conditions the beach is generally wide enough to allow the counting vehicle to move around flocks without causing the birds to take flight. At the same time the flocks are close enough for counts and identifications to be made with reasonable accuracy. Morning counts are best because the sun is behind the observers. If counting is attempted on spring tides, many flocks flush as vehicles approach. Some birds circle back behind the counting team but others settle further down the beach. Under such circumstances, count accuracy diminishes markedly.

When devising a procedure for counting the birds present in each flock some unusual challenges had to be overcome. In most parts of the world waders tend to roost in discrete flocks comprising only a small number of species (often only a single species). However, in north-west Australia it is usual for roosting flocks to contain 10–15 species. Since flocks typically comprise 1000 to 5000 birds and are fairly tightly packed, accurately determining the numbers of each species present is difficult. When counting such large, mixed flocks the total number of birds in the roosting flock was determined first, usually by means of the 'block method' (Howes & Bakewell 1989). The percentage of each species present in significant numbers in the flock was then estimated, enabling an approximate figure for each species to be arrived at.

Limitations of the counting procedure

The limitations of the procedures used for counting waders in north-west Australia have been discussed by Rogers et al. (2006b). They concluded that the complex structure of roosting flocks is the major cause of error in count data, provided all observers are experienced wader-counters familiar with the counting sites. This was the case for counts discussed here since not only were the observers experienced but consistency between the 1998 and 2001 counts was maximized by arranging for four of the teams to have the same leader and cover the same areas on each count. Flock structure is a problem since most roosting flocks contain large numbers of birds, packed relatively closely together, so that many individuals are partly or wholly obscured from view. In addition, birds often change their relative positions within the flock. Hence observers are seldom able to get a clear view of every individual bird present. Despite these problems, the level of consistency between counts conducted by different observers suggests counts of more common species are reasonably accurate. However, it is likely that there is under-counting of a few species (e.g. lesser sand plover, *Charadrius mongolus*, and broad-billed sandpiper, *Limicola falcinellus*) that are uncommon on Eighty Mile Beach and are potentially difficult to distinguish from other species in roosting flocks.

History of counts: 1981–2003

Thirty-six ground counts and 24 aerial counts of waders on Eighty Mile Beach were conducted between 1981 and 2003. All except one aerial count were conducted prior to 1986. Several covered the complete 220 km length of the beach from Cape Missiessy to Cape Keraudren but most only covered the section from Cape Missiessy to Mandora (100 km) or to Wallal (120 km). Most ground counts covered only the 70 km section (or parts thereof) south from Cape Missiessy (the 'Anna Plains' section). Aerial surveys showed that most of the waders using Eighty Mile Beach were found in this section. Counts fell into two categories: those conducted during formal expeditions, usually in March–April or August–October; and those conducted for the AWSG National Wader Population Monitoring Program (these have taken place in February and June each year since 1993).

Because juveniles of most migratory wader species arrive in Australia later than adults, the main counts in 1998 and 2001 were undertaken as late as possible in each expedition. In 1998 the complete census was undertaken in mid-October. This was preceded by a series of counts carried out on the northern section of the beach; these were designed to obtain information on the main arrival periods for different species and the rates at which their numbers increased. Evidence of onward movements to nonbreeding areas further south was also looked for. Based on experience acquired in 1998 and subsequently, a date in mid-November was chosen for the 2001 complete ground census. This count was also preceded by a count of the northern section of the beach. Details of the timing and areas covered in both the partial and complete 1998 and 2001 counts are given in Table 1.

Table 1
Count dates at Eighty Mile Beach in 1998 and 2001.

Date	Sector Counted
5 August 1998	0–70 km
19 August 1998	0–100 km
14 September 1998	0–100 km
17–18 October 1998	0–220 km (entire beach)
29 September 2001	0–70 km
12–13 November 2001	0–220 km (entire beach)

To complement the 1998 and 2001 censuses a complete ground-count of Eighty Mile Beach was carried out in July 2003. Whilst this count was undertaken primarily to determine the number of migrant waders that remain behind in Australia during the austral winter, it also provided an opportunity to assess the use made of Eighty Mile Beach by non-migratory waders over this period.

RESULTS AND DISCUSSION

Peak numbers in the overall population

Close to 479,000 waders, terns and gulls were present on Eighty Mile Beach during the ground census in November 2001, the vast majority being waders (Table 2). A strikingly similar count total was obtained in October 1998. The July 2003 count demonstrated the importance of Eighty Mile Beach as a feeding ground for over-wintering waders (Table 2).

The peak count of 479,000 was well above the population estimate of 300,000 (± 10%) derived from aerial counts conducted during 1981–86. Estimates from the three complete aerial counts were: 302,000 (September 1982), 337,000 (mid-November 1982) and 287,000 (mid-October 1984). Although two of the surveys were conducted before wader populations reach

Table 2
Wader counts for all of Eighty Mile Beach (220 km) in 1998, 2001 and 2003.

	17–18 Oct. 1998	12–13 Nov. 2001	8–9 July 2003
Waders	465,890	472,418	41,498
Terns	6,520	5,653	4,298
Gulls	1,008	615	1,056
Total	473,418	478,686	46,852

their peak, these results nonetheless suggest aerial counts underestimate wader numbers. Encouragingly, the complete ground censuses agreed closely with the population estimate of 508,539 in Lane (1987), later used by Watkins (1993) in his national population estimates. However, agreement at the individual species level is not as good, with Watkins' estimates being too high in some instances and too low in others (Table 3).

The above results indicate that, when wader numbers are at their peak, Eighty Mile Beach supports close to half a million waders: more than any other Australian site. Given that significant numbers of smaller waders use Eighty Mile Beach as a staging point while on migration, the number of waders regularly using the food resources of Eighty Mile Beach in any one year will be higher still. On occasions, conditions on Anna Plains Station create favourable foraging habitat for grassland species such as little curlew (*Numenius minutus*) and oriental plover (*Charadrius veredus*; Piersma & Hassell 2010) and, later in the season, oriental pratincole *(Glareola maldivarum)*. These species regularly roost on nearby sections of Eighty Mile Beach during the hotter periods of the day, significantly increasing the numbers of roosting waders. The most striking example was in February 2004, when an estimated 2.88 million oriental pratincoles were present along Eighty Mile Beach (Sitters et al. 2004). Assuming the normal summer population of waders on Eighty Mile Beach is around 470,000, this site holds about 20% of migrant waders visiting Australia and 6% of waders in the East Asian – Australasian Flyway (Bamford et al. 2008).

Peak numbers of individual wader species

Thirty-three wader species were recorded on Eighty Mile Beach during the complete counts (Table 3). Of these, eight species were present in small numbers (<10 individuals) on every count, while numbers of another four species never exceeded 50. Of note is that the percentages of black-tailed godwits (*Limosa limosa)*,

Table 3

Maximum counts for each wader species along the full length of Eighty Mile Beach.

	8-9 Jul 03	17-18 Oct 98	12-13 Nov 01	Maximum	*Previous estimates
Great knot	10,665	158,082	169,044	169,044	160,000
Bar-tailed godwit	13,767	110,290	97,403	110,290	34,300
Greater sand plover	3,597	63,482	64,584	64,584	30,400
Oriental plover	0	57,619	41,278	57,619	18,400
Red knot	2,316	24,891	29,679	29,679	80,700
Red-necked stint	5,094	16,766	24,005	24,005	60,000
Grey-tailed tattler	124	10,436	14,647	14,647	8,500
Terek sandpiper	296	7,989	9,820	9,820	3,000
Curlew Sandpiper	363	2,859	7,984	7,984	60,000
Ruddy turnstone	227	3,480	1,649	3,480	740
Sanderling	1,001	2,230	3,219	3,219	100
Red-capped plover	2,965	2,512	3,077	3,077	9,600
Common greenshank	152	1,738	2,432	2,432	2,440
Grey plover	138	1,416	1,585	1,585	1,650
Eastern curlew	163	709	552	709	480
Pied oystercatcher	615	653	694	694	190
Little curlew	0	224	215	224	12,000
Sharp-tailed sandpiper	0	9	193	193	25,000
Whimbrel	9	185	148	185	180
Marsh sandpiper	2	76	171	171	140
Lesser sand plover	1	162	0	162	5
Pacific golden plover	0	24	12	24	440
Black-tailed godwit	0	22	7	22	110
Sooty oystercatcher	1	3	13	13	0
Broad-billed sandpiper	0	12	3	12	55
Australian pratincole	0	9	1	9	100
Common redshank	0	5	0	5	0
Common sandpiper	0	3	2	3	0
Black-fronted dotterel	0	0	1	1	0
Black-winged stilt	2	1	0	2	0
Beach thick-knee	0	1	0	1	0
Oriental pratincole	0	1	0	1	0
Asiatic dowitcher	0	1	0	1	0
Others	0	0	0	0	9
Total waders	41,498	465,890	472,418	503,897	508,539

*Lane (1987); also quoted by Watkins (1993).

broad-billed sandpipers, Asian dowitchers (*Limnodromus semipalmatus*), whimbrels (*Numenius phaeopus*) and lesser sand plovers in local wader populations were much lower at Eighty Mile Beach than at Roebuck Bay, Broome, only 200 km to the north (unpublished AWSG data).

The most numerous species were great knot, bar-tailed godwit (*Limosa lapponica*) and greater sand plover (*Charadrius leschenaultii*). Maximum counts for these species were, respectively, 169,000 (a little under half the estimated world population), 110,000 (around a third of the estimated population for the East Asian – Australasian Flyway), and 65,000 (nearly two thirds of the estimated world population; Bamford et al. 2008). Together, these three species made up almost 70% of peak wader populations. The combined contribution of these three species was also at much the same level (67%) for the winter (July 2003) count.

Peak population estimates from the October 1998 and November 2001 counts were encouragingly similar for many species. For the three principal wader species, changes in the estimated peak population size over the three-year period were all less than 15%: great knot (+7%), bar-tailed godwit (–12%) and greater sand plover (+2%). For most other species, the differences in numbers between the two counts were reasonably small, and probably resulted from more juvenile birds being present in November 2001 than in October 1998. This happened because the 2001 count took place a month later and because waders bred more successfully in northern Siberia in 2001 than in 1998 (Minton et al. 2002a). The differences may also reflect actual changes in population size over the three-year period associated with variations in breeding productivity and survival rates. However, the numbers recorded for a few species differed considerably between the counts, and other factors are likely to have contributed to the differences in the recorded size of the peak population:

a) Oriental plover (–28%). The October 1998 count coincided with the peak arrival date, in a year of excellent breeding productivity. Also, this species feeds primarily on grasslands inland of the beach dune system and only moves to the beach to roost, in numbers that fluctuate in response to changes in local weather conditions.
b) Red-necked stint (*Calidris ruficollis*; +43%). This increase is consistent with marked increases across Australia during the 1998–2001 period after a series of above average breeding seasons (Minton et al. 2002b).
c) Curlew sandpiper (+79%). 2001 was the first good breeding season after a long series of years of below average productivity (Minton et al. 2002b) that had led to a major population decline (Wilson 2001).

For many species the peak numbers recorded in the 1998 and 2001 surveys differed from the estimates made by Lane (1987), based on counts conducted in the 1981–86 period (Table 3). Only in the case of great knot, common greenshank (*Tringa nebularia*), grey plover (*Pluvialis squatarola*), whimbrel and marsh sandpiper (*T. stagnatilis)* do the count data and Lane's estimates match closely. Species rankings (based on numbers present) also differ: whereas the 1998/2001 counts had great knot ranked first, followed by bar-tailed godwit and greater sand plover, Lane's (1987) estimates have great knot first, red knot second, with red-necked stint and curlew sandpiper equal third. These differences are partly attributable to shortcomings in the early count data. In particular, the early (9 September 1982) estimate of 80,700 for red knot (*Calidris canutus*) has long been considered questionable: only one ground count of red knot during the 1981–2003 period exceeded 10,000, and that was 20,000 in the 20–35 km section in November 1987. Conversely, the original estimate of 34,300 bar-tailed godwits appears far too low.

Differences in methodology also contributed to the above discrepancies. Whereas the 1998/2001 results were obtained from direct counts, estimates of species numbers in Lane (1987) were derived by extrapolating the results of restricted ground counts to fit total wader numbers observed during aerial counts. Later counts have shown that many wader species have non-uniform distributions along Eighty Mile Beach. For example, red knots occur primarily on particular northern sections of Eighty Mile Beach. So, if the limited-scale ground counts used by Lane (1987) were conducted on beaches where a species was locally abundant, overestimates would have resulted. Conversely, where the limited-scale counts used by Lane (1987) relate to beaches where a species was uncommon, underestimates would have resulted. For some species, additional factors may have contributed to the above discrepancies:

- Lane's (1987) estimates included 25,000 sharp-tailed sandpipers (*Calidris acuminata*) counted at an ephemeral freshwater wetland several kilometres inland, whereas other population estimates for Eighty Mile Beach have used shoreline counts only.
- The discrepancy between Lane's (1987) curlew sandpiper estimate and the 1998/2001 count data appears partly attributable to an overall population decrease associated with a series of poor breeding seasons in the 1990s (Minton et al. 2002b; Wilson 2001; Rogers & Gosbell 2006).
- Species underestimated by Lane (1987) that occur predominantly on the northern sections of Eighty Mile Beach include bar-tailed godwit, greater sand plover, oriental plover, grey-tailed tattler (*Heteroscelus brevipes*) and Terek sandpiper (*Xenus cinereus*). In the case of the oriental plover, the 1998/2001 counts were conducted at a time when large numbers of this species had recently arrived in north-west Australia and populations were close to their maximum. This species had a good breeding season in 1998 and the population was augmented by unusually large numbers of juveniles (unpublished AWSG data)—the count of 58,000 recorded at Eighty Mile Beach that year was nearly 50% above the previous population estimate for the entire flyway. Increases in numbers estimated for grey-tailed tattlers

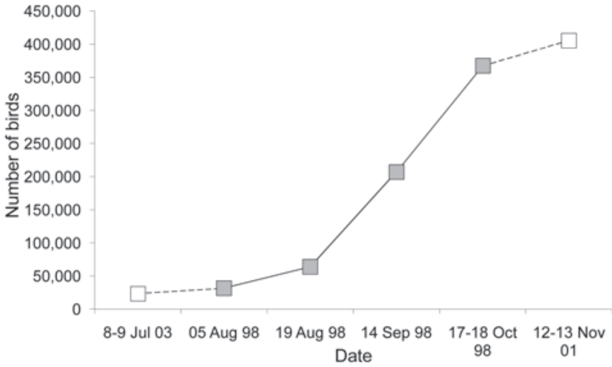

Figure 2. The change in wader numbers on the 0–70 km section of Eighty Mile Beach over the period August–October 1998 (closed symbols). Open symbols show corresponding numbers from the counts along the same section of beach in July 2003 and November 2001. These are included to show the likely annual minima and maxima in wader numbers.

and Terek sandpipers since the early 1980s may result from genuine population increases, but could also reflect improvements in identifying these species in large, mixed gatherings of waders. Other species whose numbers were underestimated by Lane (1987) include ruddy turnstone (*Arenaria interpres)*, sanderling (*Calidris alba)* and pied oystercatcher (*Haematopus longirostris*). These three species occur mainly on the southern half of Eighty Mile Beach, which was not covered in the 1981–1986 ground counts on which Lane (1987) based his estimates.

Arrival patterns (August–November)

We used data from a series of four counts conducted between early August and mid-October 1998 on the northernmost 70 km section of the beach, where wader concentrations were highest, to determine patterns of arrival for each wader species. No counts were undertaken in July and November 1998, but indications of likely wader population sizes at the start and end of the wader-arrival period in 1998 can be obtained from the July 2003 and November 2001 counts (see Fig. 2).

In 1998, waders began arriving in numbers in early August. The main arrival period was mid-August to mid-October, though arrivals continued until mid-November (Fig. 2). Aerial counts conducted during August and September in 1982 and 1986 detected similar rapid rises in wader numbers after mid-August, as did ground counts conducted over a similar period in 1982 (Fig. 3).

In 1998, many individual species showed arrival patterns similar to the overall pattern (Fig. 4). Numbers of the three principal species (great knot, bar-tailed godwit and greater sand plover) increased strongly between August and October. However, their respective peak arrival periods differed considerably. For great knot the main influx occurred in late August and early September, while most bar-tailed godwits only arrived a few weeks later. Greater sand plover numbers only started to increase rapidly after mid-September; this seems somewhat

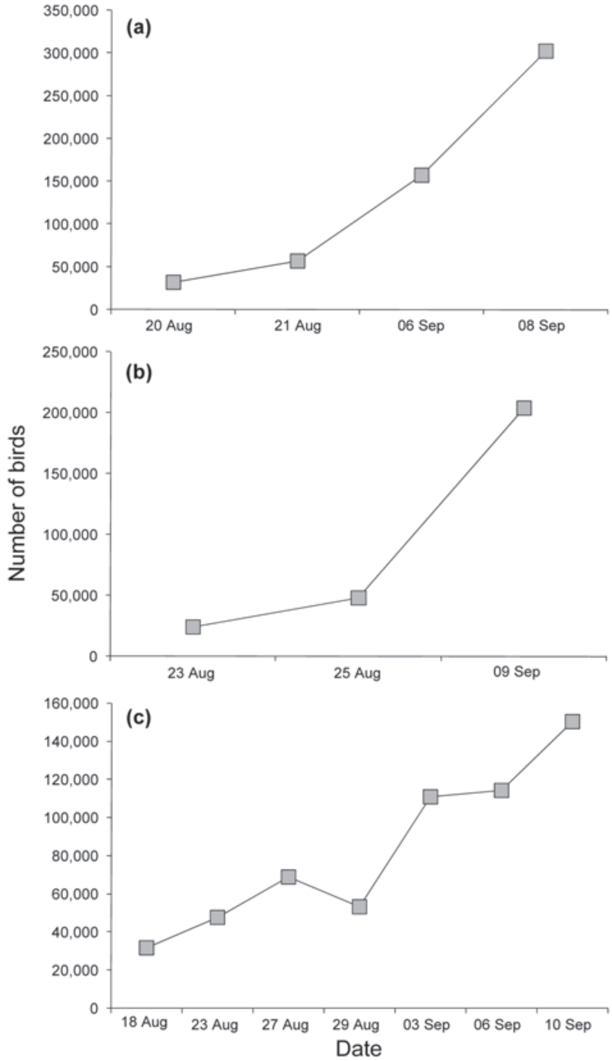

Figure 3. Series of counts along Eighty Mile Beach from 1982 and 1986 showing an increase in wader numbers during August and September: (a) wader totals from aerial surveys of the full 220 km of beach in 1982; (b) wader totals from ground surveys of the 100 km sector from Cape Missiessy to Mandora in 1982; (c) wader totals from aerial surveys of the 120 km sector from Cape Missiessy to Wallal in 1986.

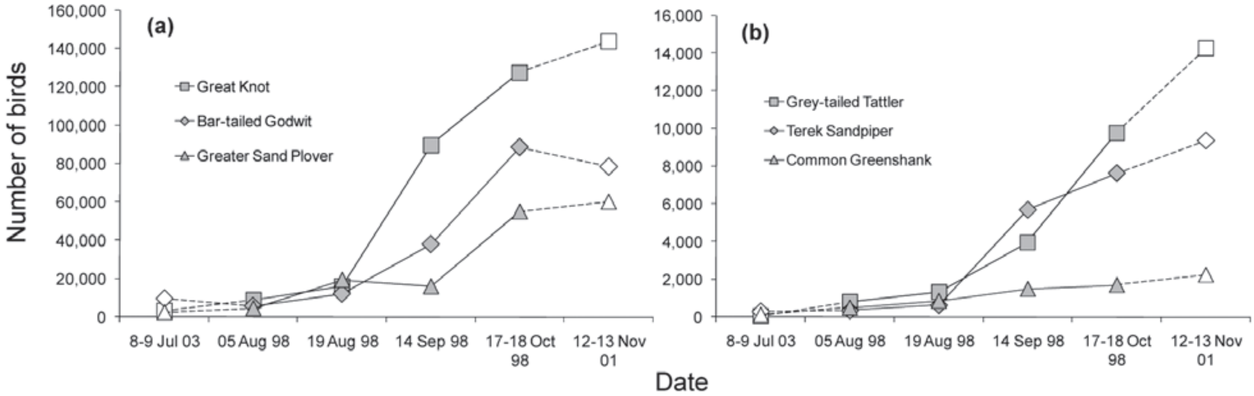

Figure 4. Data for six species that showed an overall increase in numbers along the 0–70 km section of Eighty Mile Beach during August–October 1998 (closed symbols): (a) great knot, bar-tailed godwit and greater sand plover; and (b) grey-tailed tattler, Terek sandpiper and common greenshank. Corresponding counts from July 2003 and November 2001 (open symbols) are also included.

anomalous since observations and banding data from other years all indicate an earlier arrival date for the bulk of the greater sand plover population. Numbers of Terek sandpipers and grey-tailed tattlers both built up quickly after mid-August; however, peak arrival times differed, being mid-August to mid-September for the former species and mid-September to mid-October for the latter. Common greenshanks, although much less numerous, showed an almost linear build up in numbers, with an overall average increase of 170 birds per week.

Some larger species showed no increase in numbers over the August to October period (Fig. 5) with eastern curlew (*Numenius madagascariensis*) numbers remaining stable at around 500–600 birds. This species breeds further south than most other waders, enabling it to complete its breeding cycle and undertake southward migration much earlier than species breeding in the Arctic (Minton et al. 2011). Most would already have reached north-west Australia by the time of the first count. Whimbrels arrive mainly in the first half of August, later than eastern curlews, while grey plovers show an initial influx in early August but little change thereafter (Fig. 5). This pattern differs from that at Roebuck Bay, Broome, where the main arrival of grey plovers does not occur until mid-September or later.

For red-necked stints, curlew sandpipers and red knots, the count data suggest a passage through Eighty Mile Beach (Fig. 6). Numbers of all three species peak in mid-September and then decrease in October, suggesting that many birds arriving in August are feeding up during September before proceeding further south. Evidence from banding studies supports this, at least for the first two species, as a number of birds originally banded, leg-flagged or colour-dyed in north-west Australia have either been recaptured or sighted later in the year in southern Australia (unpublished AWSG data). However, as yet there is no independent evidence of major onward movements south by red knots.

For oriental plovers, the main influx to Eighty Mile Beach in 1998 occurred from mid-September to mid-October (Fig. 7). However, observations in other years have shown that the peak arrival period for this species is

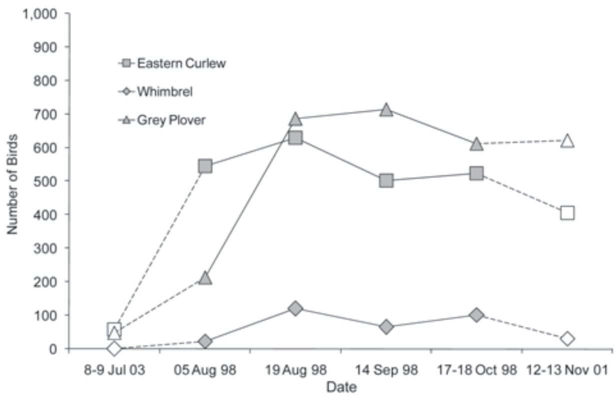

Figure 5. Data for three species (eastern curlew, whimbrel and grey plover) that showed a limited increase or relatively stable numbers in the 0–70 km sector of Eighty Mile Beach during August–October 1998 (closed symbols); corresponding counts from July 2003 and November 2001 (open symbols) are also included.

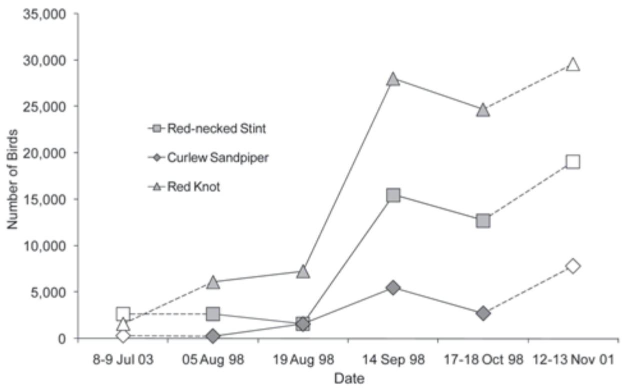

Figure 6. Data for three species (red-necked stint, curlew sandpiper and red knot) in the 0–70 km sector of Eighty Mile Beach that showed a mid-period peak in numbers during August–October 1998 (closed symbols); corresponding counts from July 2003 and November 2001 (open symbols) are also included.

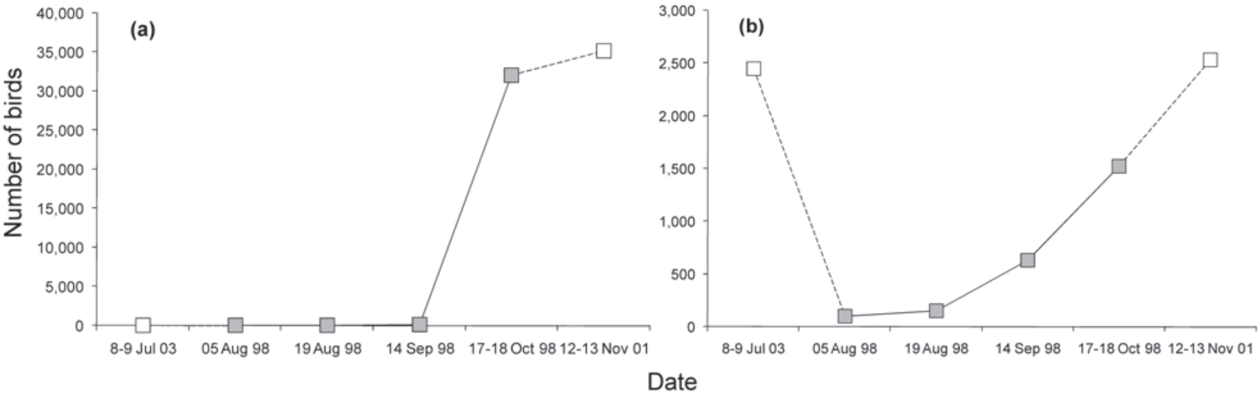

Figure 7. Changes in the numbers of (a) oriental plover and (b) red-capped plover along the 0–70 km section of Eighty Mile Beach during August–October 1998 (closed symbols); corresponding counts from July 2003 and November 2001 (open symbols) are also included.

more usually mid–late October to mid-November, considerably later than peak arrival times for most other species. Unlike most other migratory waders that commence moult of their primaries only once they reach Australia (Marchant & Higgins 1993; Higgins & Davies 1996), oriental plovers undergo much of their annual moult at some other location, presumably in Asia, before migrating to Australia. This helps explain their late arrival as well as the fact that juveniles of this species arrive at much the same time as adults.

Some red-capped plovers (*Charadrius ruficapillus*) on Eighty Mile Beach are breeding residents, but most are birds that have moved to the coast once inland breeding locations have dried up. Numbers generally follow a pattern of continuing increase throughout the August to November period as the dry season progresses (Fig. 7). However, in 2003 there was a poor wet season and high numbers were already present on the coast in July (Fig. 7).

Annual patterns of beach use by waders

Combining the above count data with other observations at Eighty Mile Beach provides a good general understanding of annual patterns of beach use by different wader species. Our observations indicate that the first adult migratory waders (predominantly eastern curlews and greater sand plovers) start to return at the end of July. Adults of most species arrive mainly between the third week in August and the end of September. Adults of species that feed away from the coast arrive later: October is the main arrival period for little curlews and oriental plovers, while oriental pratincoles normally appear in large numbers only in December. Juveniles of most species arrive a month or more after the adults. Although the first juvenile greater sand plovers arrive in late August, juveniles of most species arrive mainly in October, with some only arriving in the first half of November.

Whilst north-west Australia is the migration endpoint for most species, some, such as sanderlings and ruddy turnstones, use this area primarily as a stopover site. Many red-necked stints, curlew sandpipers and sharp-tailed sandpipers arriving in north-west Australia also move on, spending the nonbreeding season in southern Australia. Most oriental plovers and many little curlews move inland once the wet season commences.

Little movement, and hence little change in numbers, occurs between mid-November and mid-March. Eastern curlews commence their northward migration in the second week of March. Massive departures of great knot take place from about 20 March, and many greater sand plovers, together with the first cohorts of red knot, curlew sandpiper and bar-tailed godwit, start to move northwards towards the end of March. The main departures of adult birds occur in the first three weeks of April and most have left by 25 April.

Immature non-breeding birds remain in Australia. For smaller species these are exclusively one-year-old birds but, for most larger species, many two-year old and even some three- and four-year-old birds remain. These immature birds form the bulk of the wader population throughout May to July.

Superimposed on the annual pattern of migratory wader movements are sometimes less predictable weather- or season-related movements of resident wader species. For example, many red-capped plovers move to Eighty Mile Beach when inland areas dry up. Numbers of this species peaked in 1982, a time of national drought, and again in 2001 following the drying up of extensive inland ephemeral wetlands. A more consistent pattern is exhibited by pied oystercatchers that disperse to breeding territories along the southern half of Eighty Mile Beach during June to September, but form flocks at other times.

Distribution of wader species along the beach during August to November

Wader distributions along Eighty Mile Beach in October 1998 and November 2001 were remarkably consistent and show how non-uniform the spread of waders is along the beach (Fig. 8). From information on intertidal mudflat distributions (Pearson et al. 2005a) it is evident that wader concentrations are generally highest on sections of beach where the width of mudflat exposed at low tide is greatest: these sections also show the greatest species richness. Reflecting this, the northern 100 km of Eighty Mile Beach typically had 18–22 different species present within each 5-km segment, compared with 13–18 on the southernmost 90 km of beach.

In accord with earlier (and later) observations, the stretch of beach between 25 and 80 km south of Cape Missiessy (the core of the 'Anna Plains' section) held the

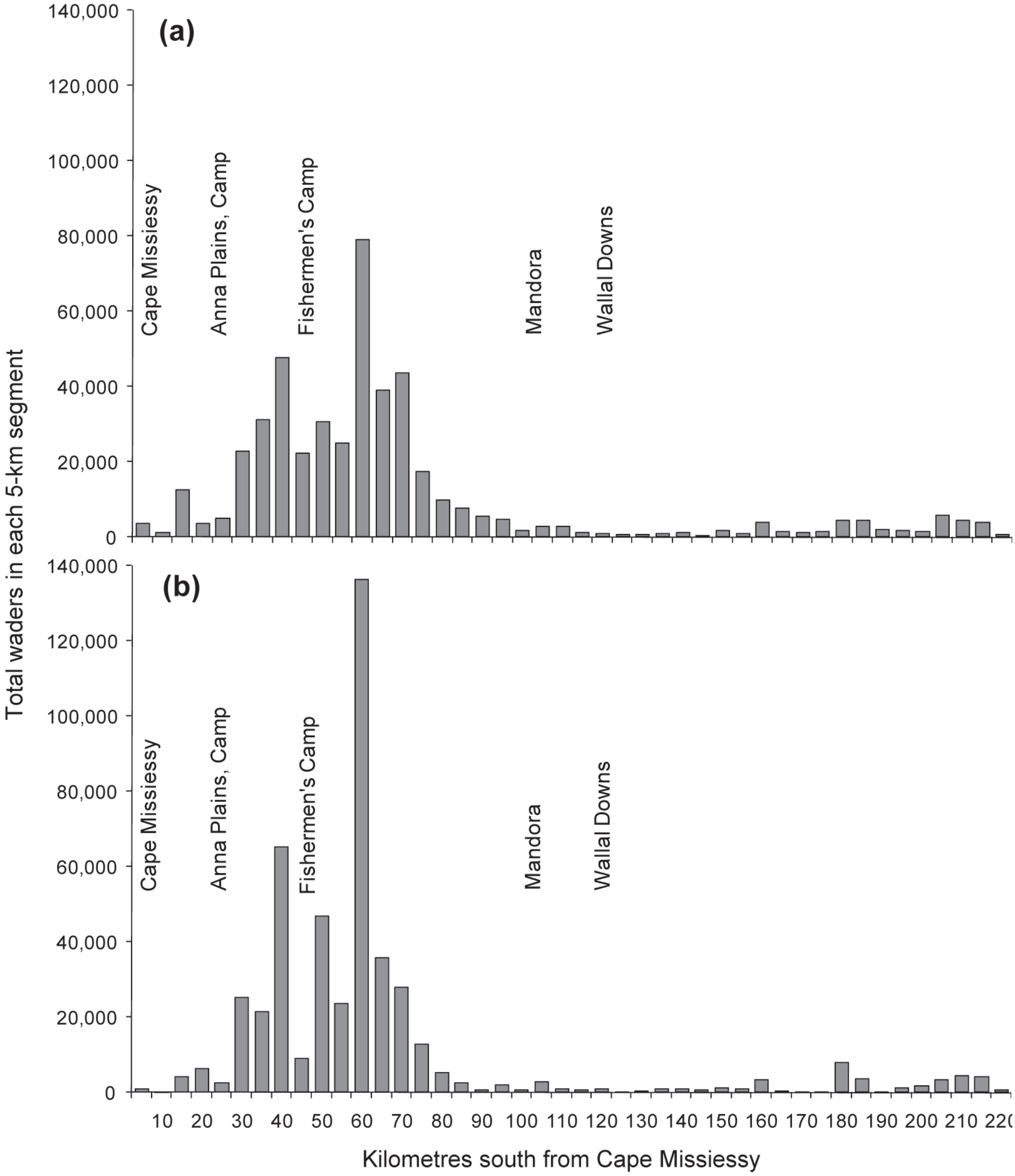

Figure 8. Distribution of waders (total number of waders in each 5-km segment) along the full 220 km length of Eighty Mile Beach: (a) 17–18 October 1998 (total count = c. 466,000); (b) 12–13 November 2001(total count = c. 472,000). Numbers on the x axis represent the upper distance for that segment, e.g. '10' corresponds to data for the segment of Eighty Mile Beach that is 5–10 km from Cape Missiessy. For clarity, only the unit for every second interval is shown.

vast majority of birds. The 369,000 waders counted in October 1998 along this 55 km stretch represented 79% of the total beach population; in November 2001 it held 410,000 birds representing 87% of the total. This gives an average density of over 7000 waders per kilometre of beach. In July, the distribution of waders along Eighty Mile Beach was largely similar to that in summer (Fig. 9).

Distributions within the 25 to 80 km section also varied widely, and in both 1998 and 2001 a marked peak occurred in the 55–60 km segment (Fig. 9). Rogers (2005)

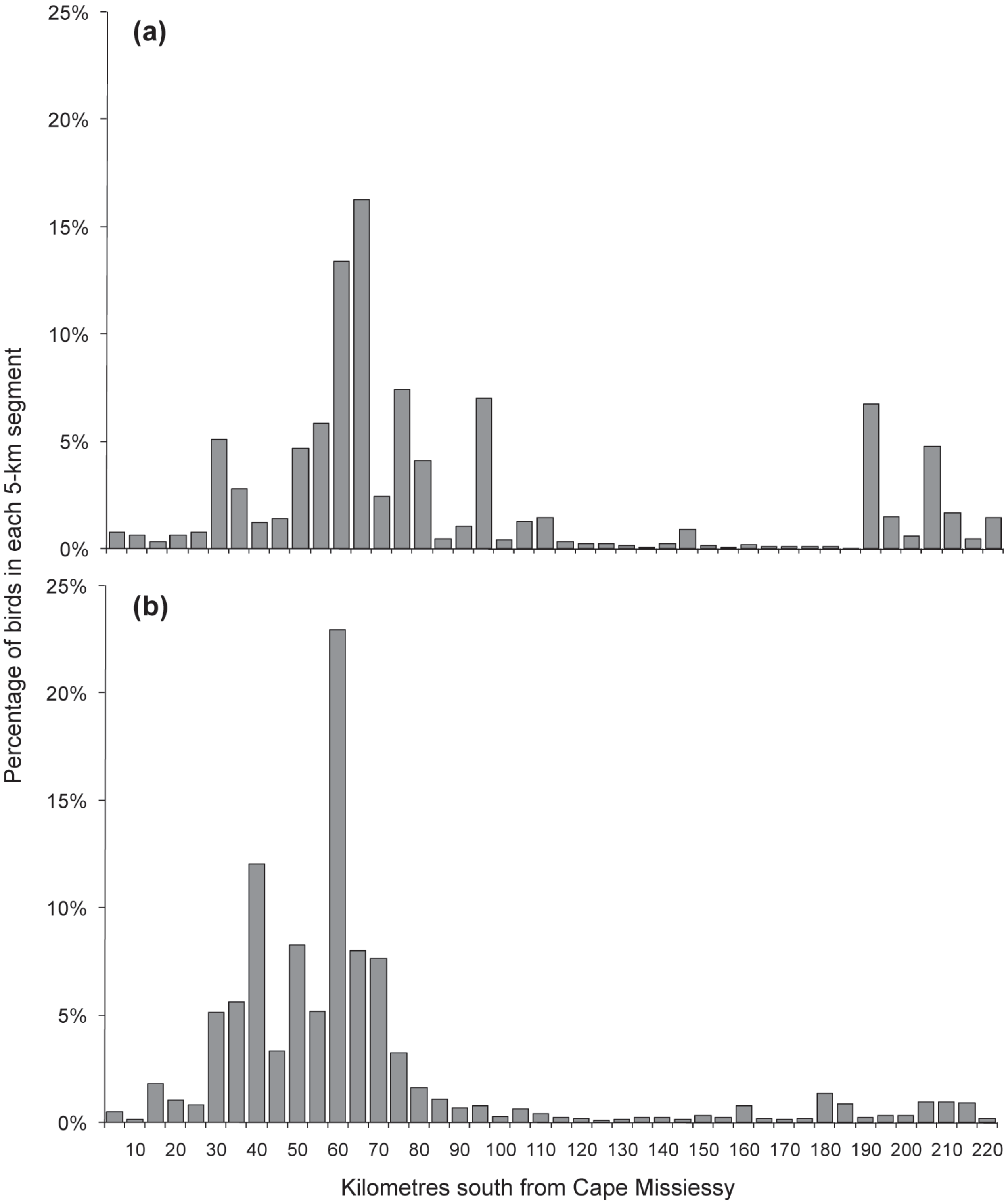

Figure 9. Percentage of total wader numbers in each 5-km segment along the full 220 km length of Eighty Mile Beach: (a) July 2003; and (b) average of counts in October 1998 and November 2001. Numbers on the x axis represent the upper distance for that segment, e.g. '10' corresponds to data for the segment of Eighty Mile Beach that is 5–10 km from Cape Missiessy. For clarity, only the unit for every second interval is shown.

found that, except on the highest tides, there is generally a good correlation between the distribution of waders feeding at low tide on the mudflats and their distribution at high tide roosts on the adjacent shoreline. However, some of the waders that feed on tidal flats in the northernmost section (0–25 km) have been observed moving along the beach as the tide advances and end up roosting further south, although the number of birds involved is small. The number of waders roosting along each 5-km segment of beach therefore appears generally representative of the numbers feeding in that segment, which implies that the intertidal zones along the 55–60 km segment are the most heavily used feeding areas along Eighty Mile Beach.

In the 40–45 km segment, wader numbers were anomalously low in both the October 1998 and November 2001 counts (Fig. 8). There was then a regularly used fisherman's campsite in this segment at the 41 km mark, and adjacent beach areas were subject to more sustained human disturbance than any other part of the Anna Plains section of beach. Counts undertaken since the campsite was abandoned in the mid-2000s showed that wader numbers in this segment have risen substantially (unpublished AWSG data), suggesting that even low levels of disturbance are enough to modify wader roosting patterns.

Data from the four counts made in 1998 (Table 1) were used to determine how wader distribution patterns change as numbers build up over the August to October arrival period. Wader distributions along the northernmost 70 to 100 km of Eighty Mile Beach, where the bulk of the wader population is concentrated, indicate that arriving birds distribute themselves along this section of beach as they do when peak numbers are present (Fig. 10). The preference birds have for the 55–60 km segment is evident throughout the arrival period.

Analysis of the count data for August to October 1998 for a number of wader species showed that their preferred locations along the Anna Plains section of beach changed little over the three-month period. Hence, species' distributions recorded in October 1998 and November 2001 can be assumed to reflect reliably their preferred roosting (and feeding; see Rogers 2005) sites. To determine each species' preferred locations, data from the October 1998 and November 2001 counts were combined. Most species show a marked preference for locations along the northern parts of Eighty Mile Beach (Figs. 11–16); however, the specific segments preferred by particular species differed quite markedly. Three species—whimbrel, sanderling and grey plover—were more generally distributed, while two others—pied oystercatcher and ruddy turnstone—were atypical, showing a distinct preference for the southern section of Eighty Mile Beach. Twelve species were present predominantly on the northern section of Eighty Mile Beach (Figs. 11–14):

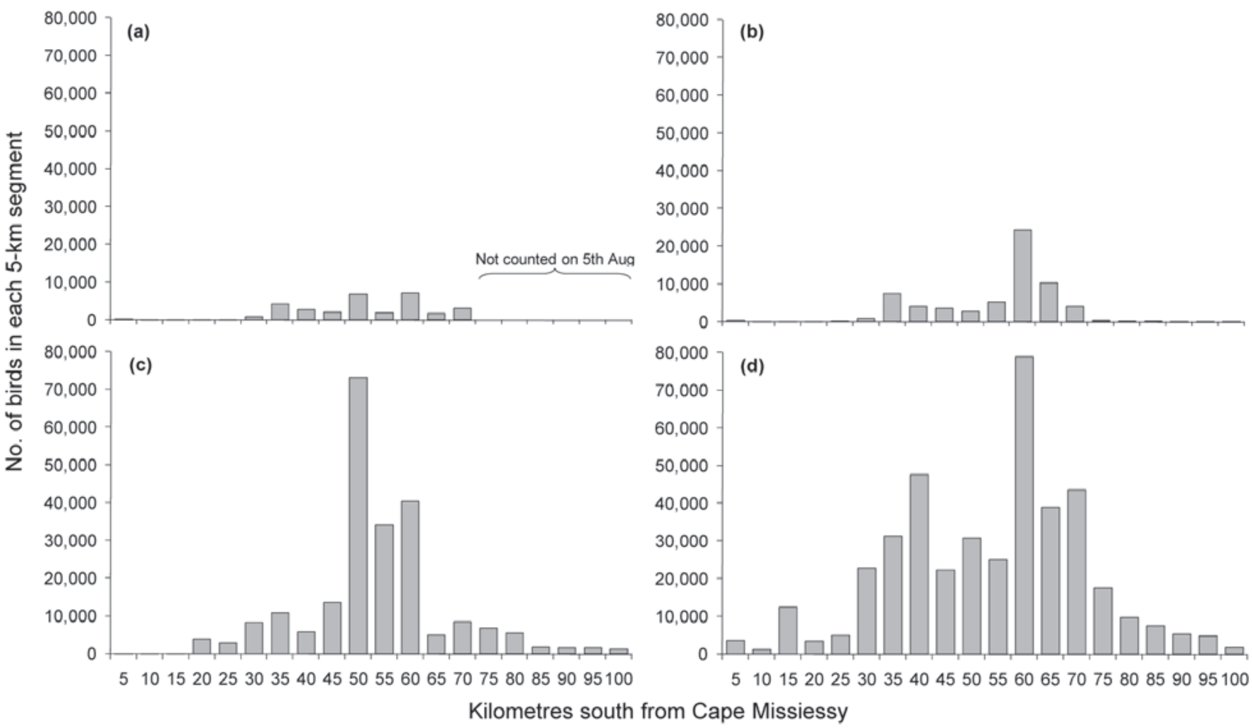

Figure 10. Distribution of all waders (total number of waders in each 5-km segment) along the 0–100 km section of Eighty Mile Beach during August–October 1998: (a) 5 August (total = c. 31,000); (b) 19 August (total = c. 65,000); (c) 14 September (total = c. 226,000); and (d) 17–18 October (total = c. 415,000). Numbers on the x axis represent the upper distance for that segment, e.g. '10' corresponds to data for the segment of Eighty Mile Beach that is 5–10 km from Cape Missiessy.

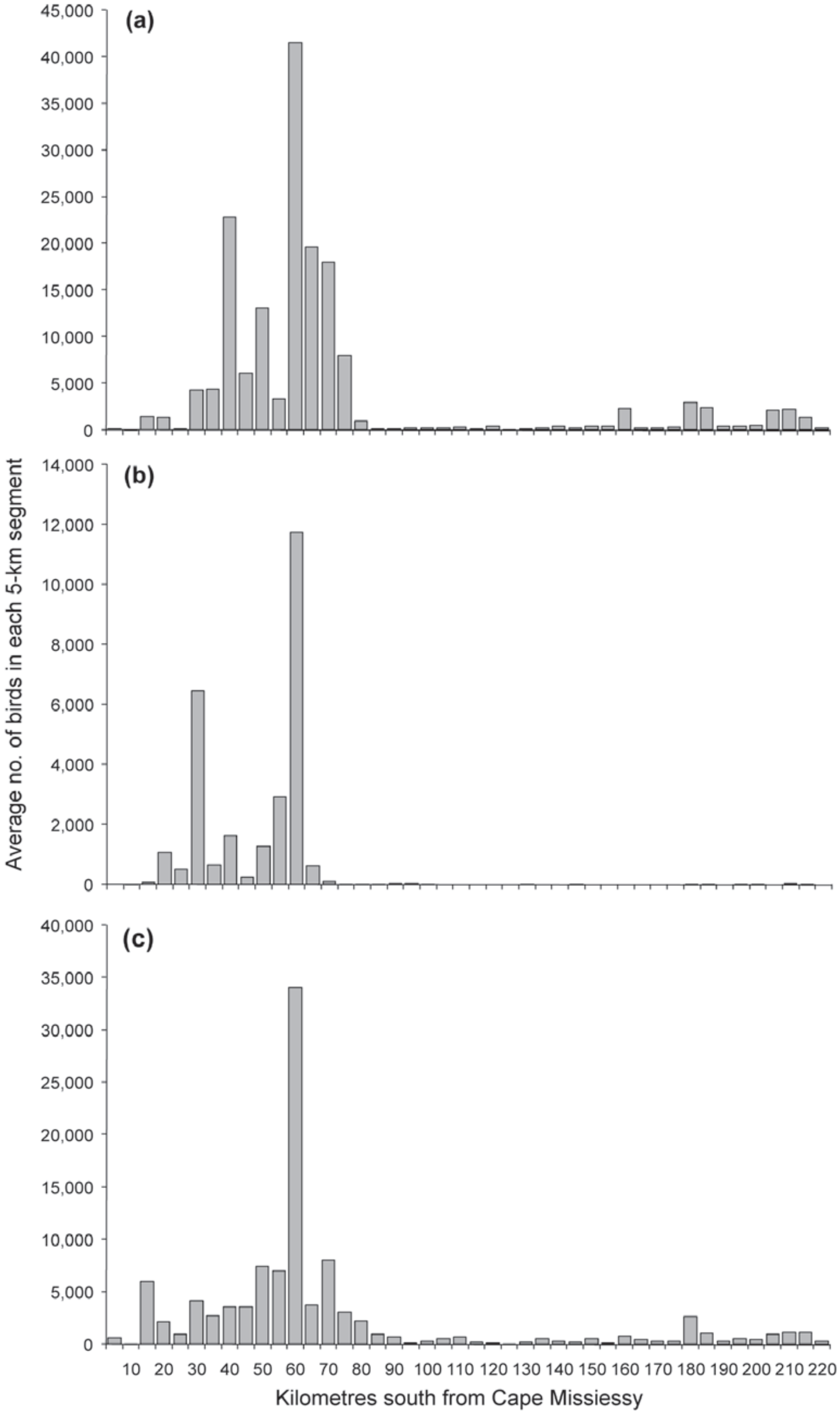

Figure 11. Distribution of wader species (average number of waders in each 5-km segment) occurring predominantly on the northern sections of Eighty Mile Beach—average of counts in October 1998 and November 2001: (a) great knot; (b)red knot; (c) bar-tailed godwit. Numbers on the x axis represent the upper distance for that segment, e.g. '10' corresponds to data for the segment of Eighty Mile Beach that is 5–10 km from Cape Missiessy. For clarity, only the unit for every second interval is shown.

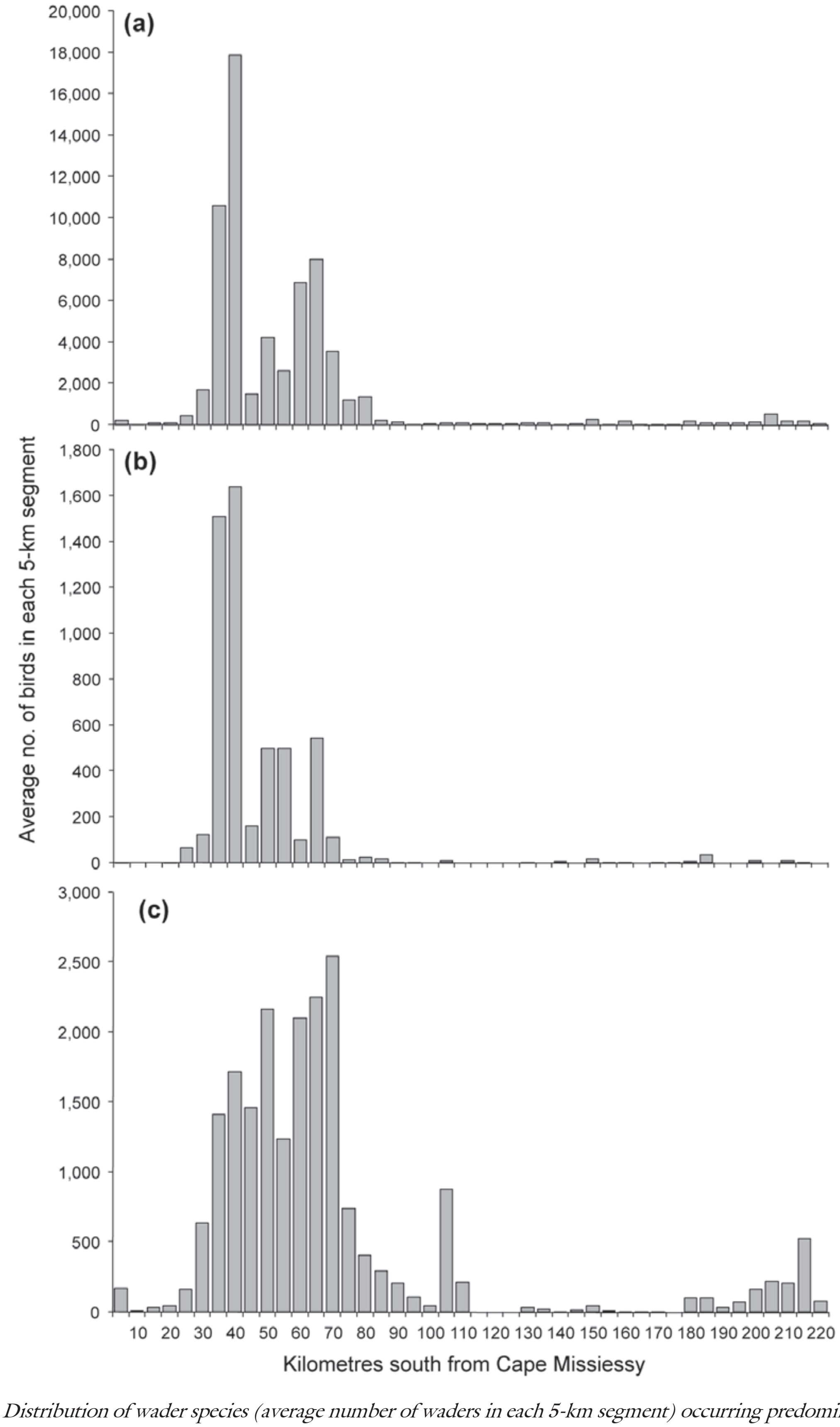

Figure 12. Distribution of wader species (average number of waders in each 5-km segment) occurring predominantly on the northern sections of Eighty Mile Beach—average of counts in October 1998 and November 2001: (a) greater sand plover; (b)curlew sandpiper; (c) red-necked stint. Numbers on the x axis represent the upper distance for that segment, e.g. '10' corresponds to data for the segment of Eighty Mile Beach that is 5–10 km from Cape Missiessy. For clarity, only the unit for every second interval is shown.

a) Great knot. This, the most numerous species, was concentrated within the 35–75 km stretch of beach (Fig. 11). The 35–40 km and 55–75 km sections held 67% of the total population, with particularly high numbers in the 55–60 km segment. Several flocks totalling around 3000 birds were present in the 0–20 km section and a further 2000 to 3000 birds were present in sections nearer Cape Keraudren. Though few birds were recorded on the 80–150 km section, great knot were present on every 5-km segment along the entire beach.

b) Red knot. Unlike great knot, this species was confined to certain favoured stretches (Fig. 11), and usually occurred in tight flocks. The 55–60 km segment was again the preferred stretch of beach, with a secondary peak in the 25–30 km segment. The beach south of the 65–70 km segment held virtually no red knot. Distribution patterns in November 2001 and October 1998 were very similar.

c) Bar-tailed godwit. This species was fairly evenly distributed across the 10–90 km section, with typically 3000–6000 birds in each 5-km segment (Fig. 11). The 55–60 km segment was a notable exception, however, holding 21,350 birds in October 1998 and 46,620 in November 2001—this latter figure represented almost half the bar-tailed godwits on the entire beach. This species was present in almost all other segments, generally in small numbers, although over 1000 birds were present in several 5-km segments towards Cape Keraudren in the south.

d) Greater sand plover. Like other common species, these birds occurred mainly on the northernmost 70 km of beach; however, within this section their preferences for specific segments were slightly different (Fig. 12). The main concentration (44% of all birds) occurred in the 30–40 km section, although numbers were still high in the 55–65 km section. Though also present in every segment south of the 70 km mark, many of these held less than a hundred birds.

e) Curlew sandpiper. The overall distribution pattern for this species was most similar to the greater sand plover. Like this species, they favoured the 30–40 km section of beach (Fig. 12) and largely avoided sections of beach south of the 80 km mark.

f) Red-necked stint. This species differs from the previous five species in having a more pronounced bimodal distribution (Fig. 12). Whilst the northern (25–110 km) sections of beach still held the most birds, small flocks totalling just over 1500 birds were present at the southern end of the beach between the 175 km mark and Cape Keraudren. This species' distribution across the 25–110 km section lacked the peaks and troughs evident in the distributions of the previous five, larger, species.

g) Terek sandpiper and grey-tailed tattler. These species had very similar distributions, both being concentrated in the 20–70 km section, and favouring the 35–40 km segment (Fig. 13). Except in November 2001, when 500 tattlers roosted near Cape Missiessy, very few birds of either species were present in the 0–20 km and 100–220 km sections.

h) Common greenshank. This species had a more northerly distribution distinctly different from those of the species discussed above (Fig. 13). Most birds occurred in the 25–40 km section and few in the 55–65 km section favoured by most other species. Except for a small concentration around Wallal (135–155 km), very few birds were present in sections south of the 65 km mark.

i) Eastern curlew. This species favoured a more southerly group of segments in the Anna Plains section than most other waders (Fig. 14). The main flocks occurred in the 45–90 km section; nevertheless some birds were present in each segment north of this. Small numbers were also present on the southernmost 50 km of beach.

j) Red-capped plover. This species occurred along the entire length of Eighty Mile Beach, but was most common in the northern half, with a peak in the 20–30 km section (Fig. 14). This non-uniform distribution was consistent with the fact that few birds were on breeding territories when counts were undertaken.

k) Oriental plover. As already noted, oriental plover typically feed inland, moving to the beach in hot weather. Therefore their distribution along the beaches (Fig. 14) was probably largely determined by conditions immediately inland; for example, the species' prevalence in the 20–95 km section is most probably due to the presence of extensive grasslands on Anna Plains Station, which abuts this section of coast.

Three species had a much more uniform pattern of distribution than the species discussed above (Fig. 15):

a) Whimbrel. Even though this species and the eastern curlew are the two largest waders on Eighty Mile Beach, their distribution patterns were distinctly different. Like many other waders, the latter has a northerly distribution whereas whimbrels were much more uniformly distributed: the only significant peak in concentration occurred close to Cape Missiessy (Fig. 15).

b) Sanderling. Although found right along the beach, this species occurred mainly south of the 70 km mark, with most records from the 85–115 km section and the southernmost 30 km of beach (Fig. 15). As discussed earlier, the substrates in the above areas are much sandier than substrates further north and better suit the sanderling's distinctive feeding technique.

c) Grey plover. This species showed the most uniform distribution, with all segments containing at least a few birds (Fig. 15). The main concentrations were in the north, with peaks in the 25–30 and 55–60 km segments, and towards Cape Keraudren in the south, with a peak in the 200–205 km segment.

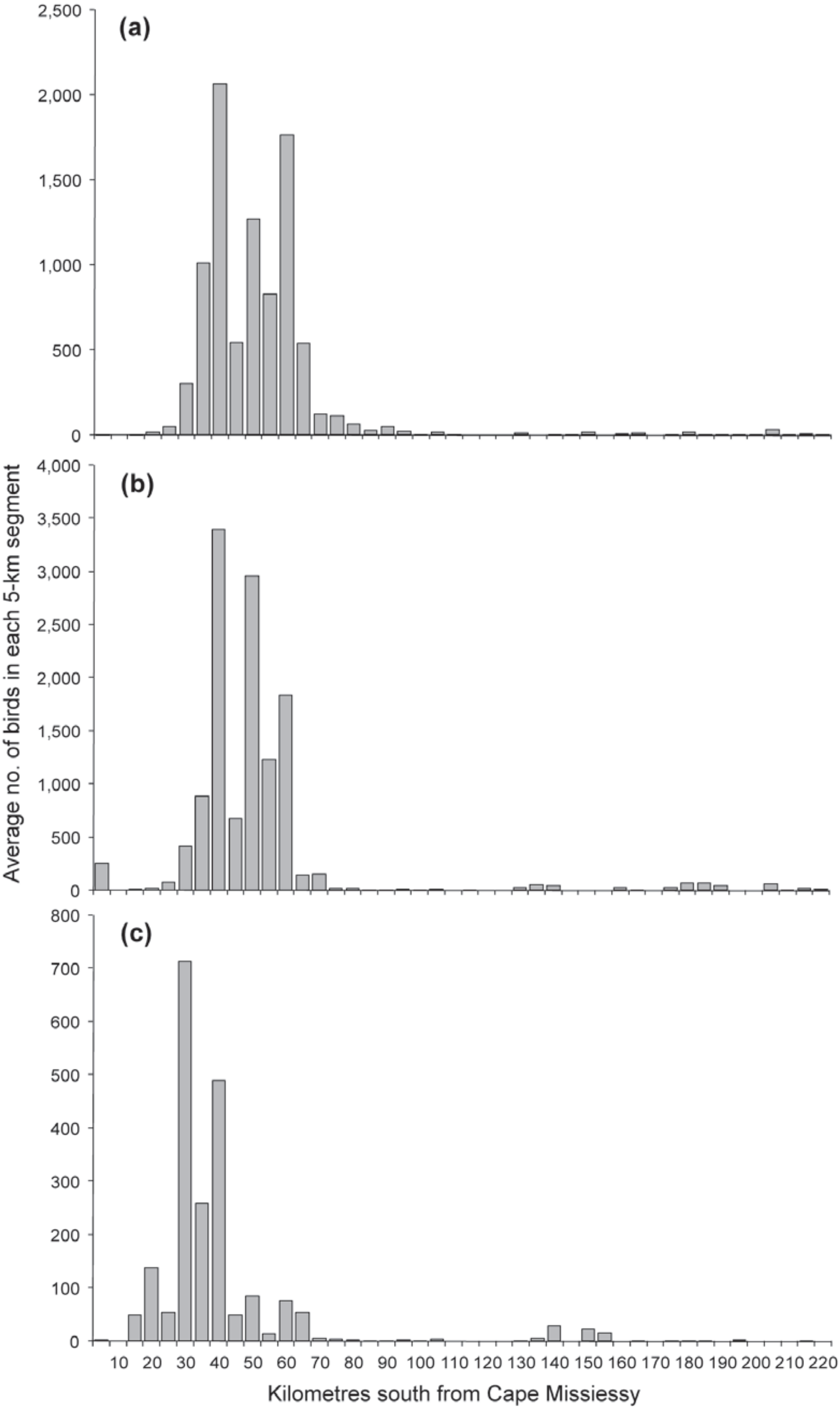

Figure 13. Distribution of wader species (average number of waders in each 5-km segment) occurring predominantly on the northern sections of Eighty Mile Beach—average of counts in October 1998 and November 2001: (a) Terek sandpiper; (b)grey-tailed tattler; (c) common greenshank. Numbers on the x axis represent the upper distance for that segment, e.g. '10' corresponds to data for the segment of Eighty Mile Beach that is 5–10 km from Cape Missiessy. For clarity, only the unit for every second interval is shown.

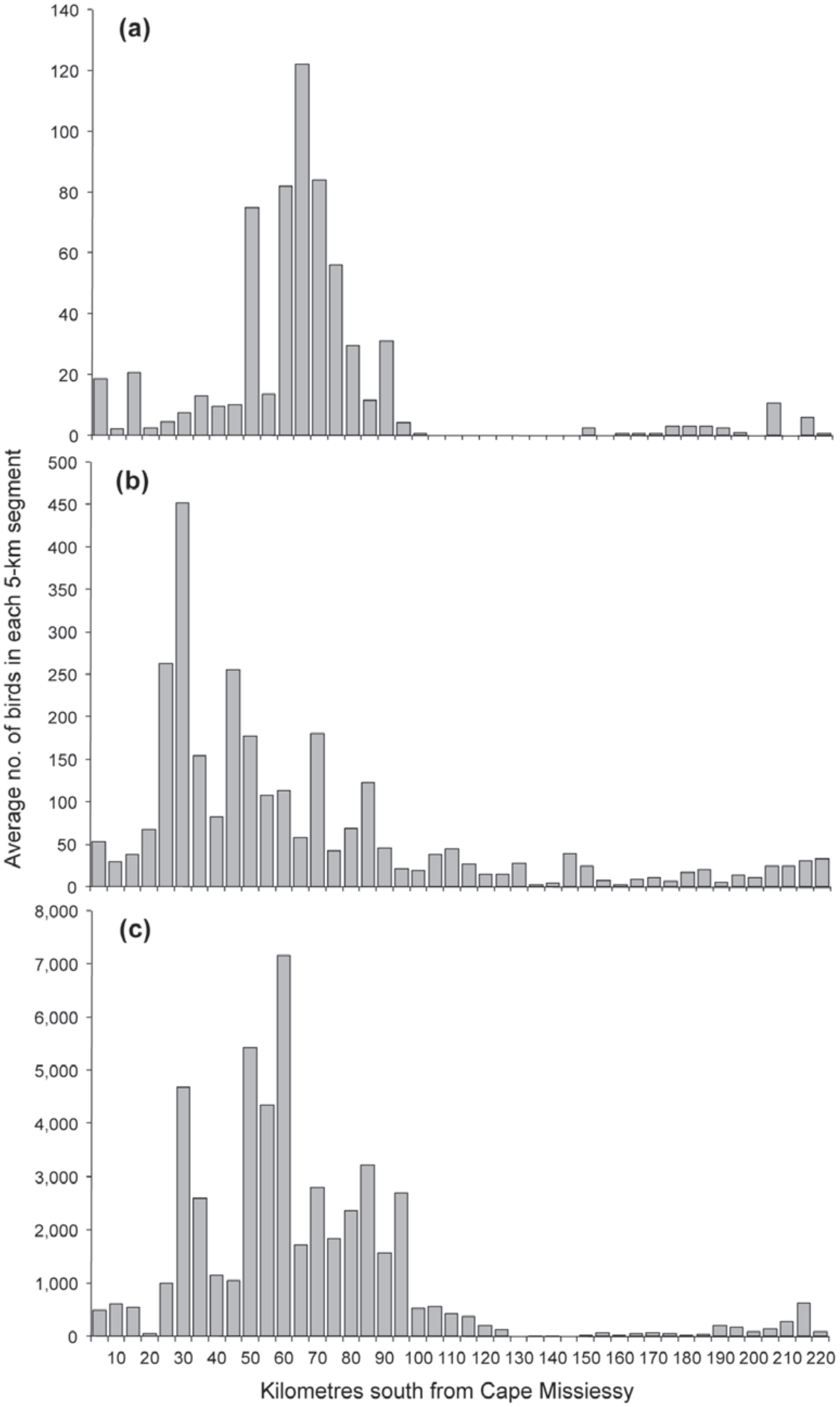

Figure 14. Distribution of wader species (average number of waders in each 5-km segment) occurring predominantly on the northern sections of Eighty Mile Beach—average of counts in October 1998 and November 2001: (a) eastern curlew; (b)red-capped plover; (c) oriental plover. Numbers on the x axis represent the upper distance for that segment, e.g. '10' corresponds to data for the segment of Eighty Mile Beach that is 5–10 km from Cape Missiessy. For clarity, only the unit for every second interval is shown.

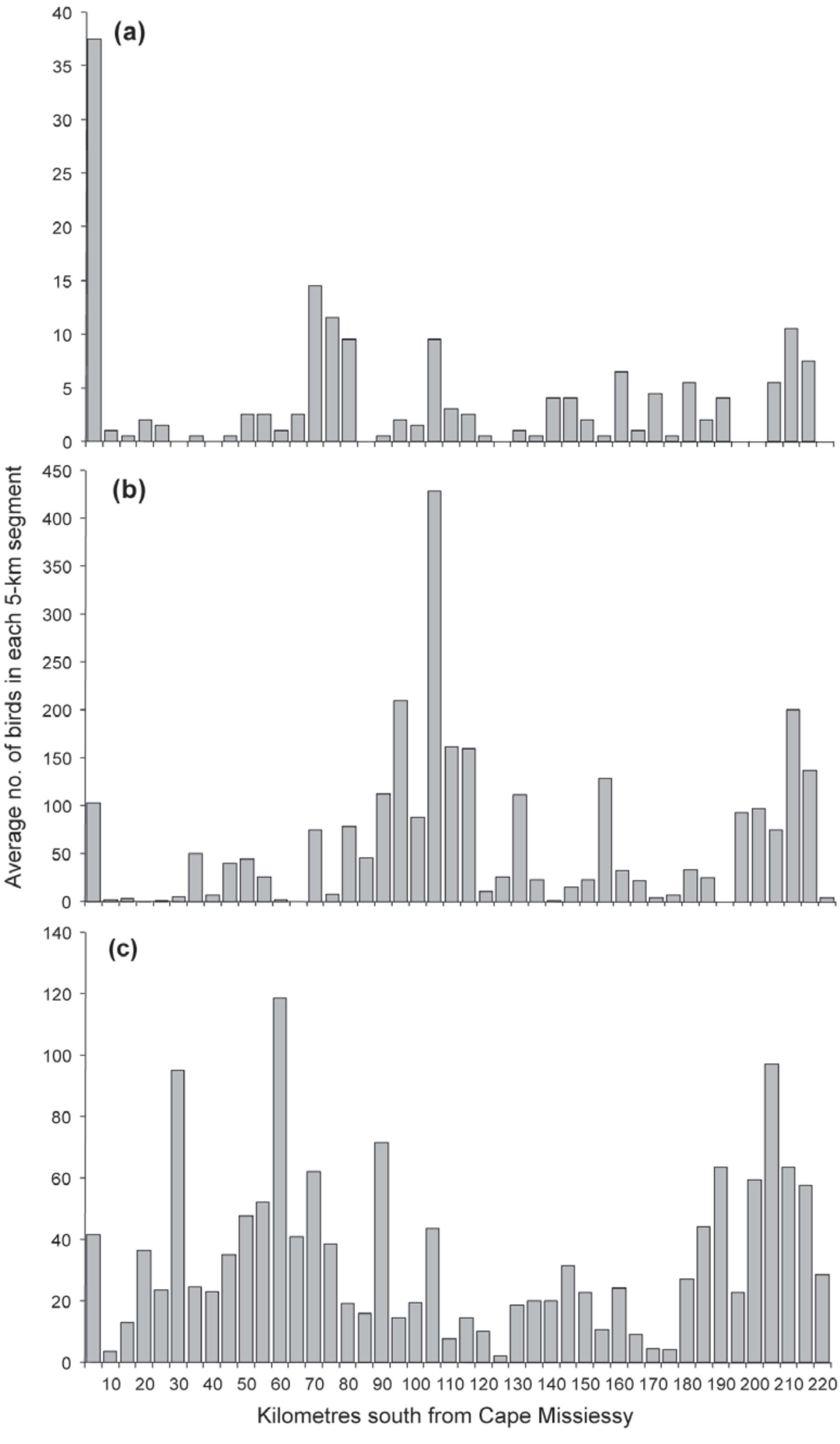

Figure 15. Species distributed more evenly along Eighty Mile Beach—average number of waders counted in October 1998 and November 2001: (a) whimbrel; (b) sanderling; (c) grey plover. Numbers on the x axis represent the upper distance for that segment, e.g. '10' corresponds to data for the segment of Eighty Mile Beach that is 5–10 km from Cape Missiessy. For clarity, only the unit for every second interval is shown.

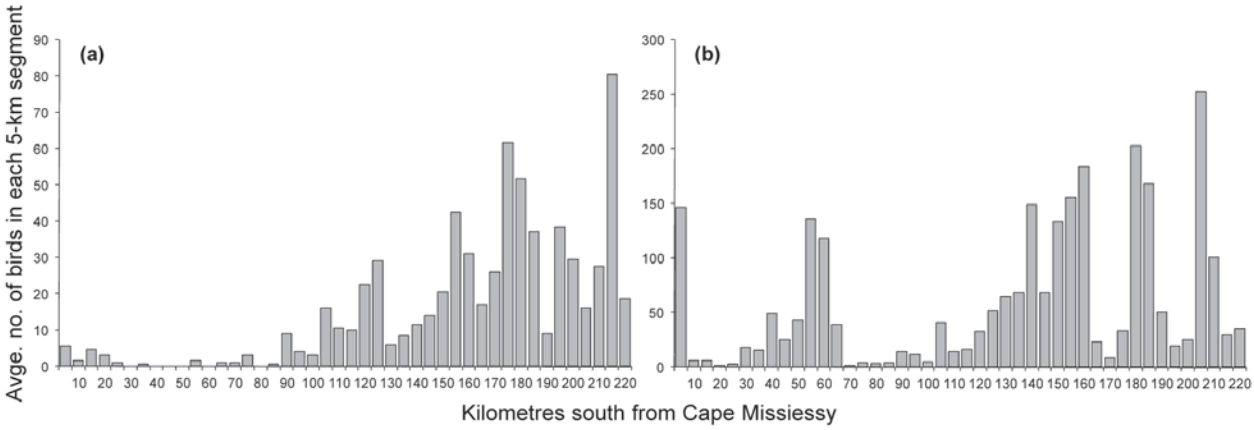

Figure 16. Distribution of wader species occurring predominantly on the southern sections of Eighty Mile Beach—average numbers of waders counted in October 1998 and November 2001: (a) pied oystercatcher; (b) ruddy turnstone. Numbers on the x axis represent the upper distance for that segment, e.g. '10' corresponds to data for the segment of Eighty Mile Beach that is 5–10 km from Cape Missiessy. For clarity, only the unit for every second interval is shown.

Two wader species were atypical in that they preferred the more southerly segments of Eighty Mile Beach (Fig. 16):

a) Pied oystercatcher. This species' distribution was the inverse of that for most other species, with most birds occurring in the southern half of the beach (100–220 km). Though most birds were in small flocks, some were still in pairs on breeding territories.

b) Ruddy turnstone. This species was also most numerous along the southern half of Eighty Mile Beach, where there are a number of small rocky outcrops. However, unlike the former species, turnstones were also quite numerous in the 25–65 km section as well as on the rocky outcrop at Cape Missiessy.

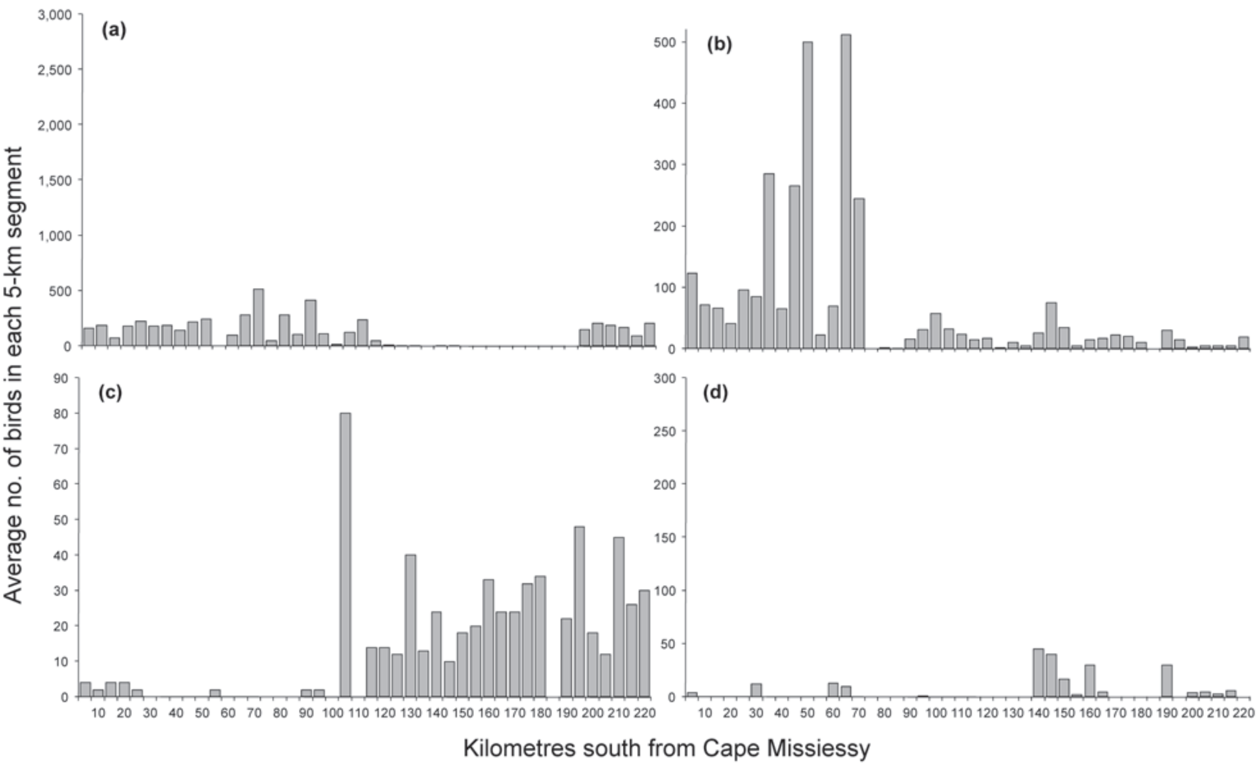

Figure 17. Distribution of wader species(average number of waders in each 5-km segment) along the full 220 km length of Eighty Mile Beach on 8–9 July 2003: (a) red-necked stint; (b) red-capped plover; (c) pied oystercatcher; (d) ruddy turnstone. Numbers on the x axis represent the upper distance for that segment, e.g. '10' corresponds to data for the segment of Eighty Mile Beach that is 5–10 km from Cape Missiessy. For clarity, only the unit for every second interval is shown.

Distribution of wader species along the beach in July

For most waders, distributions along Eighty Mile Beach in July 2003 were similar to those in October 1998 and November 2001, though with a less marked peak in the 25–80 km section. Red-necked stints and red-capped plovers were more evenly distributed along the beach than at other times, while ruddy turnstones and pied oystercatchers showed an even more marked preference for the southern half of the beach (Fig. 17). Notable in July 2003 was the presence of 192 breeding pairs of pied oystercatchers, 181 of which were on the southernmost 110 km of beach. Most were nesting at the top of the wide sandy beaches or on the seaward side of sand dunes fringing the beach. Most birds probably had eggs, or were about to lay, though one newly-hatched chick was seen. This was probably the largest concentration of breeding pied oystercatchers outside Victoria and Tasmania.

CONSERVATION ISSUES

For most migratory waders spending their nonbreeding season on Eighty Mile Beach, northward migration begins with a lengthy, uninterrupted flight to East Asia. There they replenish their fat reserves before moving on to breeding grounds further north (Barter 2003). Extensive reclamation and development is presently occurring in traditional wader staging areas in East Asia and this is having a seriously detrimental effect on wader populations (Barter 2003; Milton et al. 2003). To minimise the adverse impacts of these developments it is important that birds leave Australia in the best condition possible. This implies that birds should be subject to minimal disturbance at their nonbreeding sites in Australia, particularly during the weeks immediately prior to their departure north. Hence the ecological integrity/quality of feeding areas along Eighty Mile Beach needs to be preserved and disturbance of both feeding and roosting birds minimised.

Threats to the ecology of beaches and mudflats along Eighty Mile Beach have been reviewed by Pearson et al. (2005b). The mudflats are subject to disturbance during cyclones; however, whilst these can cause significant localised changes to the benthos (Honkoop et al. 2006), no long-lasting impacts on the mudflats' suitability as wader feeding grounds have been noted. Of potentially more importance are the direct and indirect impacts associated with fishing and the harvesting of shellfish along the beach, particularly on feeding and, more importantly, roosting waders. Even seemingly minor disturbances, such as the presence of the fisherman's campsite at the 41 km mark during the 1998 and 2001 counts, may have significant effects on the number of birds roosting on the beach. Disturbances that lead to waders roosting further than necessary from preferred feeding grounds are energetically unfavourable and therefore undesirable (Rogers et al. 2006a). However, even more detrimental are disturbances that cause waders to take flight in alarm. At Roebuck Bay, the energy expended by great knots and red knots on commuting to roosts and at roosts is 17–28% of the birds' total energy budget, with energy costs of alarm flights being 3–6 times more important than commuting energy costs (Rogers et al. 2006a). Intensified use of roosting beaches for recreational activities could be expected to increase the frequency of alarm flights, a particularly detrimental outcome when birds are trying to build fat reserves prior to departure northward. At present, fishing-related activities are infrequent on Eighty Mile Beach, and the proposed establishment of an Eighty Mile Beach Marine Park, incorporating the main wader feeding grounds along the northern part of Eighty Mile Beach, should further reduce the adverse effects of the harvesting of marine resources.

Realistically it is impossible to totally exclude people from beaches. At present, access to Eighty Mile Beach occurs primarily at Wallal Downs and near Mandora. As the distributional data show, these areas are of less importance to waders than areas further north. However, pressures to access Eighty Mile Beach at other points will undoubtedly increase. Therefore measures need to be introduced to restrict human access to the northern parts of Eighty Mile Beach, particularly the 25–60 km section, especially later in the season when waders are building up fat reserves. Protection is also desirable for pied oystercatcher breeding areas around Wallal and along the southern half of Eighty Mile Beach.

A potentially disastrous threat to Eighty Mile Beach is oil spills. Oil washing ashore detrimentally affects coastal birdlife, including migratory waders. Waders tend to vacate polluted beaches so few succumb to the heavy oiling that kills many diving birds like auks and cormorants (Bourne et al. 1967; Evans et al. 1993). Nevertheless, the plumage of many species, especially those feeding in the surf zone, is susceptible to oiling (Burger 1997), and at least 25,000 partly-oiled waders were recorded along the Arabian Gulf coast after the 1991 Gulf War (Evans et al. 1993). Oiled waders spend more time preening and less time feeding, which can lead to weight loss and kidney damage (Chapman 1984). In pre-migration periods oiled birds show reduced rates of weight gain (Burger 1997; Evans et al. 1993), a major problem for waders trying to build their fat reserves before departing on lengthy migrations. Oil also has a long term impact on intertidal mudflats and their wader carrying capacity, with full recovery in diversity and abundance of intertidal biota generally taking three to five years (Jones et al. 1998; Price 1998).

The Department of Sustainability, Environment, Water, Population and Communities (2012) recognises that oil releases from offshore oil and gas rigs (such as the 2009 well blowout in the Montara Oilfield off northern Australia) pose a potential threat to all north-west Australian beaches. Oil spills from ships are viewed as less of a threat (Department of Sustainability, Environment, Water, Population and Communities 2012) but do occur: in 1991, 20,000 tonnes of light crude spilled from the *Kirki* when it broke in half 40 km off the West Australian coast (Flood 1992). A detailed oil spill response plan has been prepared by the Department of Transport (2010). However, this contains no specific provisions for dealing with the impact of oil on the birdlife of Eighty Mile Beach. Since wader distributions vary markedly along this beach, and also seasonally, the nature and severity of oil-related impacts on coastal birdlife will depend on where, when and in what quantities oil arrives on the shore. It is strongly recommended that the response to any oil spill impacting Eighty Mile Beach be tailored to local conditions and take into account that clean-up activities can themselves have a pronounced disruptive effect on wader behaviour (Andres 1997; Burger 1997).

ACKNOWLEDGEMENTS

Thanks are due to all who participated in the ground and aerial surveys of Eighty Mile Beach described here, in particular the late Don Jeans, the pilot on all the aerial surveys and counts in the early 1980s. The extensive help and financial assistance provided throughout by the Department of Parks and Wildlife (then the Department of Conservation and Land Management of Western Australia; CALM) is much appreciated. Anna Plains Station kindly allowed Wader Expeditions to be based on their land and, together with Mandora and Wallal Downs Stations, kindly permitted access to the beach via their properties. Kandy Curran of the Roebuck Bay Working Group helped with information on oil spill response plans. Mark Barter provided valuable comments on an earlier draft.

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Feral cat control as part of *Rangelands Restoration* at Lorna Glen (Matuwa), Western Australia: the first seven years

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ABSTRACT

The *Rangelands Restoration* program at the Lorna Glen Conservation Reserve aims to achieve the successful reconstruction and conservation of biodiversity for the area. It forms part of the potential expansion of the Department of Parks and Wildlife's Western Shield fauna conservation program into the rangelands. However, reintroduction of native species to strategic areas can only occur if an effective, sustained feral cat control can be achieved. We tested the hypothesis that an effective and sustained feral cat control strategy (less than 10 cats per 100 km of track-transect) was achievable with an annual winter baiting program using the *Eradicat*® feral cat bait. Six of the seven baiting programs conducted at Lorna Glen over the period 2003–09 resulted in significant reductions in indices of cat activity. The efficacy of these programs confirms previous findings from other sites in the arid and semi-arid zone that baiting for feral cats in the winter months, when prey availability is low, can effectively control cat numbers. Rainfall will affect baiting outcomes and supplementary trapping campaigns can be used to augment effective cat control.

INTRODUCTION

The Australian arid zone has experienced a high rate of native mammal decline following European settlement. Since the 1920s, approximately 33% of all mammals and about 90% of medium-sized mammals (35–5500 g adult body-weight range) have either suffered dramatic range contractions or are extinct (Burbidge & McKenzie 1989). Many of these species are now restricted to several offshore islands and others, due to small population sizes and restricted geographic ranges, are vulnerable to extinction. A number of causes have been proposed to explain this decline. These include changed fire regimes, competition from introduced herbivores, disease, variability in weather and site fertility and predation by introduced predators, specifically the feral cat, *Felis catus*, and fox, *Vulpes vulpes* (see Burbidge & McKenzie 1989; Dickman 1996a, 1996b; Environment Australia 1999; Johnson et al. 1989; Morton 1990). Predation by feral cats has also been demonstrated to threaten the continued survival of many other native species that persist at low population densities (e.g. Risbey et al. 2000; Smith & Quin 1996) and has been identified as one of the major obstacles to the reconstruction of faunal communities, as it has prevented the successful reintroduction of a number of species to parts of their former range (Christensen & Burrows 1995; Dickman 1996b; Environment Australia 1999; Gibson et al. 1995). The suppression of introduced predators is therefore a critical component of successful reintroduction, recovery or maintenance of populations of small to medium-sized native fauna (Christensen & Burrows 1995; Fischer & Lindenmayer 2000; McKenzie et al. 2007).

Lorna Glen Conservation Reserve, a former pastoral lease, was acquired by the Department of Parks and Wildlife (DPaW) in 2000, with the objective of restoring the natural ecosystem by: (1) controlling introduced predators, in particular feral cats as foxes are rare or absent in this arid environment; (2) controlling introduced herbivores; (3) introducing ecologically appropriate fire regimes; and (4) reintroducing native mammals to the area. The site is typical of the arid zone rangeland ecosystems from which many Australian medium-sized native mammals have declined or become extinct. The project, known as *Rangelands Restoration*, aims to reintroduce 11 species of mammals to Lorna Glen over the next ten years (Dunlop & Morris 2009). The 11 species are: bilby (*Macrotis lagotis*), brushtail possum (*Trichosurus vulpecula*), rufous hare-wallaby (*Lagorchestes hirsutus*), burrowing bettong (*Bettongia lesueur*), golden bandicoot (*Isoodon auratus*), western barred bandicoot (*Perameles bougainville*), numbat (*Myrmecobius fasciatus*), red-tailed phascogale (*Phascogale calura*), chuditch (*Dasyurus geoffroii*), Shark Bay mouse (*Pseudomys fieldi*) and pale field-rat (*Rattus tunneyi*). If successful, this will not only improve the conservation status of these species, but also reinstate some of the ecological processes that these animals once provided to the rangelands (Dunlop & Morris 2009). The project forms part of the potential expansion of DPaW's *Western*

Shield program, which aims to achieve the successful reconstruction and conservation of faunal biodiversity of this area, in the rangelands. However, reintroduction of native species to strategic areas can only occur if effective and sustained feral cat control can be achieved.

Poison baiting is recognized as the most effective method for controlling feral cats on mainland Australia by most practitioners (Algar & Burrows 2004; Algar et al. 2007; Environment Australia 1999; Short et al. 1997). As part of *Rangelands Restoration*, an ongoing campaign to bait feral cats has been conducted, in order to develop and prove baiting strategies that provide for sustained and effective feral cat control at Lorna Glen. The project follows research programs and operational feral cat baiting trials conducted in the interior arid zone at the Gibson Desert and Wanjarri Nature Reserves (Algar & Burrows 2004; Burrows et al. 2003). This earlier research in the arid and semi-arid zones indicated that the effectiveness of baiting programs for feral cats is maximized by distributing baits during the cool, dry winter periods (Algar & Burrows 2004). At this time, the abundance and activity of all prey types, in particular predator-vulnerable young mammals and reptiles, is at its lowest, and bait degradation due to rainfall, ants and hot, dry weather is significantly reduced.

The hypothesis tested was that an effective and sustained feral cat control strategy was achievable with an annual winter baiting program that distributed feral cat baits at a density of 50 baits km^{-2}. A benchmark of 'reducing and maintaining cat numbers to less than 10 per 100 km of track-transect (hereafter referred to as 10 cats per 100 km) had previously been proposed as the level at which reintroductions of native species could potentially occur (Morris et al. 2004). Thus the efficacy of the baiting strategy on feral cat activity could be assessed against this predetermined benchmark. Monitoring the rate of cat reinvasion and distribution provided an indication of the effectiveness of this strategy over time or whether there was a need for additional control effort (e.g. trapping and on-track baiting) to maintain low numbers of feral cats. In this paper we report the impact of this feral cat control strategy over the first seven years (2003–2009) of the project.

METHODS

Site description

Lorna Glen pastoral station was purchased by DPaW in 2000 for the creation of a conservation reserve; its current status is Unallocated Crown Land. Lorna Glen was destocked over a period of three years. The reclaimed pastoral lease is situated approximately 180 km east-north-east of Wiluna at 26° 13' S, 121° 33' E and is 2350 km^2 in area. The station has common boundaries with Wongawol, Yelma, Millrose and Granite Peak pastoral leases as well as a small area of Unallocated Crown Land that separates Lorna Glen from Earaheedy pastoral lease. The lease straddles the boundary between the Murchison and the Gascoyne Bioregions (IBRA; Thackway & Cresswell 1995). The study site comprises two main land systems: (1) Bullimore—sand plains and dunes dominated by spinifex (*Triodia* spp.); and (2) Sherwood—breakaways and stony plains dominated by mulga and other acacia shrublands. The vegetation unit most common across the station is the hummock grasslands, shrub steppe (Beard 1974): *Acacia aneura* (mulga) and *Eucalyptus kingsmillii* over *Triodia basedowii* (hard spinifex). Smaller areas of low *A. aneura* woodland are also present. The geology and geomorphology of the area is described by Mabbut et al. (1963).

The climate of the area is characterized by low and erratic rainfall with the annual average of 255 mm (Bureau of Meteorology records 1940–2003). Annual rainfall in 2003, 2007 and 2008 approximated the average (255 mm; 1940–2002), in 2004 and 2006 it was significantly greater than average, and in 2005 and 2009 annual rainfall was significantly less than the average (Table 1). Average maximum daily temperatures range from 19.4 °C in winter to 39 °C in summer.

Baits and baiting programs

The feral cat baits (*Eradicat*®) used during this and earlier baiting campaigns in the arid zone (Algar & Burrows 2004; Burrows et al. 2003) were manufactured at DPaW's bait manufacturing facility at Harvey, Western Australia. The bait is similar to a chipolata sausage in appearance,

Table 1

Monthly rainfall data (mm) over the study period. Missing values are where data were not supplied to the Bureau of Meteorology for the month and rainfall is presumed to be zero.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2003		8.4	39.0	163.4	0.2	3.4	0.0	11.8	0.0		19.4	6.8	252.4
2004	50.8	92.0	28.6	77.0	35.4	1.2	20.2	0.0	7.2	0.0	9.8	15.8	337.8
2005	0.0	0.4	13.2	7.8	2.8	4.3	36.3	10.6	0.0	0.5	8.8	37.1	121.8
2006	203.7	124.6	64.8	48.2	3.6	0.0	1.4	0.6	10.7	67.8	29.4	80.7	633.5
2007	110.0	3.0	59.2	71.4	10.2	0.0	5.2		0.0	1.2	2.0	34.7	296.9
2008	15.2	91.5	5.0	7.8	0.4	19.6	1.4	16.4	2.1	1.0	66.7	32.2	259.3
2009	7.6	11.2	101.6	15.4	0.0	8.2	0.4	2.6	2.4	0.4	12.1	5.8	167.7

approximately 20 g wet-weight, dried to 15 g, blanched and then frozen. This bait is composed of 70% kangaroo meat mince, 20% chicken fat and 10% digest and flavour enhancers (Patent No. AU 781829). Toxic feral cat baits were dosed at 4.5 mg of sodium monofluoroacetate (compound 1080) per bait. Prior to being laid, feral cat baits were thawed and placed in direct sunlight. This process, termed 'sweating', causes the oils and lipid-soluble digest material to exude from the surface of the bait. All feral cat baits were sprayed, during the sweating process, with an ant deterrent compound (Coopex®) at a concentration of 12.5 g l^{-1} as per the manufacturer's instructions. This process is aimed at preventing bait degradation by ant attack, which may also deter bait acceptance by cats because of the physical presence of ants on and around the bait medium.

The baiting programs were conducted from a dedicated baiting aircraft which deployed the baits at predetermined drop points. The baiting aircraft flew at a nominal speed of 130 knots and 500 feet above ground level and a GPS point was recorded on the flight plan each time bait left the aircraft. The 'bombardier' released 50 baits into each 1 km map grid, along flight transects 1 km apart, to achieve an application rate of 50 baits km^{-2}. The ground spread of 50 baits is a cluster of approximately 200 × 50 m (D Algar, unpub. data).

The multi-faceted umbrella program *Rangelands Restoration* evolved under an adaptive management framework. As a consequence, the area baited, and monitoring techniques used, were not consistent throughout the years of this study, which is a reality for large-scale management programs such as this. However, the baiting strategy remained the same. In 2007, there was a major shift in the emphasis of the program with commencement of the native species reintroduction phase of *Rangelands Restoration* (Dunlop & Morris 2009). Unfortunately in 2006, no decline in cat activity indices had occurred following baiting and thus to increase the likelihood of survivorship of reintroduced species the management committee for the project requested that short-term, small-scale trapping programs be integrated into the control regime. At the conclusion of each survey period, excluding the pre-baiting survey, monitoring data were examined to assess whether this option was warranted.

In 2003, a small-scale pilot baiting trial was conducted. Two sites of similar habitat were selected, each 625 km^2 in area (25 km × 25 km quadrat) separated by a distance of at least 5 km. One site was the treatment (baited) site and the other was the control (non-baited) site. In 2004, the baited area was increased to cover an area of 1725 km^2, which encompassed the entire Lorna Glen lease but excluded the control area that was not baited in 2003. Baiting programs conducted from 2007 on covered the whole lease, an area of 2350 km^2.

Surveys of cat activity

Monitoring the abundance of feral cats, as for many other mammalian carnivores, is difficult because they occur at low densities, have large home ranges and tend to be secretive and cryptic (Long et al. 2007; Marks et al. 2009; Saunders et al. 1995; Witmer 2005). Capture–recapture studies to estimate abundance are usually impractical because mammalian carnivores are difficult to trap, leading to low capture rates and recapture probabilities (Saunders et al. 1995). Consequently, most monitoring schemes are reliant on indices of abundance derived from data such as track (footprint) counts. We acknowledge that the number of tracks encountered during a track-based survey is likely to be a function of population density as well as activity levels of individuals in the population. Activity levels may be influenced by factors such as seasonal changes in behaviour during breeding and dispersal and the availability of resources including food and shelter (Berry et al. 2012; Edwards et al. 2000; Engeman et al. 2002; Wilson & Delahay 2001). Baiting is also likely to influence the activity patterns of feral cats, as movements may be influenced by removal of neighbours and the imposed changes in population density, or as a consequence of disrupted social structures. Despite these potentially confounding factors, track-count indices were used at Lorna Glen as an index to abundance because mark-recapture methods were unlikely to yield estimates due to low predicted recapture rates. Here, the track-based surveys were simple to implement and time-efficient as extensive lengths of track needed to be surveyed rapidly. The intention was not to estimate population size but to compare activity indices immediately prior to and immediately following baiting programs. Apart from the pilot study, surveys were conducted for four (or five, depending on year) consecutive days immediately prior to the day of baiting (pre-baiting survey period) and for four or five consecutive days approximately ten days directly after baiting (post-baiting survey period). Over this short time period, the population was assumed closed and therefore the difference in indices pre- and post-baiting was a measure of baiting impact. To monitor broad trends over time, cat activity was also surveyed at approximately seasonal intervals (October, December, April and the baiting period of July/August) to provide information on the rate and magnitude of reinvasion into the baited site. The surveys to derive indices of activity were initially conducted along lengths of continuous track (2004–2007). In 2007, survey tracks were repositioned to focus on the area that encompassed the proposed reintroduction site. Not all these tracks were suitable to conduct continuous track counts so sand plots were also included in the survey method to monitor feral cat activity over the period 2007–2009.

Continuous track counts

An extensive network of tracks and roads was present throughout the study area. Many of these tracks consisted of a sandy surface substrate that enabled cat footprints to be observed and thus daily cat activity to be monitored along their length. The monitoring methods used were similar to that outlined in Edwards et al. (2000) and Burrows et al. (2003). Prior to the commencement of each survey period, each track was cleared of previous cat activity by towing a heavy iron drag behind a 4WD vehicle. Track counts were conducted each survey by two highly experienced observers, driving all-terrain vehicles (ATVs) at a speed of 10–15 km h^{-1}. Tracks were inspected for cat tracks each morning one hour after sunrise, and cleared of animal activity by towing a light-weight chain iron drag. To reduce potential observer bias, inspection of tracks between the observers was rotated on a daily basis. Similarly, survey periods were alternated between two different skilled observer groups. Footprints of individual animals were differentiated on the basis of location on the track. While cats usually followed the dragged tracks for some distance, occasionally they would wander on and off the track. To reduce the possibility of double counting, footprints were assigned to an individual animal if no other foot prints were present on at least the previous 1 km of track. Subsequent footprints were also assigned to that individual unless at least 1 km was traversed with no new foot prints present or the imprint could be clearly differentiated on the basis of size or the direction of travel or the direction of entry/exit to and from the track. Each time new cat footprints were encountered along the track, data were recorded on the direction of movement (i.e. whether the animal walked along the track or crossed it), distance of the footprints from the start of the track, approximate size of imprints and whether more than one animal was present. Using these rules and the same skilled observers, the technique provided a reliable and repeatable survey protocol.

Sand plots counts

From 2007–09, 10 permanently marked sand plots, located at 1 km intervals along the survey tracks, were also used to monitor feral cat activity. Each sand plot, 1 ×

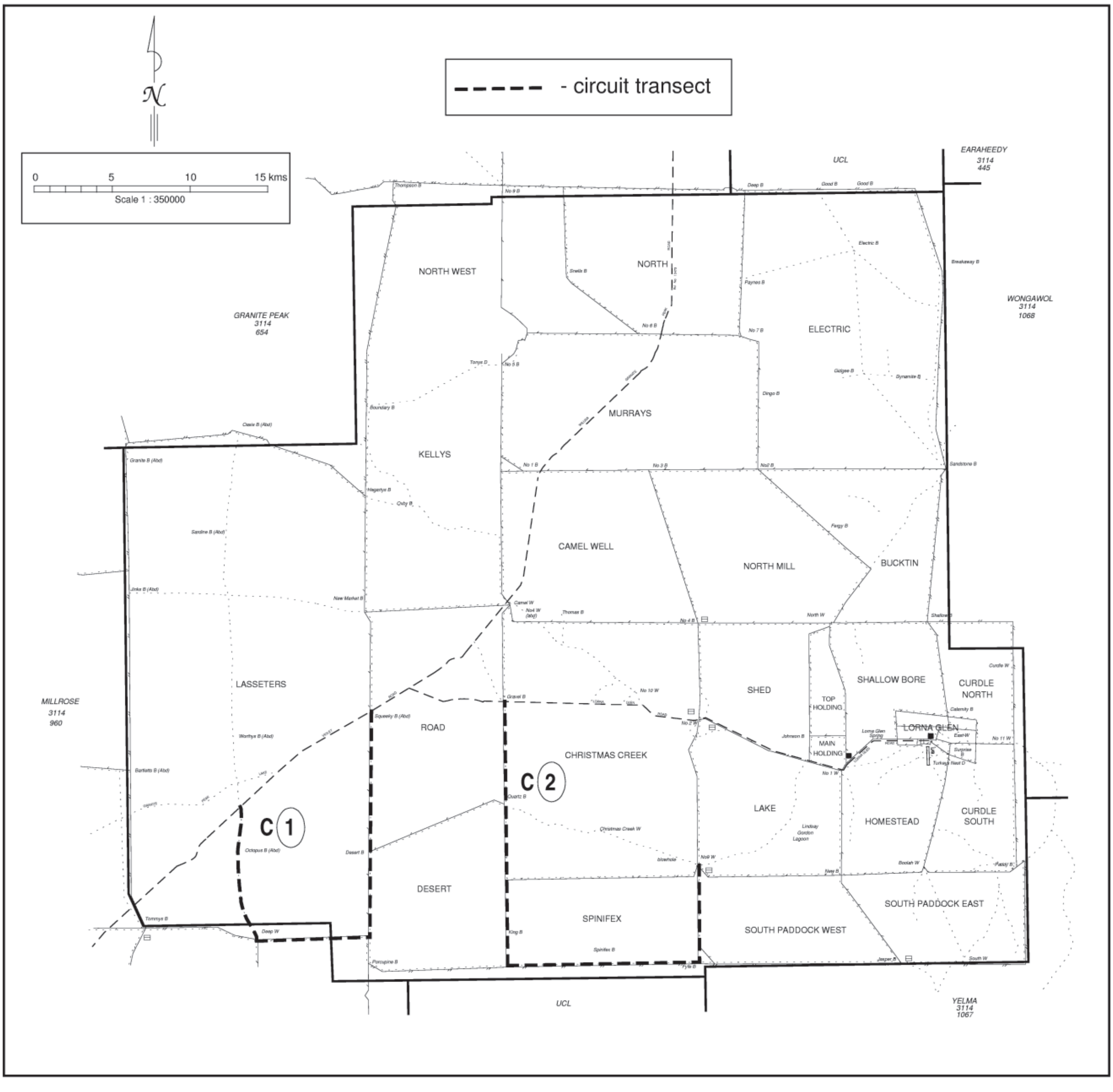

Figure 1. Location of the two circuit survey tracks (2003); C1 in baited site and C2 in non-baited site.

1 m in size, was positioned on the track edge and cleared into a bush or manufactured with brush/fallen trees. Lures were used at each sand plot to increase the likelihood of detecting animals, particularly at low density, and to maximize the number of plot incursions for each survey period. Plots that have no attracting lure generate sample sizes that are too low to adequately monitor population changes (Fleming et al. 2001). In this study, plots contained an audio lure (Felid Attracting Phonic, Westcare Industries, Western Australia) and a non-toxic *Eradicat*® bait to attract cats to the sand plots. The use of a non-toxic *Eradicat* ® bait also enabled us to monitor non-target bait take through the year (M Onus & D Algar, unpub. data). The audio lure was located at the back of the plot, either concealed under leaf litter or hidden within the bush. The *Eradicat* ® bait was located approximately halfway into the plot from the entrance and sprayed with an ant deterrent compound (Coopex®). *Eradicat*® baits were replaced following removal. Both lures were removed outside the survey periods. Each plot was observed for the presence or absence of tracks, as it was not possible to determine the number of intrusions by individual animals onto the plot. Each day, the plots were swept to clear evidence of previous activity.

Phase 1: 2003

In 2003, feral cat activity was monitored along two track circuits, each 36 km in length, with one track circuit located in the baited site and the other in the non-baited site (Fig. 1). A baiting program was conducted on 13 July with each circuit monitored daily for three consecutive days prior to the baiting program (10–12 July) and similarly for 13 days two days after the baiting program (15–27 July).

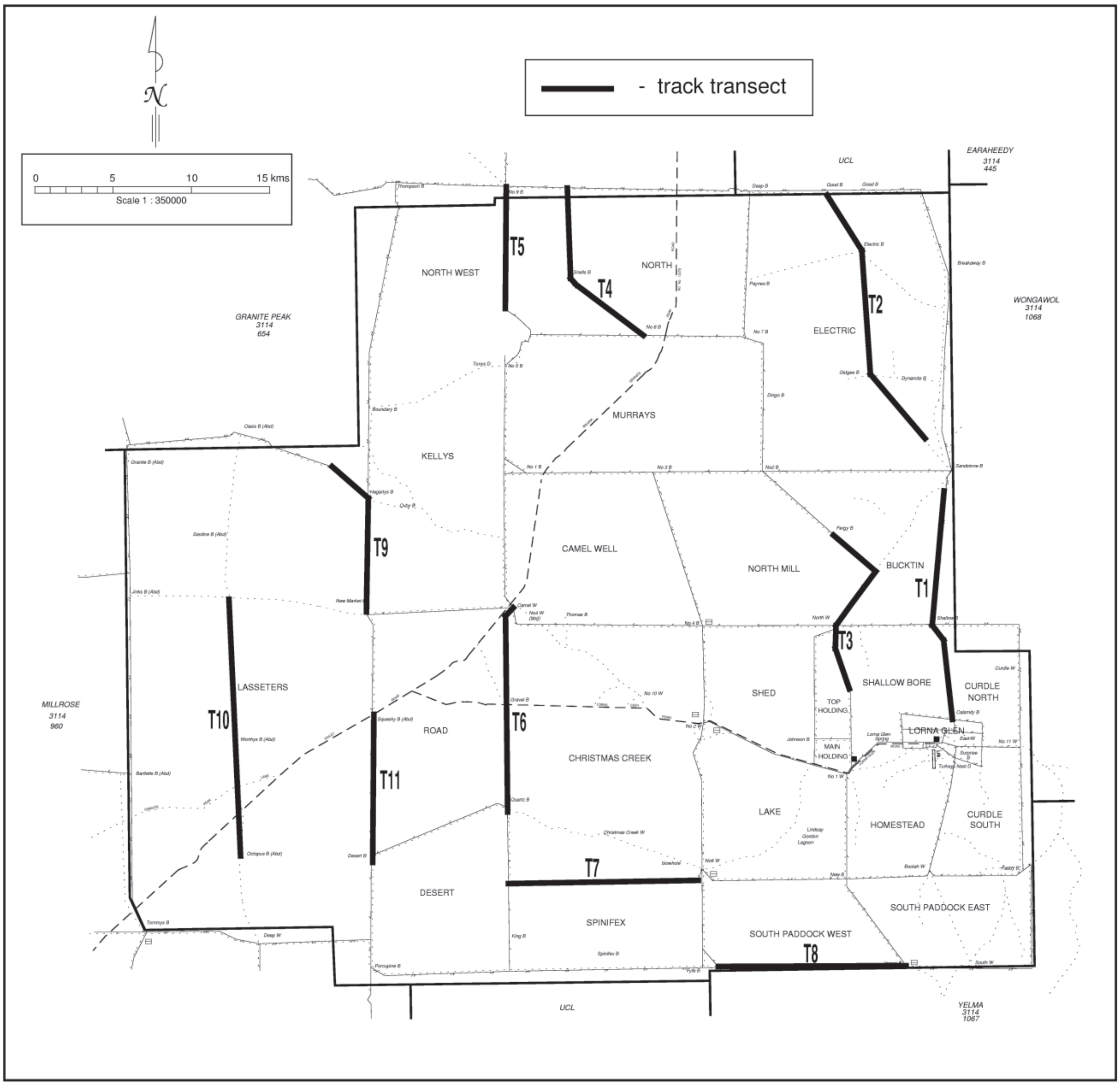

Figure 2. Location of the 11 permanent survey tracks (2004–2006). Survey tracks T1, T2, T3, T4, T5, T9, T10 and T11 were in the baited site and survey tracks T6, T7 and T8 were in the non-baited site.

Phase 2: 2004–06

Over the period 2004–06, the efficacy of baiting programs and subsequent reinvasion was assessed by comparing the track activity of feral cats in the baited and non-baited sites. To be able to make valid statistical comparisons of cat activity indices over time, it was essential to have data from a number of tracks rather than a single continuous circuit. It was also necessary to separate the tracks by sufficient distance so that the tracks were spatially-independent sampling units, thus minimizing the probability of a single animal being recorded on more than one track in any single survey period (e.g. Beier & Cunningham 1996; Edwards et al. 2000; Kendall et al. 1992; Sargeant et al. 1998; Wilson & Delahay 2001; Zielinski & Stauffer 1996).

In 2004, 11 permanent survey tracks were established across the study site. Eight tracks were located within the baited site and three tracks were placed in the non-baited site (see Fig. 2). The tracks varied in length from 10 to 16.5 km. To ensure independence (Harrison et al. 2002), tracks were separated by a minimum distance of at least 5 km, a distance that has been adopted at other sites in the arid zone (Edwards et al. 2000; Burrows et al. 2003) and was considered to be larger than the average diameter of a feral cat home range for the area. The survey tracks chosen aimed to provide a broad coverage of the entire study area and an efficient and representative sampling of the population using the surrounding habitat. As a number of surveys were conducted over time on the same area, the same locations were used (Engeman et al. 2002).

Counts of cat footprints were conducted along each

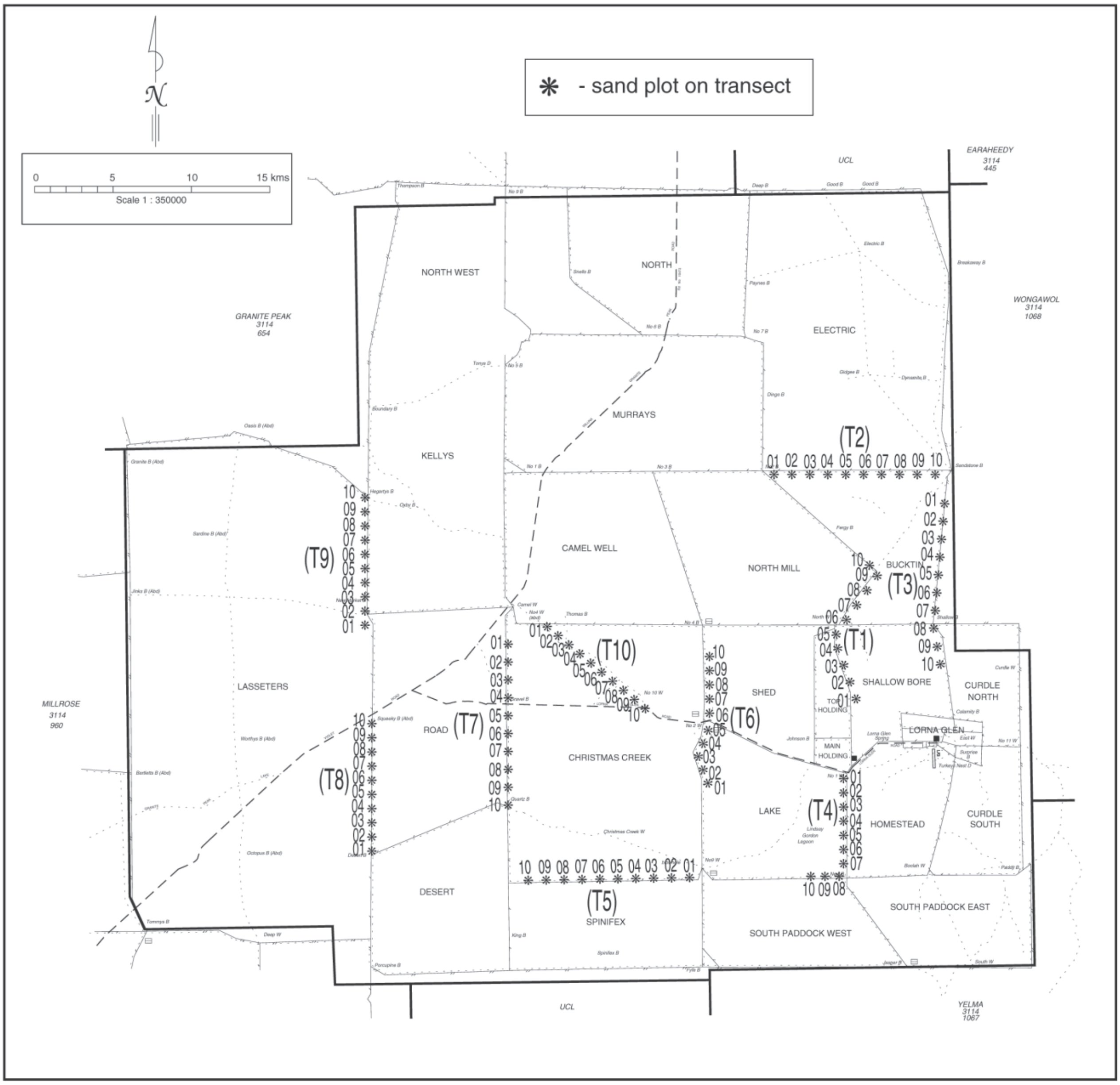

Figure 3. Location of the 10 permanent survey tracks (T1–T10) used in 2007–2009.

track for five consecutive days (where possible) during each survey period in 2004. Preliminary examination of this data was conducted using site level standard error, based on sub-sampling sets of 1, 2, 3, 4 or 5 consecutive days. Standard errors were 0.121, 0.088, 0.077, 0.074 and 0.076 for days 1 to 5 respectively and indicated that precision increased with increased number of sampling days up to four days, but the fifth day added virtually nothing to the precision. As such, surveys in 2005 and 2006 were conducted over four-day periods.

Phase 3: 2007–09

In 2007, the existing feral cat monitoring tracks were repositioned to focus on the area that encompassed the proposed reintroduction site. Ten permanent survey tracks were established across the reintroduction site (see Fig. 3). Each track was 10 km long and aimed to provide a broad coverage of the proposed fauna reintroduction area. The soil substrate along the length of three tracks was unsuitable (i.e. not continuous sand) to conduct continuous track counts. Continuous track counts were performed on tracks T1, T2, T3, T5, T7, T8 and T9 in conjunction with the introduction of sand-plot counts on all tracks to monitor feral cat activity. With the introduction of sand-plot counts, five-day survey periods were reinstated to monitor cat activity along the tracks.

Cat trapping

During Phase 3, a trapping program was implemented seasonally in 2007 (but not following the pre-baiting survey) and less frequently in subsequent years. Feral cats were trapped at locations around the track network, a circuit of 210 km in length. Trapping was conducted on an ad hoc basis and only where cat activity was routinely observed. Padded leg-hold traps, Victor 'Soft Catch'® traps No. 3 (Woodstream Corp., Lititz, Pa., USA) were used, with a mixture of cat faeces and urine as the attractant. A number of different trap sets were used; however, the main type of set employed open-ended trap sets, parallel to the track, with two traps positioned lengthwise (adjoining springs touching) and vegetation/sticks used as a barrier along the trap sides. Trapped cats were destroyed using a 0.22 calibre rifle. All animals captured were sexed and weighed; a broad estimation of age (as either kitten, juvenile or adult) was recorded using weight as a proxy for age. The pregnancy status of females was determined by examining the uterine tissue for embryos.

Calculation of indices and analyses

Continuous track count index

The Track Count Index (TCI) provided an estimate of the minimum number of individual animals responsible for footprints on the tracks. The TCI was calculated by summing the minimum number of cats responsible for the footprints based on the standard rules outlined earlier (TI_{min} of Edwards et al. 2000). Repeated counts of the same sampling unit are not independent because environmental conditions are related across days (Edwards et al. 2000; Engeman et al. 1998) and because some animals may follow the same pattern of movement from day to day. To avoid this problem of temporal non-independence in the track-based population indices, the footprint counts were summed over sampling days for each track (Edwards et al. 2000) and then standardized to the number of individual cats per 100 km. The mean TCI for all tracks was then calculated for each survey period.

Sand-plot counts

Because individuals cannot be identified on the basis of track characteristics, it is customary to just record whether an animal was detected at the station (Ray & Zielinski 2008). These presence/absence data are more robust to statistical analysis than the total number of detections recorded at a station or multiple-station sample units. Thus in this case, sand-plot counts have an index of usage expressed as the mean number of positive plots per night. The track Plot Activity Index (PAI) was formed by calculating an overall mean from the daily means for each survey period (Engeman 2005; Engeman et al. 1998). The VARCOMP procedure within the SAS statistical software package produced the variance component estimates. The PAI does not require assumptions of independence among plots to be made (Engeman et al. 1998). The PAI can be used to monitor populations at different times and statistical comparisons can be made between them (Engeman et al. 1998).

Data analysis

Over the period 2004–06, the program was a BACI design (before–after control–impact; Smith 2002), with a baited site (impact) and non-baited site (control). The data from 2007–09, where no control was available, followed a BA design (before–after; Smith 2002). The data were treated as independent samples and compared using two-sample tests ($\alpha = 0.05$), with any difference attributed to baiting impact. The data were tested for normality and homoscedasticity to satisfy the assumptions necessary for ANOVA and t-tests. Data for the years 2004–06 were analysed using an ANOVA. With removal of the non-baited control in 2007, the impact of baiting was assessed by comparing indices in the baited zone immediately prior to and following individual baiting programs. Comparison of activity changes before and immediately after the baiting program were analysed using a paired t-test. Pearson correlation analysis was used to examine the relationship between the two activity indices (Edwards et al. 2000)

Data for the baited site in 2004–05, 2005–06, 2007–08 and 2008–09 were examined for a reinvasion effect. Comparison of TCIs post-baiting with TCIs pre-baiting the following year were analysed using a paired t-test. Trend analysis was also performed on seasonal TCIs post-baiting through to pre-baiting the following year, using linear regression on log-transformed counts (Elzinga et al. 2001) to detect any consistent changes in TCIs over time.

RESULTS

Baiting programs

Of the seven baiting programs conducted at Lorna Glen to date, six resulted in significant declines in cat activity being recorded after baiting. Prior to any baiting program being conducted, the TCI summed over the period and standardized to number of cats per 100 km was 26.4. The average TCI (mean ± SE) since broad-scale baiting began in 2004 was 6.4 ± 0.7 and only once since 2007 has it been above 10 cats per 100 km.

Phase 1: 2003

During pre-baiting, the TCIs summed over the period and standardized to number of cats per 100 km were 25.9 for the non-baited site and 26.8 for site yet to be baited (Fig. 4). Over the survey period post-baiting, the TCI in the non-baited site was 31.8, while in the baited site the TCI decreased to 0 by day 10 following baiting, indicating a 100% decrease in cat activity.

Phase 2: 2004–06

Analyses indicated that the TCIs, including transformed data, were not normally distributed for combinations of period and site each year, as assessed by Shapiro Wilk's test ($P < 0.05$), and therefore two-way ANOVAs could not be conducted. This was most noticeable in the 2004 dataset, where part of the baited site had been baited the year before. As such, a one-way ANOVA was performed to determine whether there were differences between period–site groups using the non-parametric Kruskal–Wallis test (Allen & Bennett 2012), which does not require the assumptions of normal distribution and equal variances. Pair-wise comparisons were then conducted with a Bonferroni correction for multiple comparisons.

In 2004, TCIs were statistically significantly different between the period–site groups; $Chi^2(3) = 13.098$, $P = 0.004$. Post-hoc analysis revealed a statistically significant decline in TCIs following baiting in the non-baited site (*Mdn* = 28.30 pre-baiting) and (*Mdn* = 18.30 post-baiting; $P = 0.047$) and a highly significant decline in the baited site (*Mdn* = 14.30 pre-baiting) and (*Mdn* = 3.45 post-baiting; $P = 0.006$). The decline in TCIs in the non-baited site was of a much smaller magnitude than that observed in the baited site (Fig. 5). It does, however, suggest that there may have been some impact of baiting on cat activity in the non-baited site, which was adjacent to the much larger baited area.

In 2005, TCIs were statistically significantly different between the period–site groups; $Chi^2(3) = 10.136$, $P = 0.017$. Post-hoc analysis revealed no statistically significant difference in TCIs following baiting within the non-baited site (*Mdn* = 6.10 pre-baiting and *Mdn* = 6.80 post-baiting; $P = 0.827$), but a highly significant decline in the baited site (*Mdn* = 10.00 pre-baiting and *Mdn* = 1.50 post-baiting; $P = 0.006$ (Fig. 5).

In 2006, there was a statistically significant increase in TCIs post-baiting in both the baited and non-baited sites; $Chi^2(3) = 10.250$, $P = 0.017$. TCIs in the non-baited site were *Mdn* = 13.60 pre-baiting and *Mdn* = 35.40 post-baiting, and TCIs in the baited site were *Mdn* = 8.75 pre-baiting and *Mdn* = 15.85 post-baiting. A survey conducted in the baited site along five of the tracks a month later indicated no significant difference between the two

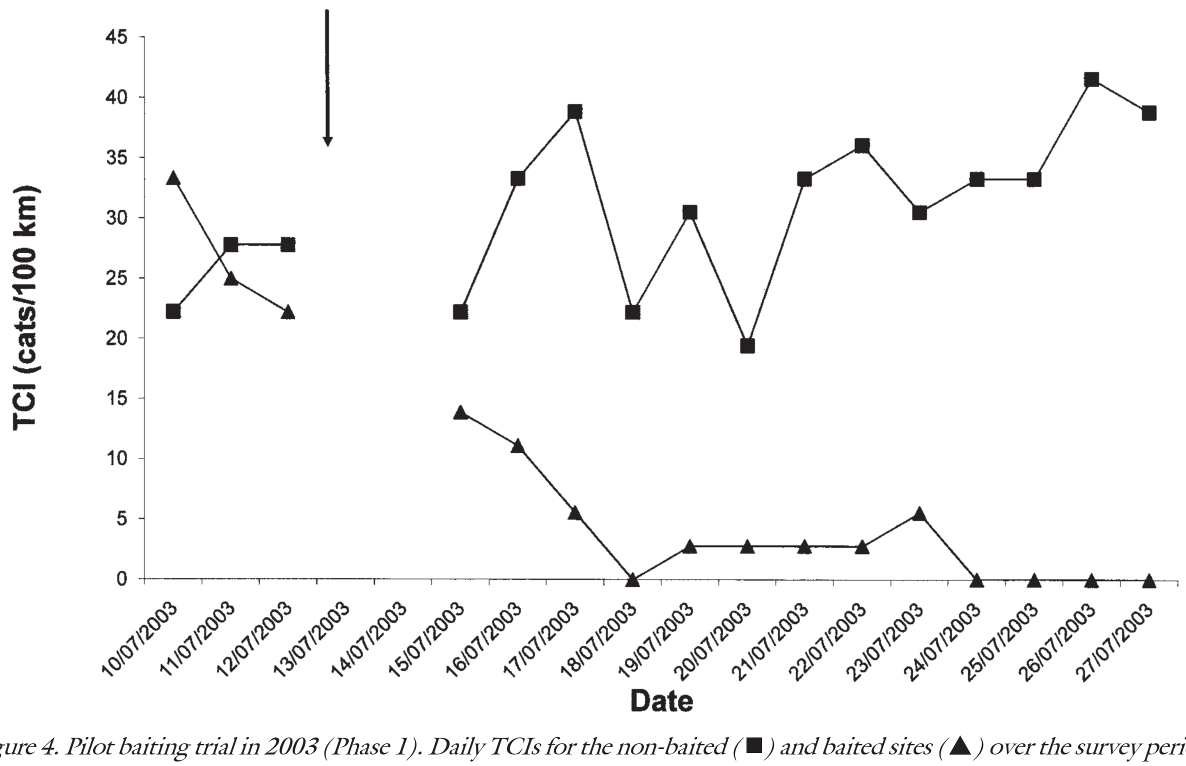

Figure 4. Pilot baiting trial in 2003 (Phase 1). Daily TCIs for the non-baited (■) and baited sites (▲) over the survey period. The arrow indicates the day baiting occurred (13 July 2003).

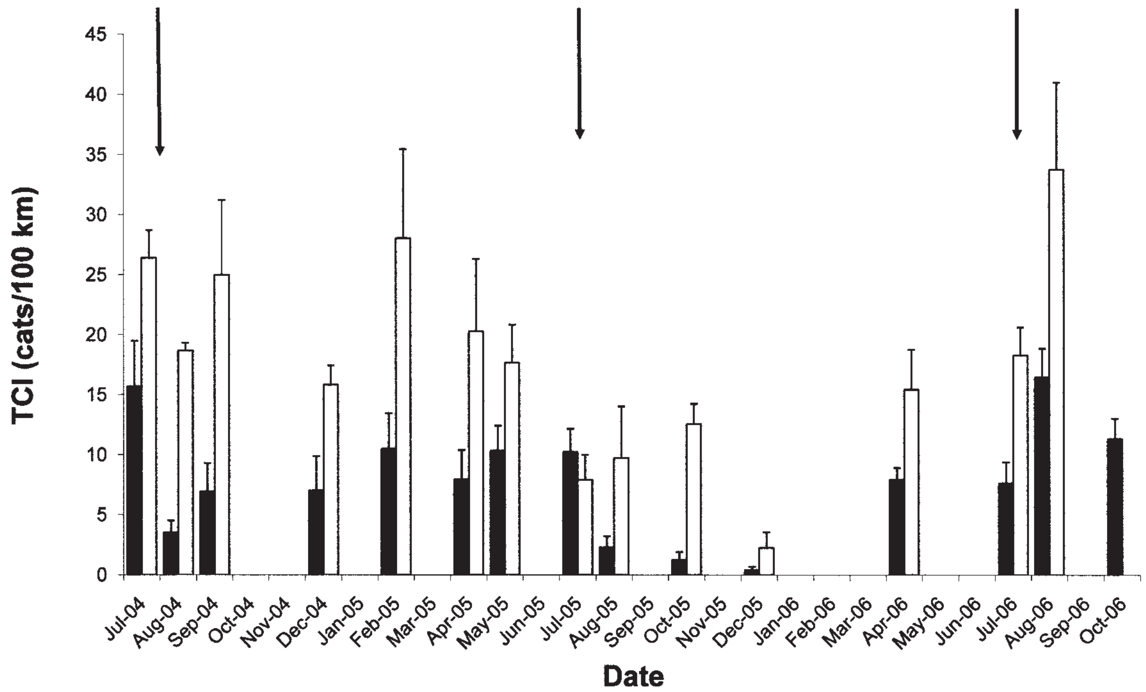

Figure 5. TCIs ± SE for each survey period across 2004–2006. Closed bars represent baited sites and open bars represent non-baited sites. No survey of the non-baited site was conducted in October 2006. Arrows indicate the timing of baiting programs.

survey periods (t = –1.33, P = 0.13). TCIs ± SE for these five tracks were 9.04 ± 2.06, 18.52 ± 2.96 and 11.34 ± 1.70 for pre-bait, post-bait and one month post-bait survey periods respectively (Fig. 5).

Phase 3: 2007–09

Paired t-tests were used to test whether there was a statistically significant mean difference between TCIs before and after baiting. The difference scores for pre- and post-baiting were normally distributed as assessed by the Shapiro Wilk's test ($P > 0.05$) for all years. In 2007, TCIs were lower post-baiting (6.00 ± 1.15) than pre-baiting (11.43 ± 1.89; Fig. 6); a statistically significant reduction of 5.43 (95% CI, 1.47 to 9.38), t(6) = 3.36, P = 0.015, d = 1.27. In 2008, TCIs were lower post-baiting (2.67 ± 1.12) than pre-baiting (9.67 ± 2.44; Fig. 6); a statistically significant reduction of 7.00 (95%

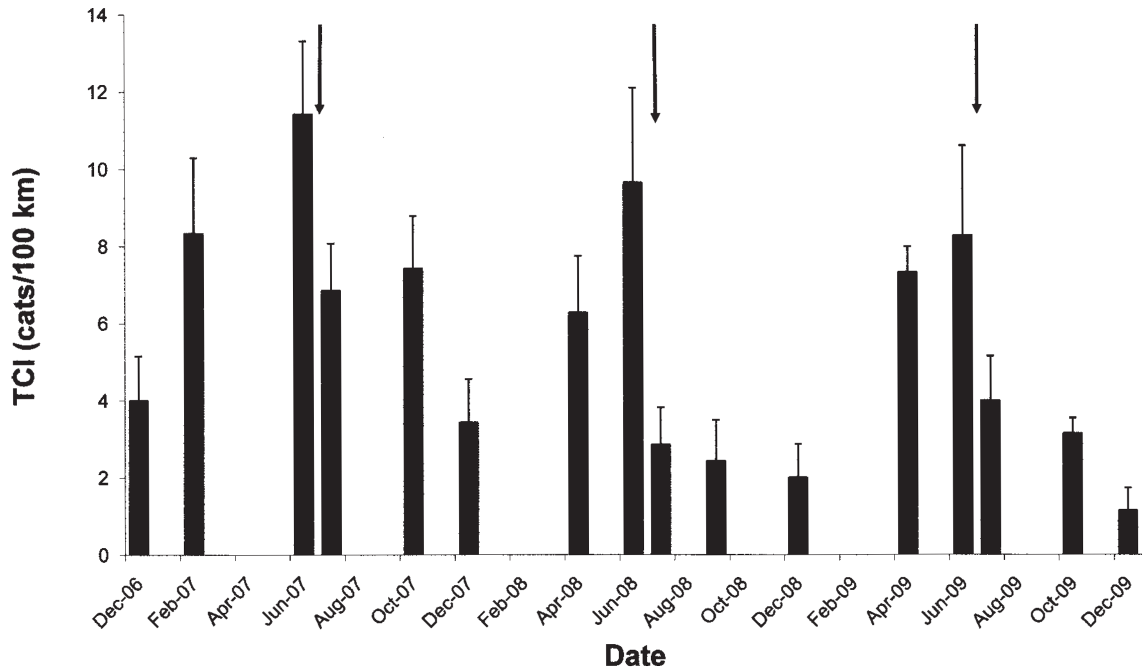

Figure 6. TCIs ± SE for each survey period across 2007–2009. Arrows indicate the timing of baiting programs.

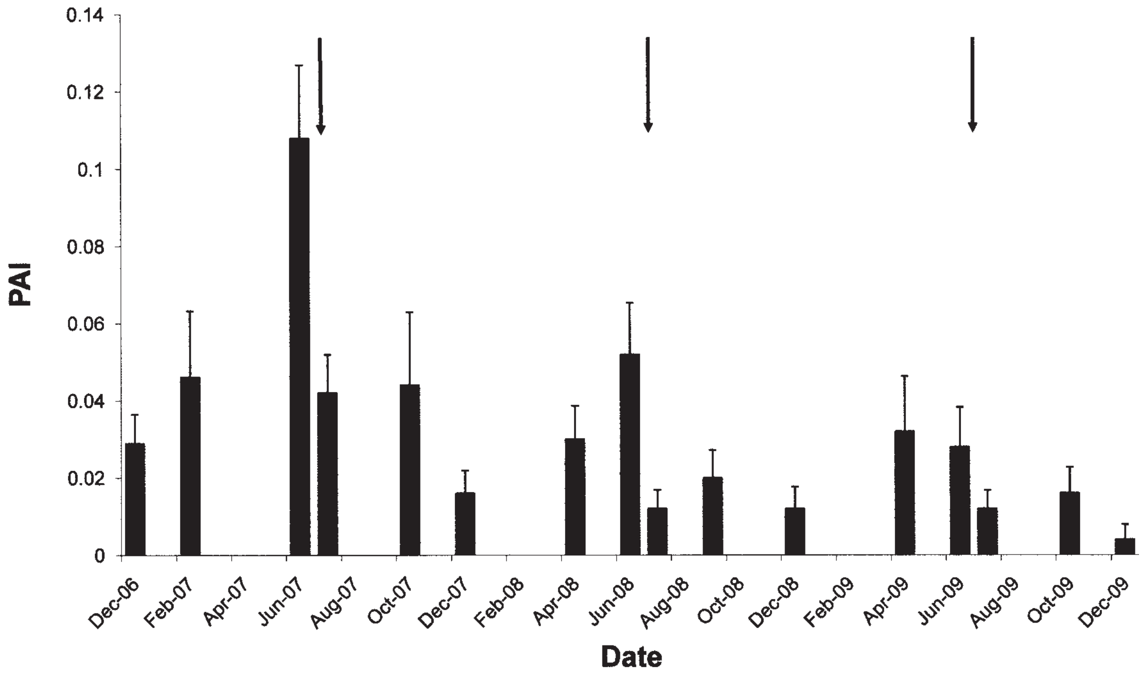

Figure 7. PAIs ± SE for each survey period across 2007–2009. Arrows indicate the timing of baiting programs.

CI, 0.13 to 13.87), t(5) = 2.62, $P = 0.047$, d = 1.07. In 2009, TCIs were lower post-baiting (3.67 ± 1.31) than pre-baiting (9.00 ± 2.62; Fig. 6); a statistically significant reduction of 5.33 (95% CI, 0.80 to 9.87), t(5) = 3.02, $P = 0.029$, d = 1.23.

Paired t-tests were used to test whether there was a statistically significant mean difference between PAIs before and following baiting. The difference scores for pre- and post-baiting were normally distributed as assessed by the Shapiro Wilk's test ($P > 0.05$) for all years. One of the data points in the 2007 pre-baiting dataset was found to be an extreme outlier (PAI = 0.48): rather than removing this value from the dataset it was modified by replacing the outlier's value with the next largest PAI (0.12). In 2007, PAIs were lower post-baiting (0.036 ± 0.011) than pre-baiting (0.072 ± 0.013; Fig. 7); a statistically significant reduction of 0.036 (95% CI, 0.003 to 0.069), t(9) = 2.48, $P = 0.035$, d = 0.78. In 2008, PAIs were lower post-baiting (0.012 ± 0.004) than pre-baiting (0.052 ± 0.014; Fig. 7); a statistically significant reduction of 0.040 (95% CI, 0.008 to 0.072), t(9) = 2.80, $P = 0.021$, d = 0.89. In 2009, there was a lowering of PAIs following baiting (Fig. 7) but it was not statistically significant, t(9) = 2.08, $P = 0.068$, with PAIs of 0.010 ± 0.005 post-baiting and 0.028 ± 0.009 pre-baiting, respectively. There was a strong positive correlation between TCIs and PAIs (r = 0.926, $P < 0.0005$).

Reinvasion

Paired t-tests were used to test whether there was a statistically significant mean difference between post-baiting TCIs in one year with pre-baiting TCIs in the following year. The difference scores for pre- and post-baiting were normally distributed as assessed by the Shapiro Wilk's test ($P > 0.05$) for all years. In 2004–05, TCIs were lower in the post-baiting period in 2004 (4.66 ± 1.33) than in the pre-baiting period in 2005 (10.24 ± 1.93); a statistically significant increase between periods of 5.58 (95% CI, 1.67 to 9.99), t(4) = –3.51, $P = 0.025$, d = 1.57. In 2005–06, TCIs were lower in the post-baiting period in 2005 (2.29 ± 0.94) than in the pre-baiting period in 2006 (7.84 ± 1.87); a statistically significant increase between periods of 5.55 (95% CI, 0.66 to 10.44), t(7) = –2.69, $P = 0.031$, d = 0.95. In 2007–08, there was a increase in TCIs in the post-baiting period in 2007 compared with the pre-baiting period in 2008, but it was not statistically significant t(5) = –0.93, $P = 0.394$, with TCIs post-baiting in 2007 of 7.00 ± 1.44 and pre-baiting in 2008 of 9.67 ± 2.44. The lack of a significant increase in cat activity between these two periods was probably because the majority of cats trapped (73% of the total, see below and Table 2) were captured over this period.

Table 2

Cat capture records over the period 2007–2009.

Trapping Period	No. Captures	
	No. males	No. females
February 07	11	8
July 07	2	2
October 07	10	6
December 07	1	1
February 08	1	2
October 08	2	1
December 08	1	2
February 09	4	2

In 2008–09, TCIs were lower in the post-baiting in 2008 (2.86 ± 0.96) than in the pre-baiting in 2009 (8.29 ± 2.33); a statistically significant increase between periods of 5.43 (95% CI, 0.12 to 10.74), $t(6) = -2.50$, $P = 0.046$, d = 0.95.

Trend analyses indicated that 2004–05 was the only period when there was a statistically significant increase in TCIs detected over time, $t(5) = 3.43$, $P < 0.05$, $\beta = 0.0171 \pm 0.0050$. In 2005–06, 2007–08 and 2008–09 there were no statistically significant increases in TCIs detected over time (2005–06: $t(3) = 2.65$, $P = 0.08$, $\beta = 0.0222 \pm 0.0084$; 2007–08: $t(3) = 0.48$, $P = 0.67$, $\beta = 0.0003 \pm 0.0006$; 2008–09: $t(3) = 2.61$, $P = 0.08$, $\beta = 0.0015 \pm 0.0006$). There was, however, a general tendency across years of increases in cat activity indices in late summer, through autumn and early winter prior to the baiting programs.

Trapping Programs

Over the period 2007–09, 56 cats were trapped comprising 32 males and 24 females (Table 2). Seventy-three per cent of these cats were trapped in 2007. Body weight (mean ± SE) for males was 3.7 ± 0.1 kg (range 2.5–5.1 kg) and 2.7 ± 0.1 kg (range 1.5–3.3 kg) for females. Using the yearling weight/age classes reported by Jones and Coman (1982), the population age structure of trapped cats at Lorna Glen were defined. Body weights for male cats indicated four were less than 3.0 kg and considered to be juvenile animals, 20 cats were between 3.0–4.0 kg, a weight that approximates that for sexual maturity and considered to be young adults of between 1–2 years of age and eight cats were >4.0 kg and were considered to be greater than two years of age. Body weights for female cats indicated eight were less than 2.5 kg and considered to be juvenile animals, nine cats were between 2.5–3.0 kg, a weight that approximates that for sexual maturity and considered to be young adults of between 1–2 years of age and seven cats were 3.0 plus kg and were considered to be greater than two years of age. The majority of adult females had kittens in utero during the spring, suggesting a main birth season in the late spring/early summer.

DISCUSSION

Baiting Effect

Prior to the implementation of baiting programs at Lorna Glen, the average cat activity index was 26.4 cats per 100 km. Following broad-scale baiting in 2004, the average cat activity index over the period of this program has been 6.4 ± 0.7 (mean ± SE) and only three times has it been much greater than 10 cats per 100 km (16.5 ± 2.4 in August 2006, 11.3 ± 1.9 in September 2006 and 11.4 ± 1.9 in June 2007). Reducing and maintaining cat numbers to less than 10 per 100 km was our benchmark, as this is the suggested level at which reintroductions of native species could potentially occur (Morris et al. 2004).

Six of the seven baiting programs conducted at Lorna Glen resulted in significant reductions in cat activity indices immediately after baiting. The baiting program conducted in 2006 was the only one that did not result in a significant decline in cat activity after baiting; in fact, an increase in cat activity occurred. The reason for this increase in the indices of cat activity in both the baited and non-baited site during this year is unclear. The following survey indicated that there was no difference in indices of cat activity between the two periods; indicating that baiting had no impact on cat activity that year. The lack of response to baiting was most likely due to the significant rainfall events that occurred over the summer months, which probably led to irruptions of small mammal populations that resulted in a major increase in prey availability (Dickman et al 1999; Morton 1990). The relationship between prey availability and bait consumption is discussed further below.

What is clear from this project is that, in most cases, the implementation of an annual baiting strategy can provide for the effective and sustained control of feral cats at the landscape level. This statement needs some qualification, as the imposition of a trapping program in 2007, following the lack of baiting impact in 2006, would have had contributed to the control of cat numbers throughout the year. In 2008 and 2009, the limited amount of cat trapping would have had little impact on the overall control achieved. The cat control strategy will benefit from the addition of supplementary, limited trapping programs, which may be required in years of high rainfall when baiting is less likely to have an impact because of the probable increase in prey resource.

The efficacy of these programs confirms previous findings from other sites in the arid and semi-arid zone (Algar & Burrows 2004; Burrows et al. 2003) that baiting for feral cats in the winter months, when prey availability is low, can achieve highly effective control. Similar results were also achieved following baiting programs in 2006 and 2007 at Mt Gibson in the southern rangelands, which resulted in significant reductions in cat activity recorded in both years. Since the 2006 baiting program at Mt Gibson, indices of feral cat activity did not recover to their original level with the implementation of an annual baiting regime (Algar & Richards 2010). A number of baiting programs conducted on islands have also been successful and have led to eradication of cats on Hermite Island, Montebellos (Algar et al. 2002) and Faure Island, Shark Bay (Algar et al. 2010), and will be the primary tool in the proposed eradication of cats on Dirk Hartog Island, Shark Bay (Algar et al. 2011a; Algar et al. 2011b).

The impact of broad-scale cat baiting at several other mainland sites has, however, been highly variable and/or less successful. There appear to be three factors that are critical to the outcome of baiting programs: 1) baiting intensity and bait encounter, 2) the abundance of prey items, and 3) weather conditions at the time of baiting. Cats, despite being opportunistic predators, will only consume a food item if they are hungry (Bradshaw 1992). If a cat encounters a bait when not hungry it may not be consumed regardless of the acceptability of the bait. The relationship between bait consumption and hunger can be extended to prey abundance, which is also a function of long-term weather conditions (season/rainfall). The likelihood of cats encountering baits when hungry is potentially diminished in the presence of an abundant prey population. Therefore bait uptake is invariably low when prey availability is high (Algar et al. 2007). The impact of baiting can also be substantially reduced if significant rainfall occurs immediately following the baiting program. Rain renders the baits less palatable to cats by washing away the oils and flavour enhancers that sweat to the surface of the bait. Bait longevity in the field is a critical component in developing successful baiting campaigns to target feral cats.

At Roxby Downs, South Australia, feral cat baiting programs using non-recommended bait application rates of 10–25 baits km^{-2}, have met with little success (Moseby et al. 2009). Movement patterns of radio-collared cats and inferred bait detection distances were used to suggest optimum baiting densities of at least 30 baits km^{-2} (Moseby et al. 2009). This baiting application rate, however, does not take into account that cats must encounter the bait when hungry and any reduction of bait availability due to non-target bait consumption.

When prey is plentiful—such as on the Peron Peninsula in Shark Bay, Western Australia, where there is an abundant rabbit (*Oryctolagus cuniculus*) population—cat baiting programs have met with varied success (Morris et al. 2004). Rabbits, when present, can form a substantial proportion of a feral cat's diet (e.g. Jones & Coman 1981; Martin et al. 1996; Risbey et al. 1999; Project Eden, unpub. data). The presence of such an abundant prey resource can impact upon bait acceptance by feral cats, as was found on the adjoining Heirisson Prong (Short et al. 1997). Subsequent studies on Peron Peninsula and with sites where rabbits were absent or in low numbers have shown that bait uptake by feral cats can be driven by the abundance of this primary prey (Algar & Burrows 2004; Algar & Angus 2008; Algar et al. 2007). Reduction of rabbit abundance on the peninsula could improve bait acceptance and extend the period of effective baiting.

Baiting programs conducted at Lorna Glen in 2004 and 2005 were likely to have been adversely affected by inclement weather, which may have resulted in a reduction in baiting efficacy. Cloudy conditions and rainfall hindered both bait preparation in the field and aerial deployment. Baiting programs conducted at Mt Gibson and Karara–Lochada in 2008 had no significant impact on indices of feral cat activity at either site (Algar & Richards 2010). This lack of response to baiting was most likely due to a major rainfall event that occurred immediately after baiting. Baiting outcomes could be improved if long-term weather forecasts are used to ensure that baiting programs are only conducted when prolonged periods of fine weather are assured. An operational protocol has now been established within DPaW to minimize the possibility of poor baiting outcomes due to adverse weather conditions (Algar & Richards 2010). Preparation of the baits prior to aerial delivery is also of critical importance to the success of the baiting program. In the field, baits must be permitted to sweat on racks under sunny conditions to allow the oils and lipid-soluble digest material to exude from the surface of the bait. If this process is prevented or interrupted due to adverse weather conditions, the baits may rapidly deteriorate and become either rancid or mouldy and, as a consequence, unpalatable to cats.

Reinvasion

The dispersal of young cats is not clearly understood; however, dispersal cannot occur before the permanent canines have erupted, which commences three and a half months after birth (Hemmer 1979). Females rarely venture as far afield as males, often establishing a territory close to that of their mother. Yearling/subordinate males tend to remain within their natal range until they are old and strong enough to establish themselves as dominants (Liberg 1981, cited in Liberg & Sandell 1988). As they grow they come under increasing attack from older males and in their second year they usually disperse (Liberg 1981).

At Lorna Glen, there was a general trend across years that indices of cat activity only tended to increase six months following baiting, that is, in the late summer, through autumn and early winter prior to the following baiting program. These results suggest that immediately after baiting there was little movement into vacated territories by resident animals that survived the baiting program. The majority of reinvasion appears to have come from natal recruitment or dispersal/immigration of young adult animals from outside the baited area. Assuming no bias in trappability, the body weights of the majority of trapped animals (73%) were within the first and second year cohort and therefore support this proposal. The impact of reinvasion by feral cats could be mitigated to some extent by increasing the size of the area baited. This will essentially provide a buffer zone around a core area of conservation significance.

This project has demonstrated that sustained control of feral cats can be achieved in the rangelands using an annual baiting strategy occasionally augmented with trapping. In the short term that this program has been operational, we have demonstrated sustained control of feral cats to levels of 10 cats per 100 km. It is anticipated that refinements to bait preparation and deployment, and trapping techniques, will further enhance the effectiveness of the control strategy and provide the sustained control required to allow reintroduction of a suite of native mammals.

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Early survival and canopy characteristics of retained habitat trees after timber harvesting and rough-heaped regeneration burning: implications for stand structural complexity in the karri forest

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ABSTRACT

Areas of karri (*Eucalyptus diversicolor* F Muell.) regrowth forest subject to timber harvesting (termed 'coupes') are thinned two to three times until the forest is predominantly mature, after which it is clearfelled. Forest structure in these karri coupes is characterised by even-aged regeneration that lacks a high degree of structural complexity, such as large mature and senescent trees. The Karri Silvicultural Guideline provides for some stand structural complexity in regenerating karri coupes by stipulating the retention of two immature (secondary) habitat trees per hectare. Mature and senescing (primary) habitat trees are not required by the guideline to be retained within karri clearfell coupes. However, a change in regeneration burning practices away from high intensity, broad-scale regeneration burns to milder, rough-heaped (i.e. piling up of non-commercial vegetation) regeneration burns offers greater scope to protect primary habitat trees if they were to be retained within clearfell coupes. In this study, 298 primary and secondary habitat trees (karri, marri, jarrah and blackbutt) were retained during clearfelling operations. Crown condition and survival of the retained trees were recorded before and 22 months after the regeneration burn. Most retained habitat trees (92%) survived the rough-heaping and regeneration burning. There was a significant decline in the canopy condition of karri ($p < 0.001$) and marri ($p = 0.017$) trees to a more intermediate crown senescence; increasing their probability (immediate or longer-term) of hollow occurrence. Assuming that these habitat trees will survive a typical karri harvest rotation (100 years), their presence will enhance the structural complexity of the regenerating stand and provide greater numbers of mature habitat elements, such as tree hollows. Research should continue to assess the survival of the retained habitat trees over a longer time period, and also their use by endemic fauna.

Keywords: clearfelling, eucalypt, habitat trees, retention, rough-heaping, structural complexity

INTRODUCTION

Unharvested forests are generally characterised by a complex and continuously changing mosaic of early, mid and late successional stands that generally contain a high level of structural complexity (Lindenmayer & Franklin 2002; Bradshaw & Rayner 1997a). Structural complexity refers to the number of different structural attributes that characterise a stand (e.g. canopy cover, tree height, tree species, understorey vegetation, etc.) and the relative abundance of each (McElhinny et al. 2005). A high level of stand and landscape structural complexity provides a variety of niches, providing habitat for a wider range of species than stands with low structural complexity, and subsequently corresponds with high levels of biodiversity (Lindenmayer & Franklin 2002; McElhinny et al. 2005; McElhinny et al. 2006). However, stands subject to clearfell harvesting are often characterised by a lack of structural complexity and have been found to be used less frequently by some species of fauna compared with areas of undisturbed stands containing a higher stand structural complexity (Lindenmayer et al. 2010; Stephens et al. 2012). Consequently, harvest planning and many silvicultural practices aim to provide for stand structural complexity through retaining mature forest features and creating a mosaic of stand ages in forests subject to clearfelling.

In karri (*Eucalyptus diversicolor* F Muell.) regrowth forest subject to timber harvesting, regenerated coupes (defined harvest area) are thinned two to three times until the forest is mature, after which it is clearfelled (approximately 100 year cycle; Department of Conservation and Land Management 2005). Regeneration is therefore predominantly even-aged at the local (operational) scale (Bradshaw & Rayner 1997a; Bradshaw & Rayner 1997b). Forest management practices aim to provide some structural complexity at the landscape scale by retaining harvested exclusion areas and structural diversity at the local scale by retaining mid- and over-storey habitat trees within harvest coupes (Conservation Commission of Western Australia 2004; Department of Conservation and Land Management 2005; Wardell-Johnson et al. 1991). Two types of habitat trees are recognised in native forests in south-west Western Australia: primary (mature) habitat trees, being habitat trees that have a moderate to high probability of bearing hollows; and secondary (immature or recruitment) habitat trees, being habitat trees that have a lower probability of bearing hollows at the time of harvesting, but provide for the sustained availability of hollows through time (Department of Conservation and Land Management 2005). Tree hollows are important habitat for many mammal and avian species in the karri forest (Christensen et al. 1985; Abbott & Whitford 2002), including the forest red-tailed black cockatoo (*Calyptorhynchus banksii naso*) and Baudin's cockatoo (*Calyptorhynchus baudinii*) that nest in large hollows in standing trees (Williams et al. 2001; Abbott 1998). Retaining mature habitat trees in clearfell coupes also ensures the perpetuation of coarse woody debris that is essential habitat for fungi and invertebrates and important for various ecosystem processes (Wardlaw et al. 2009; Grove & Forster 2011; Lindenmayer et al. 2002). Secondary habitat trees are retained within karri clearfell coupes at a rate of two trees per hectare (Department of Conservation and Land Management 2005). However, for reasons detailed below, primary habitat trees are not retained within karri clearfell coupes, although such trees usually occur in nearby formal and informal reserves and fauna habitat zones (Conservation Commission of Western Australia 2004; Department of Conservation and Land Management 2005; Wardell-Johnson et al. 1991).

Until recently, retention of primary habitat trees within karri clearfell coupes has been problematic for two main reasons. First, mature karri trees can suppress the growth of nearby regeneration, mostly by out-competing regenerating trees for water (Rotheram 1983). Second, the high intensity, broad-scale burns associated with karri regeneration, along with increased exposure after harvesting, have been observed to make mature trees more vulnerable to rapid crown deterioration and tree death via scorching and/or windthrow. Rapid crown deterioration and death not only results in the loss of trees possibly intended for future harvest but also the loss of a potential habitat tree for hollow-dependent fauna. Burning of harvested karri coupes is undertaken to provide a receptive mineral seedbed for eucalypt germination (Loneragan & Lindenmayer 1964). Additionally, the boles and crowns of retained karri trees are intentionally scorched to promote epicormic growth and increase the likelihood of future hollow formation (Department of Conservation and Land Management 2005). However, an alternative approach for managing structural complexity in karri stands, involving the retention of primary habitat trees within the karri coupe, may now be possible due to changes to regeneration burning practices (predominantly driven by environmental concerns and a growing viticulture industry). Karri coupes are now smaller and, once trees are harvested, residual vegetation (i.e. non-commercial vegetation matter) is now piled into rough heaps (see Appendix 1, Fig. A1) which are burnt in late autumn. These autumn regeneration burns are cooler than traditional summer, broad-scale burns and consequently they may offer a greater scope to retain and protect a greater proportion of mature habitat elements within karri coupes.

This study provides a sound foundation on which to develop and implement measures that maintain greater stand structural complexity, and potentially biological diversity, in karri clearfell coupes. The overall objective of the study was to assess the survival and changes to the canopy condition of mature trees (jarrah, marri, blackbutt and karri) before and after rough-heaped karri regeneration burns.

METHODS

Description of study site

The study site, Channybearup 3, was located in the Channybearup forest block within the Warren Region, approximately 10 km south-west of Manjimup, Western Australia (Fig. 1). The area harvested was 88.5 ha and consisted of a complex mixture of even-aged regrowth (harvested in 1933) and two-tiered karri forest (previously selectively harvested) standing at around 150 stems per hectare (spha). Middle-storey tree species in the study site included jarrah (*E. marginata* Sm.), marri (*Corymbia calophylla* [Lindl.] KD Hill & LAS Johnson) and blackbutt (*E. patens* Benth.). The species composition of the site varied with landform and soil type. Mixtures of karri and blackbutt dominate in the wetter valley floors, grading into mixtures of karri and marri upslope and transitioning to jarrah/marri mixtures on crests and ridges. Prior to harvest, the average height of karri in Channybearup 3 was approximately 42 m, jarrah 29 m, marri 32 m and blackbutt 33 m. Channybearup 3 consisted of seven harvest cells (Fig. 1) that were broken up by stream reserves, other informal reserves, and previously planted areas (2003). The majority of the harvested area faces south or west and ranges from 223 to 280 m in elevation. The soils in the study area consist of mainly yellow duplex soils or gravely duplex soils, formed on weathered mottled and pallid zone material (McArthur 2004). Harvesting occurred between April and November 2010.

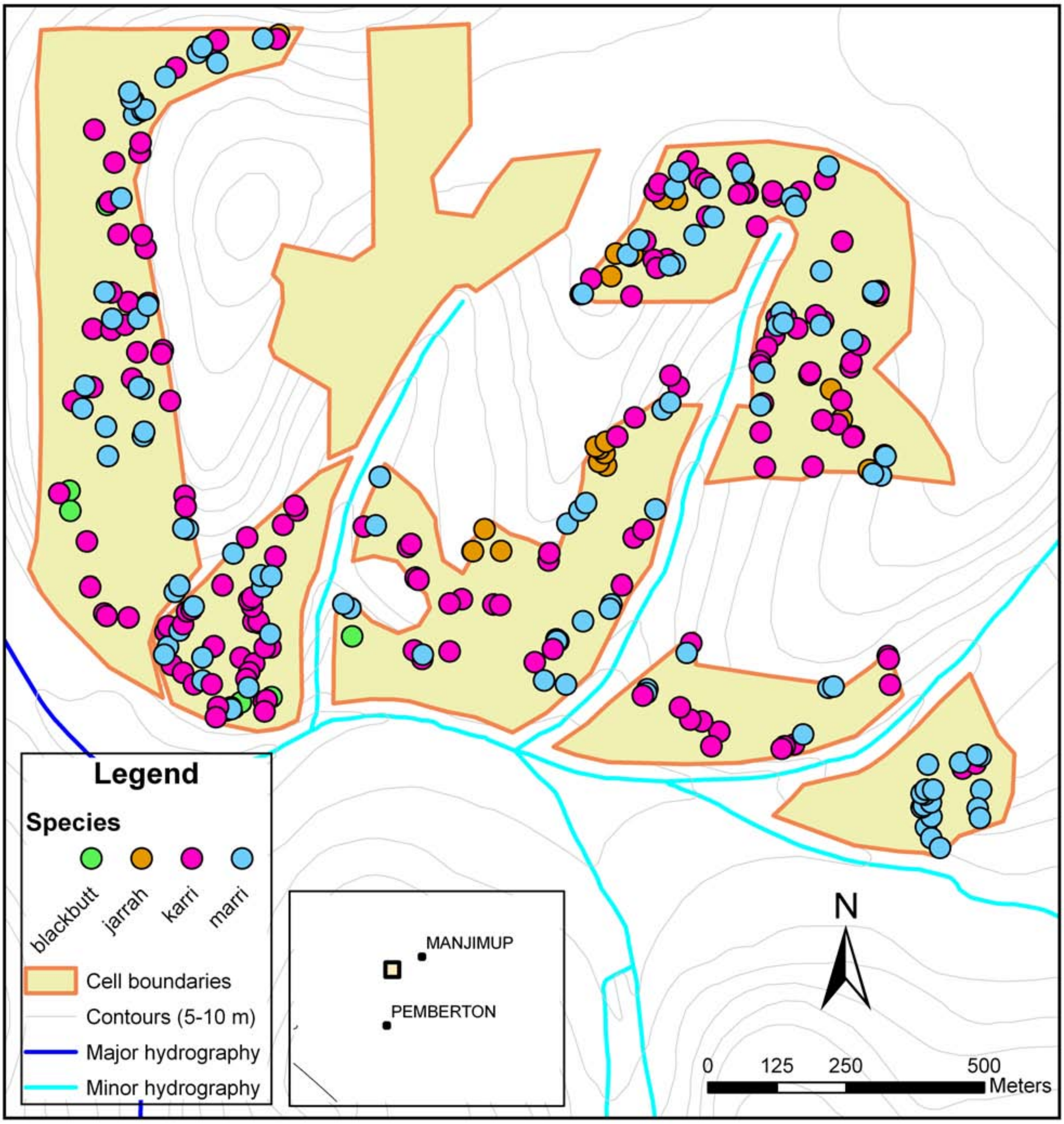

Figure. 1. Map of Channybearup 3 showing the location of the retained habitat trees within harvest areas. Tree crowns are not to scale. Additional habitat trees were contained in the mature forest buffering each stream (both major and minor hydrography); these stream zone buffers are not shown on the map.

Weather conditions

Channybearup 3 rough heaps were ignited on the 15 April 2011. The maximum temperature that day was 27 °C with a dew point of 7 °C (Bureau of Meteorology 2002). Maximum temperatures in the days leading up to the burn ranged from 20 to 25 °C (Bureau of Meteorology 2002). The soil dryness index on the day of the burn was 151, which is much lower than during traditional burning practices in the karri forest (Li et al. 2003).

Field procedures

In order to achieve a greater structural diversity in Channybearup 3 after harvesting, our intention was to retain primary and secondary habitat trees in lieu of the same number (≥ two trees per hectare) of secondary habitat trees normally retained under the Karri Silvicultural Guidelines (Department of Conservation and Land Management 2005). The inclusion of primary habitat trees allowed a more senescent canopy than what would

Figure. 2. Classes of crown senescence (SENES1 to SENES8) for eucalypt trees (from Whitford 2002). Assessment of crowns may be better (SENES0) or worse (SENES9 and SENES10) than those shown.

normally be marked. The crown senescence classes described in Whitford (2002) were used to achieve this (Fig. 2). Where safe to do so, marked trees were in a crown senescence class between SENES4 and SENES8 (Fig. 2), which allowed senescent trees that already contained hollows to be retained. Only living trees were marked as habitat trees. Tree marking was completed by Department of Parks and Wildlife (DPaW) and Forest Practices Commission (FPC) officers during felling operations. Although it is preferential to mark habitat trees before harvesting, the density of the understorey makes marking by tree markers difficult without the removal of at least some of the vegetation. Furthermore, it is difficult to assess the crown characteristics of karri trees in mature stands. Therefore, not every hectare contained trees in the higher senescence classes. Apart from changes to the regeneration burn and the senescence of retained trees, harvesting of Channybearup 3 was completed according to current Karri Silvicultural Guidelines (Department of Conservation and Land Management 2005).

For each tree marked to be retained, the following information was recorded: tree location, habitat tree species, tree diameter at breast height (DBH; cm), crown senescence class of the tree prior to rough-heaping and the regeneration burn, and clearfell gap size (ha). Rainfall (mm), dew point (°C), and temperature (°C) were recorded on the day of the regeneration burn as well as the days and months preceding the burn.

Six months after the regeneration burn, the retained trees were inspected to assess their survival and whether any limbs were lost. Trees that had died but were still standing were recorded. If any trees had fallen over, the

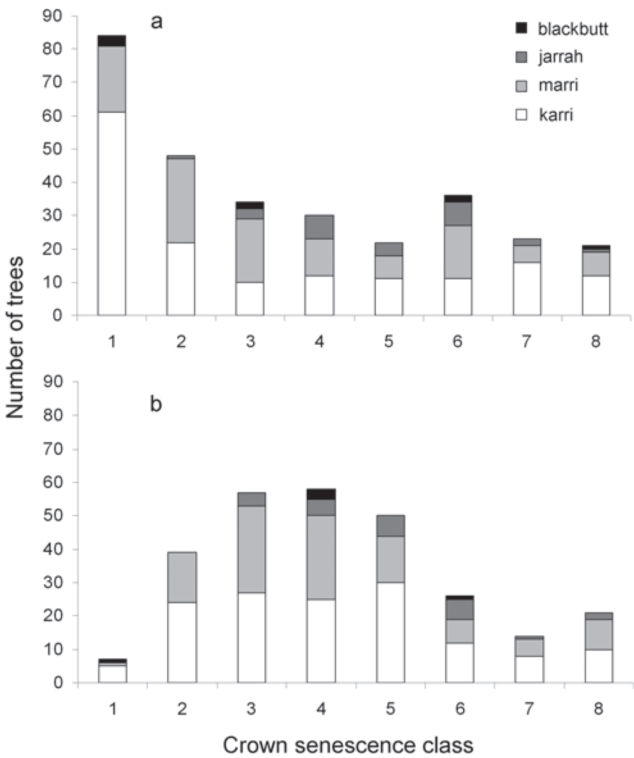

Figure. 3. The shift in crown senescence class distribution before (a) and after (b) regeneration burning in Channybearup 3 (22 months after the regeneration burn).

likely cause was recorded (i.e. fire, exposure). The survival and crown senescence of all remaining habitat trees was re-assessed 22 months after the regeneration burn.

Data analysis

Differences in the median rank of crown senescence for each species before and after the regeneration burn were assessed using Wilcoxon signed-rank tests (Quinn & Keough 2002). The null hypothesis was that the median difference between pairs of crown senescence observations (i.e. before and after burning) was zero. Wilcoxon signed-rank tests were used because this test allows the comparison of paired (same samples before and after an event) data on an interval scale and when the population cannot be assumed to be normally distributed (Quinn & Keough 2002). A comparison test for blackbutt habitat trees could not be undertaken because of the small sample size ($n = 5$). All statistical analyses were conducted in Microsoft Excel 2003 with a significance level of $p \leq 0.05$.

RESULTS

Characteristics of marked trees before harvesting and regeneration burning

In the trial area, 298 trees were retained as habitat trees (Fig. 3a). This corresponds with a retention rate of over three trees per hectare, exceeding the two trees per hectare required under the current Karri Silvicultural Guidelines (Department of Conservation & Land Management 2005). Retained trees were mostly karri (52%) or marri (37%), with a small proportion of jarrah (8%) and blackbutt (3%; Fig. 3a). Due to safety precautions, most of the marked karri trees were skewed towards crown senescence classes SENES1 (39%) and SENES2 (14%), but 32% were recorded within the target crown senescence classes of SENES5 to SENES8 (Fig. 3a). The other tree species had a more even distribution through all crown senescence classes (Fig. 3a). The diameter class distribution of all marked tree species was skewed towards the lower diameter classes (40 to 100 cm DBH; Fig. 4). Not surprisingly, however, karri trees dominated the higher diameter classes (>140 cm DBH; Fig. 4). The stand basal area of the retained trees was 3.1 m^2 ha^{-1} in total, comprising 1.8 m^2 ha^{-1} of karri, 1.0 m^2 ha^{-1} of marri, 0.22 m^2 ha^{-1} of jarrah, and 0.08 m^2 ha^{-1} of blackbutt.

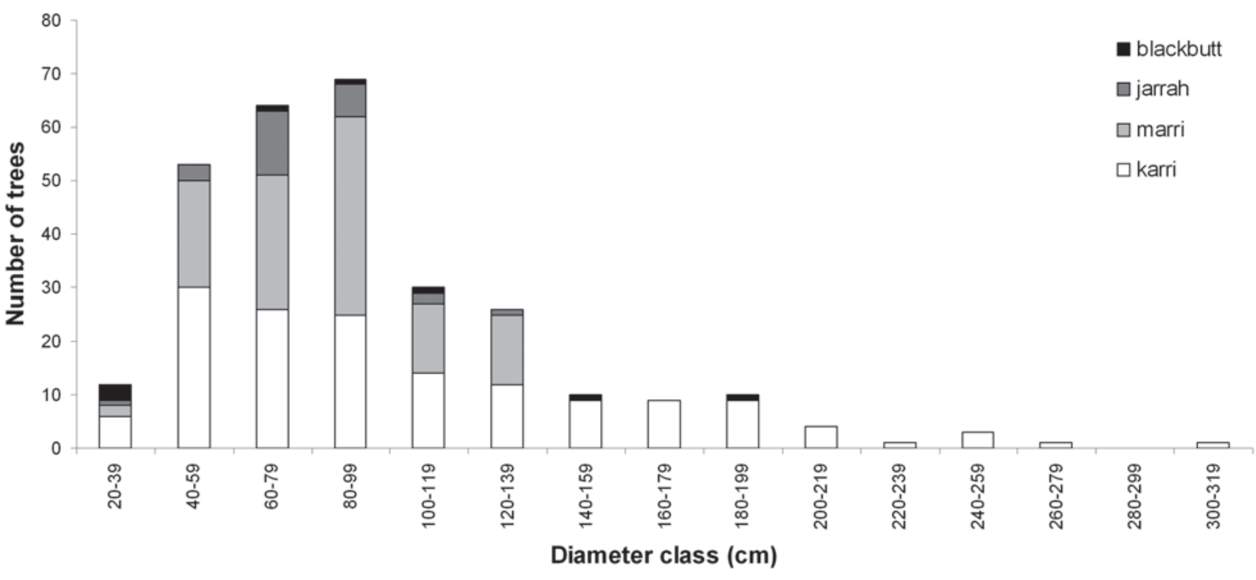

Figure 4. The number of karri, marri, jarrah and blackbutt habitat trees recorded in each diameter class at Channybearup 3.

Tree survival and characteristics

Six months after the regeneration burn

Approximately 94% (280 individuals) of the retained trees were still standing six months after the burning of Channybearup 3. Of the karri trees, 94% (145 individuals) were standing. Of the 18 trees that were no longer standing, three were felled (for safety reasons), nine were burnt down during the regeneration burn, five were knocked down during the rough-heaping of the post-harvesting debris (for safety reasons), and one tree was uprooted, presumably by strong winds. Most of these fallen habitat trees were karri (10 individuals), with five marri, two blackbutt and only one jarrah. Many retained trees were damaged, but not killed, during the harvesting and regeneration burn. This damage included loss of limbs and/or minimal to 100% crown and trunk scorching.

Twenty-two months after the regeneration burn

Twenty-two months after the regeneration burn a further seven habitat trees were no longer standing, presumably blown over due to strong winds (although the exact cause is not known). These fallen habitat trees included three karri, three marri, and one blackbutt. This brought the total number of fallen habitat trees to 25 individuals or 8% of the total number of marked habitat trees. The fallen karri trees were skewed (relative to pre-harvesting and burning data) towards the upper (SENES6 to SENES8) crown senescence and diameter classes but there was no obvious pattern in crown senescence for other species

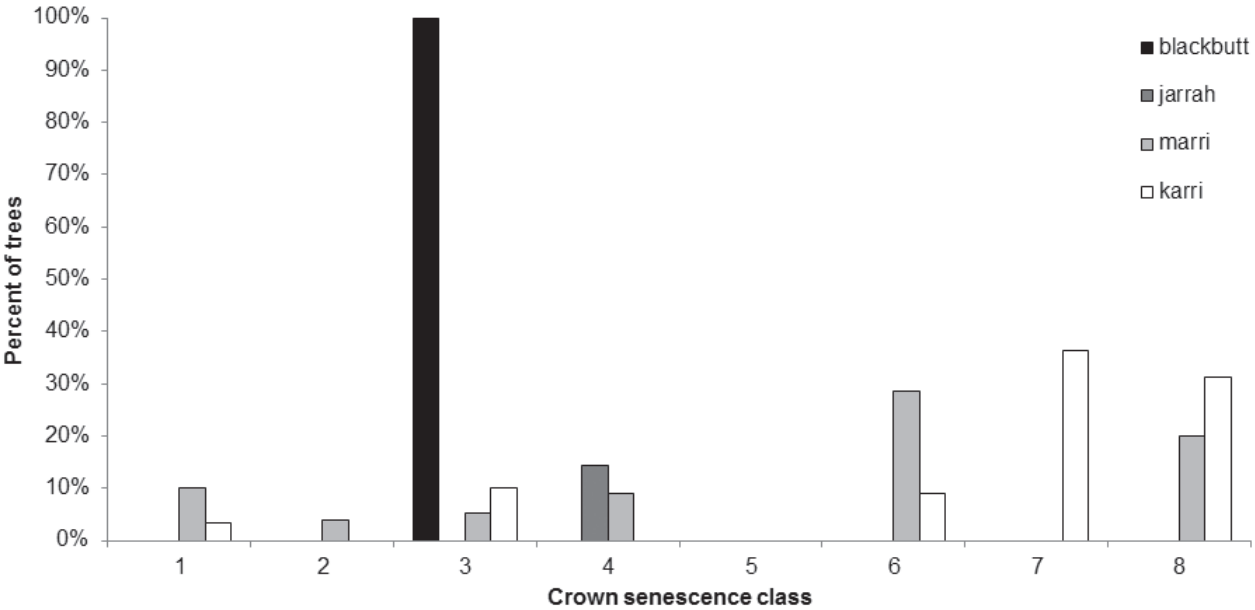

Figure 5. The pre-disturbance crown senescence class distribution of the karri, marri, jarrah and blackbutt trees that fell after the harvesting and regeneration burn within Channybearup 3, expressed as a percentage of all retained trees in each class for each species (note n = 8 for blackbutt).

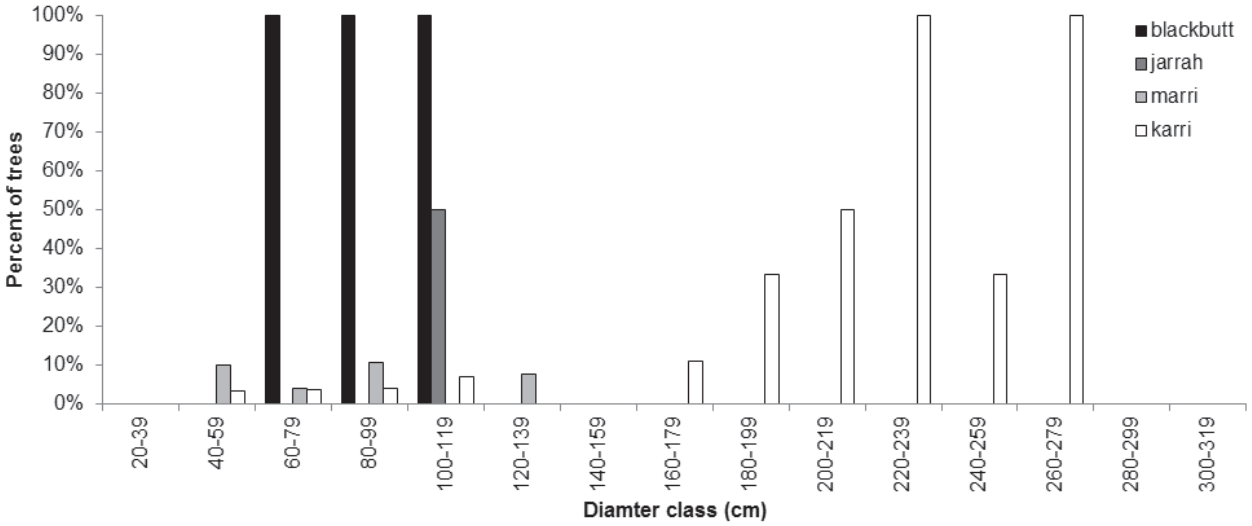

Figure 6. The pre-disturbance diameter class distribution of karri, marri, jarrah and blackbutt trees that fell after harvesting and regeneration burn within Channybearup 3 expressed as a percentage of all retained trees in each class for each species (note n = 8 for blackbutt).

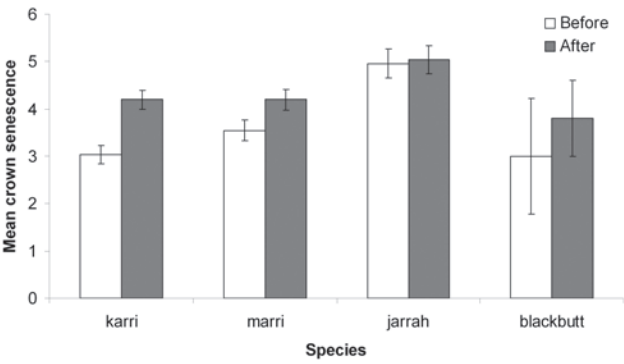

Figure 7. The mean crown senescence (± SE) for each habitat tree species before and after the regeneration burn at Channybearup 3.

(Figs. 5 and 6). Three karri and eight marri habitat trees were dead but still standing 22 months after the regeneration burn.

There was a significant deterioration (i.e. increase in crown senescence) in the crown structure of both karri ($p < 0.001$) and marri ($p = 0.017$) trees after the regeneration burn (Fig. 3b, Fig. 7). The deterioration in crown structure of six retained karri trees is evident in Fig. 8. However, there was no change in crown senescence for jarrah ($p = 0.9$) and no discernible change for blackbutt (Fig. 3b, Fig. 7).

DISCUSSION

Most retained habitat trees (92%) survived the clearfelling and burning of Channybearup 3 and persisted for a further 22 months, including a number of large karri trees with senescent crowns. These findings provide quantitative evidence that retained habitat trees from a variety of life stages, including senescent stages, can survive harvesting and rough-heaped regeneration burns and persist in the short-term. However, the most desirable habitat trees are the most vulnerable to damage from windthrow (Scott & Mitchell 2005). Assuming that these habitat trees will continue to survive, they will increase the structural diversity of the regenerating stand and allow for mature habitat elements, such as tree hollows, to be present. Without the retained primary habitat trees, mature habitat elements would not be present within the coupe until secondary (i.e. immature) habitat trees or karri regeneration reach maturity and begin to senesce (>120 years in age; Bradshaw & Rayner 1997a). For secondary habitat trees of 70 cm diameter this would be about 50 years from the time of regeneration (Bradshaw & Rayner 1997a). The persistence of retained habitat trees in Channybearup 3 should be monitored over a longer time period (>2 years). This will provide valuable information regarding the persistence of mature habitat trees in association with a regenerating karri stand. Many of the large, senescent karri trees are very exposed (Appendix 1, Fig. A2) and may be weakened and blown over during successive winter storms. In particular, the assessment of the condition of tree butts and boles should be incorporated into any future monitoring because their condition (i.e. fire scarring, extent of hollowing, evidence of decay and/or termites, etc.) will likely be related to tree fall (Everham & Brokaw 1996; Mitchell 2013).

While most habitat trees survived the regeneration burn, there was a significant increase in crown senescence of karri and marri trees from low crown senescence to a more intermediate senescence. Previous research found an increased probability of hollow occurrence for trees of intermediate crown senescence (Whitford 2002), raising the possibility of an increased hollow occurrence over time in the retained habitat trees in Channybearup. Although fire can create and extend hollows (Inions et al. 1989), any substantial increase in hollow occurrence will likely occur over a longer period of time, due to the promotion of decay on burnt limbs. The research by Whitford (2002) focused on jarrah and marri trees but similar relationships between crown senescence and hollow occurrence would likely be found in karri trees; however, research is required to confirm this.

The age of karri trees is likely to be an important factor for their survival during and after clearfelling. Many of the karri habitat trees that were killed by the regeneration burn (some still standing), and/or fell over in subsequent years, were large and observed to be in the later stages of crown senescence before harvesting (i.e. SENES6 to SENES8; Figs. 5 and 6). Observations following the regeneration burn revealed large hollow butts in many of the fallen karri trees, indicating a high degree of wood decay (Appendix 1, Fig. A3). This wood decay may have been caused by *Armillaria luteobubalina*, an endemic fungus that attacks the roots of susceptible karri trees causing root rot (Robinson et al. 2003), although this cannot be confirmed. Retaining habitat trees with hollow butts may reduce their longevity as habitat for arboreal species; however, once they fall they provide coarse woody debris that is essential habitat for terrestrial invertebrates and fungi (Grove and Forster 2011; Wardlaw et al. 2009). It must, however, be emphasised that many of the large karri trees in the later stages of crown senescence survived in the coupe up to 22 months after the regeneration burn. The cause of death of the remaining karri and other habitat tree species was mixed and included intentional felling due to safety reasons and also fire and/or wind damage. The damage of some habitat trees is inevitable but reduction of such deaths in the future can be made by (1) ensuring, where feasible, that rough heaps are not near marked habitat trees, or vice versa, and (2) that harvest contractors are more vigilant and aware of the presence of marked habitat trees.

Although rough-heap regeneration burns allow for a greater structural diversity in a regrowth karri stand, the potential ecological benefits need to be considered in the context of reduced growth and density of karri regeneration. Mature karri trees have been shown to suppress karri regrowth up to two crown radii around them (Rotheram 1983). Rotheram (1983) found that a 5% increase in mature karri canopy cover was associated

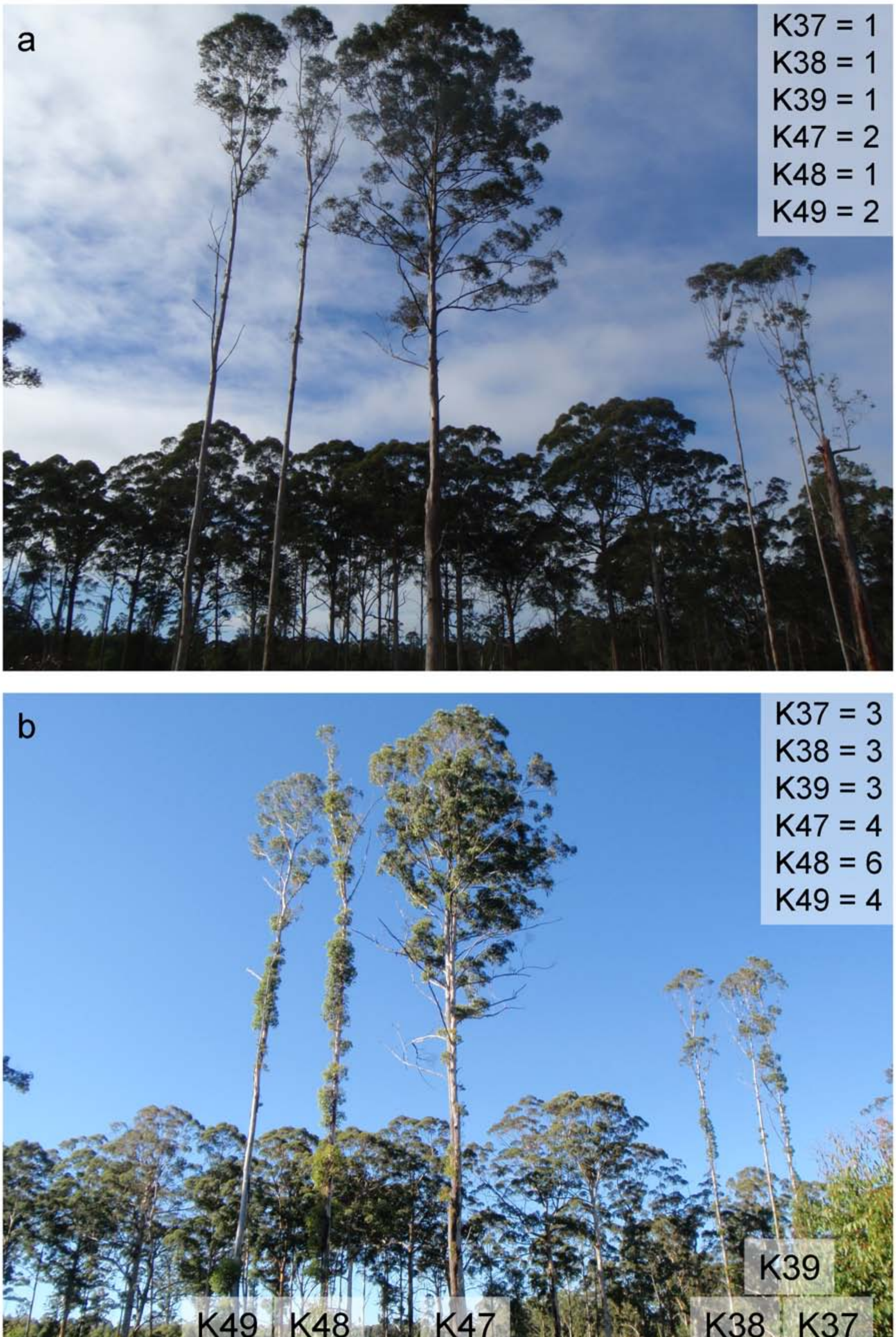

Figure 8. Photos of six retained karri trees (K37, K38, K39, K48 and K79): (a) before the regeneration burn and (b) 22 months after the regeneration burn. The crown senescence score for each retained karri tree is displayed in the top right hand corner in (a) and (b).

with a 10% reduction in regrowth stem volume and 15% understocking of karri regeneration. Root competition for moisture and nutrients, not shading from the canopy, was the likely cause for the suppression of regrowth (Rotheram, 1983). Therefore, the retention of large, mature habitat trees in karri clearfell coupes will likely lead to a reduction of merchantable regrowth volume. Additionally, because competition for moisture likely contributes to the suppression of karri regrowth, the sustained reduction in rainfall in the region (Bureau of Meteorology 2002; Department of Water 2009; Ruprecht & Rodgers 1999) may exacerbate this depressive effect.

Given the potential loss of merchantable regrowth it may be necessary to quantify the effectiveness of the increased stand structural complexity in maintaining the coupe's biological diversity relative to existing measures (Wardell-Johnson et al. 1991; Conservation Commission of Western Australia 2004; Department of Conservation and Land Management 2005). For instance, research could investigate biodiversity recovery in coupes with increased stand structural complexity compared with (1) biodiversity recovery in coupes harvested under current prescriptions (Department of Conservation and Land Management 2005), and (2) the biodiversity in existing formal and informal reserves and stream habitat zones. Research in Tasmania found that Tasmanian common brushtail possums (*Trichosurus vulpecula*) favoured hollow-bearing trees in surrounding mature, dry eucalypt forest compared with mature, hollow-bearing trees retained in recently harvested coupes (<10 years since harvest; Cawthen & Munks 2011). Importantly, the use of habitat trees by brushtail possums was greatest in the oldest regenerating coupe (17 years since harvest) assessed (Cawthen & Munks 2011). Time since disturbance is a key mechanism for species re-establishment in harvested stands (Baker et al. 2013), and it is important that any future research assesses the use of retained habitat trees by biota over the full rotation length between karri harvests (approximately 100 years). Research could also document the vertebrate and invertebrate species associated with each species of retained habitat tree through the senescence stages, giving a broad ecological understanding of the use of habitat trees in regenerating karri stands. Lastly, it is important that any research investigating the recovery of biodiversity in harvested stands compared with the surrounding unharvested forest account for other threats, such as predation from introduced species, as this can override or confound the findings (Wayne et al. 2011).

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APPENDIX 1

Figure A1. Photographs of (a) rough heaped piles at Channybearup 3 and (b) the burning of rough heaped piles.

Figure A2. Photographs of four large, exposed karri habitat trees in Channybearup 3.

Figure A3. A photo of a hollow butt on a large karri habitat tree that fell over after the regeneration burn.