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FRONT COVER: Forestcheck plot burnt during the Perth Hills fire. The photos show
the same location in September 2004 prior to the fire (top), in January 2005 a few days
after the fire (middle), and then again in 2008 showing crown recovery (bottom).
The grass trees and logs in the photo act as reference points. (Photographs by Richard Robinson, DEC)

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Volume Seven
Number Three
September
2010

Conservation Science Western Australia

Conservation Science Western Australia 7 (3) September 2010



Department of
Environment and Conservation



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Recommended abbreviation:
Conservation Science W. Aust.

Published by the Science Division, Department of Environment and Conservation, Locked Bag 104, Bentley Delivery Centre, Western Australia 6983.

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SUBSCRIPTION ENQUIRIES

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<http://www.dec.wa.gov.au/content/view/2321/1808/>

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ISSN 1447-3682

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Fire behaviour during the Pickering Brook wildfire, January 2005 (Perth Hills Fires 71 – 80)

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ABSTRACT

Wildfire burnt 27 700 ha of jarrah (*Eucalyptus marginata*) forest in the Pickering Brook area of the Perth hills during January 2005. Fuels in the area ranged from 1 year-old to 22 year-old in a broad mosaic. A detailed reconstruction of the spread over two days allowed the testing of fire-spread prediction models and the examination of the effects of prescribed burning on fire behaviour.

The Forest Fire Behaviour Tables for Western Australia grossly under-predicted fire spread when a wind ratio of 5:1 was used to convert open wind speed to in-forest wind speed. Using a wind ratio of 3:1, the tables predicted reasonably well at low to moderate wind speeds but over-predicted at high wind speeds.

The fire spread equations based on Project Vesta experiments predicted fire spread reasonably well over the full range of fuel loads and wind speeds. However, the data suggested the need for better models to predict fuel moisture content, particularly after a day of low humidity

Comparison of predicted and observed rates of spread indicated that reducing fuel load by prescribed burning reduced the rate of spread below the rate predicted in 20 year-old fuel loads for at least 8 years. Fire in 3 year-old fuel spread six times slower and was 20 times less intense than fire in 20 year-old fuel

In the absence of a prescribed burning program and assuming the area had not been burnt for 20 years it was estimated the fire would have burnt into the outer suburbs of Perth with the potential for extensive property damage. The final burnt area could have exceeded 100 000ha, or more than three times the area actually burnt.

Keywords: bushfire, jarrah, fuel reduction, Project Vesta

INTRODUCTION

The Pickering Brook fire burnt on lands managed by the Department of Environment and Conservation¹¹ (DEC) east of Karragullen during a ten day period from 15–25 January 2005. The fire resulted from a number of deliberate ignitions, and subsequent spot fires identified as Perth Hills Fires numbers 71–80.

The fire was influenced by strong easterly winds which persisted during the night on several days. A period of strong north-easterly winds preceded the passage of a trough line across the fire area on 17 January. These winds carried the fire across the Brookton Highway, but the forward spread of the fire was immediately stopped in 1 year-old fuels resulting from recent prescribed burning.

On 18 January a new fire, possibly a lightning ignition associated with the passage of the cold front, started to the east of the previous fires. South-westerly winds after the change pushed the main fire east and north though the Beraking pine plantation. On 19 January south-easterly winds pushed the lightning fire into the main fire and

drove the fire towards Mundaring weir. The fire took a further 6 days to bring under control and eventually burnt 27 700 ha.

The easterly spread of the fires directly threatening Karragullen was checked after two days, but the fire had the potential to penetrate the proposed Pickering Brook National Park and posed a major threat to the township of Roleystone in the event of an extreme fire danger with strong north-east to north-westerly wind.

This report reconstructs the spread of the fires during the initial period of easterly spread from 15–17 January. The fire burnt over gently undulating terrain east of the Darling Escarpment and was stopped before it reached the steeper terrain west of the escarpment. Where the fire ran into one or two year-old fuel resulting from recent fuel reduction burns its spread was either stopped completely or checked to such a degree that suppression was easy. However, a detailed reconstruction was required to assess the impact of prescribed burning on fire spread and suppression difficulty in older fuels and to check the applicability of new fire spread equations developed during Project Vesta (Gould *et al.* 2007a).

Project Vesta was a seven-year fire behaviour study of fire behaviour in dry eucalypt forest (jarrah) fuels of different ages. More than 100 experimental fires were conducted in the jarrah forest over three fire seasons to

¹¹ Prior to 1 July 2006 fire management on State forests and conservation reserves was the responsibility of the former Department of Conservation and Land Management.

determine the relationship between fire behaviour and wind speed, fuel moisture content, and fuel characteristics.

The fire event illustrates the potential threat of fire to the peri-urban areas of the Perth Hills and has implications for the management of the proposed Pickering Brook National Park and other parks on the Perth Hills close to suburban development. In particular, this event highlights the need to manage fuels by prescribed burning to reduce rates of spread and make fire suppression easier.

Sources of Data

Details of fire spread were drawn from information in fire diaries maintained by departmental staff, planning documents prepared by incident management teams, satellite imagery taken both during and after the fire, photographs taken by departmental staff and through personal interviews in the field with some of the key firefighting personnel.

Fuel conditions in the fire area were determined by visiting nearby areas of similar fuel ages and assessing the fuel hazard according to the system used in Project Vesta. This system is being recommended to fire agencies, both to quantify the fuel characteristics used in equations to predict fire spread and to better assess the fire threat and

suppression difficulty of different fuel types. Fuel load was determined using the load/age relationship in the Forest Fire Behaviour Tables (FFBT, Sneeuwjagt and Peet 1985).

Weather data were obtained from Perth Airport (30km north-west of the fire area) and automatic weather stations located at Bickley (13km north) and Wandering (50km south-east). Although the anemometer at Bickley was mostly less than 13km from the areas of measured fire spread, the wind direction indicated by the anemometer was not necessarily consistent with the direction of spread of the fire as indicated by the field observations and the scorch pattern apparent in the Landsat imagery.

The wind speed recorded at Bickley was used to compare the observed rate of spread and the predicted rate of spread from the Project Vesta equations and FFBT. It is possible that wind speeds experienced over the fire area varied considerably from those recorded at Bickley.

Fuel moisture content during the period of the fire was estimated using the initial moisture content calculated at the DEC office at Mundaring Weir and interpolated using a process-based fuel moisture transport model (Matthews 2006) and the equations to determine absorption moisture content developed by Alan McArthur (McArthur 1962; 1967).

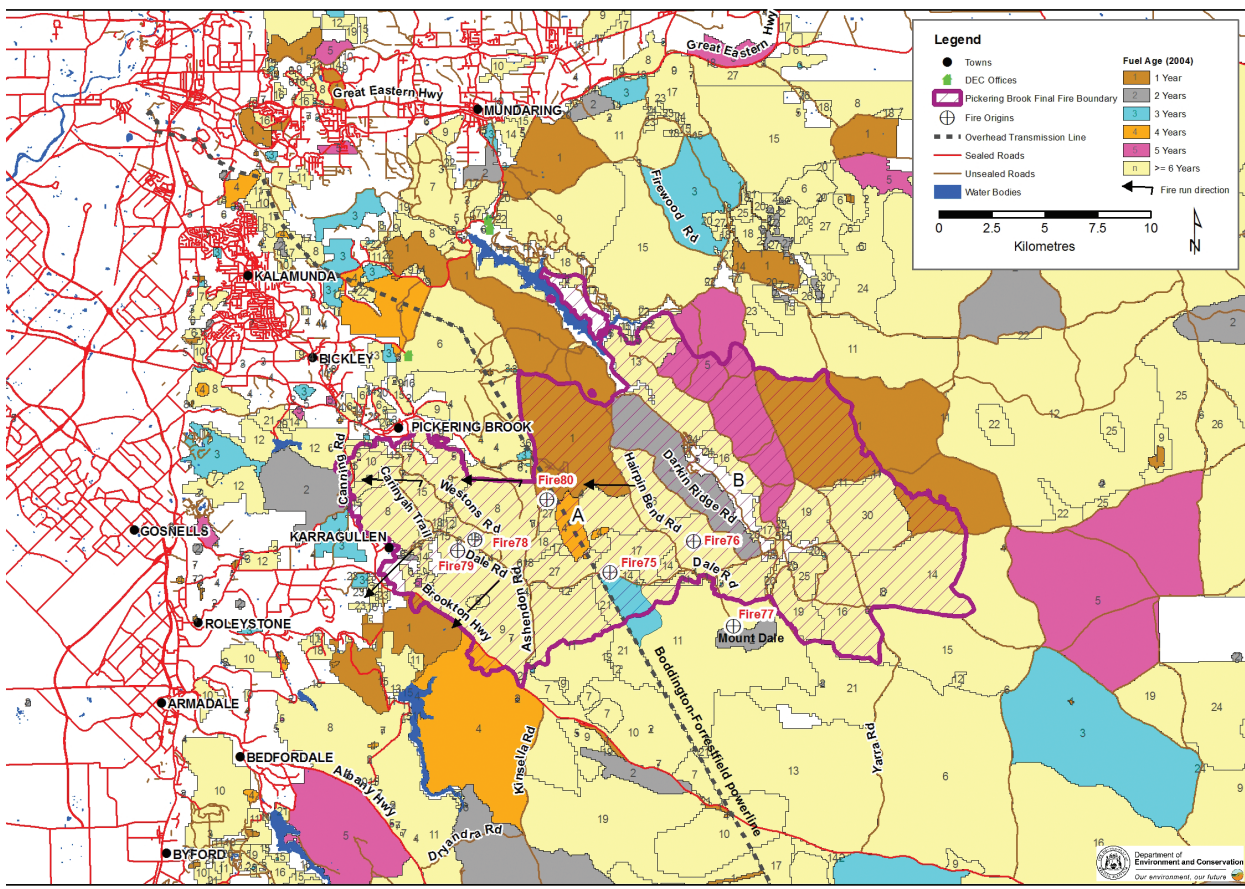


Figure 1. Overview map of the Pickering Brook fire showing the final fire boundary major place names and features mentioned in the text, and fuel age as at January 2005.

Origin and development of the Fires

1800 hours Saturday 15 – 1200 hours Sunday 16 January 2005

The fires were the result of deliberate ignition (arson) during the evening of Saturday 15 January 2005. The first fire, Fire 75, was lit near the junction of a forest track and Dale Road about 500 m east of the Boddington-Forrestfield powerline (Fig. 1)²². The fire was detected at 1815 hours after routine aerial detection had been completed for the day. It is possible that the fire was lit some 15 to 20 minutes earlier than when detected. For the purpose of determining average fire spread, it was assumed that the fires originated 15 minutes before they were detected.

The second fire, Fire 76, was detected off a forest track between Hairpin Bend Road and Darkin Ridge Road at around 1825 hours. This fire may have been lit at around 1810 hours. It was not attacked early because it was headed towards an area of low fuel near the Boddington-Forrestfield powerline and resources were directed to other fires.

Fire 77 was detected at 2030 hours burning in light fuel on Mount Dale and was quickly suppressed.

Fire 75 was initially burning in 16 year-old fuel and was held at the Boddington-Forrestfield powerline for several hours by crews from DEC and the Roleystone Bush Fire Brigade. A spot fire was detected east of the powerline and burning towards Permit Road. No time was recorded for this ignition, but I have assumed that it was around 2200 hours when the fire approached the powerline break. East of the powerline, the fire was burning in 26 year-old fuel and reported to be spotting up to 1km ahead of the main flame front. Attempts were made to control fire on

tracks 500 m east of Ashendon Road at around 0300 hours but these were unsuccessful due to short distance spotting and equipment breakdown. From ignition, the wind direction was steady from the east-south-east.

A further fire (Fire 78) was detected 2km west of Ashendon Road near Dale Road at 0130 to 0140 hours on Sunday morning. This fire was thought to be another deliberate ignition, although it was only a little over 2km directly downwind from a fire spreading vigorously in 26 year-old fuel (Fire 75) and may well have been a spot fire originating from Fire 75. Another fire, Fire 79 was located near Carinyah Trail at about the same time and was also thought to be a deliberate ignition. The location of this fire was a little south of the projected centre line of Fire 75 but was still within the 12 degree arc where spot fires are most likely to occur downwind (Cheney & Bary 1969). Both fires were contained to a small area and did not contribute to the spread of the larger fires.

By 0800 hours on Sunday morning Fire 75 had crossed Ashendon Road into eight year-old fuel, and by 1100 hours the western end of the fire had been contained by heavy equipment after burning about 300 m west of Ashendon Road.

Fire 76 burnt unchecked in 16 year-old fuel in a west-north-westerly direction. It soon crossed Hairpin Bend Road and continued to burn strongly until it ran into an area of sparse fuel. This area was rated as a three year-old fuel but it was an area that had been logged and regenerated and was carrying little or no surface litter fuel. A new fire, Fire 80, was detected in 1 year-old fuel between the Boddington-Forrestfield powerline and Ashendon Road at 0200 hours. This fire was also downwind of Fire 76 and, in my opinion, was probably a spot fire originating from a fire burning in heavy 16 year-old fuel. No suppression action was taken on this fire and it was allowed to spread slowly in light fuel.

There was only limited information on the initial spread of Fire 76, but between 0400 and 0500 hours an

²² Spread maps in this article are reproduced at too small a size to legibly show all place and road names included in the text. Readers are referred to 1:50 000 Operational graphics (COG) map sheets 2134 III Mundaring, 2134 II Chidlow, 2133 IV Kelmscott and 2133 I Beraking.



Figure 2. Southern flank of Fire 76 at 0411 hours, 16 January 2005. (Photograph courtesy of Sam Hurd, CALM)

officer mapped the head of the fire and photographed the flank of the fire (Fig. 2). The measurement at the head of the fire indicates that it had entered the light fuel and was almost at the extent of its run for that period and was reported to have dropped in intensity considerably compared to the flank fire, which was photographed at 0411.

These observations suggest that between 1810 and 0410 hours the fire burnt 6km at an average speed of 600 m h⁻¹. However, it is likely that it took some time for the fire to build to its potential rate of spread for the prevailing conditions, and at times may have been spreading at twice this rate in 16 year-old fuel. The fire burnt under steady easterly winds and was unconfined by suppression action on the flanks, and at 0400 hours had a length-to-breadth ratio of 6:1. This ratio indicates very slow flank fire rate of spread and was used in the reconstruction of other fires.

By 1100 hours the northern flank of Fire 75 had moved north towards the southern flank of Fire 76 and the crews had edged the eastern side of Ashendon Road between the Fire 75 and the spot fire (Fire 80) in the 1 year-old fuel. As conditions became more severe during the morning, crews were experiencing increasing difficulty with hop-overs from the edging in the 16 to 17 year-old fuel which would have had a bark hazard rating of between 3 and 4 (Gould *et al.* 2007b). The southern edge of the fire between the Boddington-Forrestfield powerline and Ashendon Road was contained by direct attack along the flank.

1200 – 2400 hours Sunday 16 January

Shortly after 1200 hours the fire broke away at a number of locations along 2km of Ashendon Road at the north-western end of Fire 75 and at Fire 80, and suppression efforts were abandoned at 1215 hours (Fig. 1). Wind speed at Bickley was 27 km h⁻¹ from a direction of 100° at 1200 hours and then backed to due east (90°) at 1400 hours. The wind speed then decreased slowly to 16.5 km h⁻¹ after 1700 hrs.

The fire started spreading from a number of locations in separate narrow heads, which made field observations and interpretation of the scorch pattern from satellite imagery difficult (Fig. 3). There was an observation of a narrow head fire crossing Westons Road at around 1500 hours, and an observation of strong fire activity in the gully north of Westons Road suggests that the main head fire was further advanced to the west at this time.

An air-observer plotted the position of the fire at 1547 hours, at which time it appears that the individual fire fronts had coalesced into a single front. Between 1215 and 1547 hours the fire travelled 5.25km at an average rate of spread of 1475 m h⁻¹

The air observer estimated that the rate of spread of the fire at 1710 hours was 1200 m h⁻¹. This estimation was made by selecting GPS way-points over a period of 5 minutes. Spot fires were thrown 2–3km ahead, starting to the west of Canning Road and Springvale Road.

At 1737 hours the wind changed to the north-east and the fire behaviour and rate of spread reduced dramatically. The fire had also burnt over a low ridge south

of the Munday Brook Walk which further slowed the rate of spread as it backed downhill against a fire-induced eddy wind. Fire fighters commenced burning-out from a private property boundary near Karragullen at around 1800 hours.

Over this period the fire burnt mostly through 8 year-old fuel. There was a block of 18 year-old fuel between Westons Road and Carinyah Road which would have dramatically increased the intensity of the fire in the period from 1500 to 1530 hours. Fire in this heavy fuel may well have been the source of firebrands that caused spot fires east of Canning Road some 5km downwind.

The fire crossed Canning Road at 2200 hours and a spot fire was reported west of Springvale Road. Two and three year old fuel west of Canning Road enabled fire crews to contain the breakaway and the spot fires to a relatively small area.

Fire suppression along the eastern flank proceeded from Ashendon Road west across Dale Road and Carinyah Trail to private property in line with Illawarra Road.

2400 – 1200 hours Monday 17 January

Most of DEC's resources were attending to the protection of private property in conjunction with Fire and Emergency Service Authority staff and bushfire brigades, with the result that the southern flank of the fire was largely unattended. At 0400 hours the wind at Bickley was 90° and rose to 28 km h⁻¹ and maintained this speed until shortly before 1000 hours. After 0600 hours the wind direction at Bickley started shifting towards the north and was 60° at 1000 hours and 30° at 1100 hours. There were no observations of wind direction in the fire area in the early morning hours, but it appears from interviews with staff and examination of the scorch pattern from Landsat imagery that the wind at the fire area went to the north-east earlier than at Bickley, and tended to blow more consistently from a direction of 45°.

DEC staff observed a break-away burning in a swamp south of Dale Road at 0445 hours between Permit Road and Ashendon Road. The fire was 500 m long and described as burning quietly close to the road which indicates that the fire had broken away from the southern flank some time earlier and burnt under an east-north-easterly wind. The time that the wind direction shifted to the north-east is uncertain, but the pattern of the fire spread indicates that it did not travel much further west than the location at 0445 hours and I have assumed that it started travelling in a south-westerly direction at 0500 hours.

Air observation plotted the head of this breakaway across Ashendon Road at 0630 and at 0951 hours Landsat imagery mapped the headfire at Brookton Highway with significant spotting south of the highway. There is significant thermal flare in the Landsat imagery which exaggerates the extent of the fire perimeter, but from examination of the imagery and the scorch pattern in the vegetation I have concluded that the fire had just reached the Brookton Highway at 0951 hours. I have assumed that the fire travelled 4.5km between 0445 and 0951 hours at an average rate of spread of 900 m h⁻¹.



Figure 3. Scorch pattern resulting from fire spread on 16 January looking north-east along Dale Road from the junction with Westons Road. The green band on the left side indicates slow spread where the fire was checked overnight before breaking away at 0430 hours on 17 January (Photo: Tim Foley).

The Landsat image at 0951 hours showed that a wind change associated with a cold front had just reached the fire area and was blowing from the west, although the wind at Bickley did not shift to 260° until 1500 hours. In any event, the scorch pattern shows that there was little spread towards the south-west after 1000 hours. As the cold front passed over there was very unstable cold air above the area which resulted in a spectacular convection cloud over the fire, but as the wind speed was low there was only slow spread on the northern and eastern sectors of the fire.

Fuel characteristics

Fuel age maps maintained by DEC were used to identify adjacent unburned areas where fuels were of similar ages to those in the burnt areas. Fuels were inspected in October 2005 with Dr Lachie McCaw^{3,3}. The areas inspected had only a small addition of leaf fall over the winter months since the fire, and were therefore considered to be of a similar hazard for equivalent forest types in the burnt area. Fuel hazard ratings for selected fuel types are given in Table 1 using the fuel hazard and

fuel scoring procedure adopted for Project Vesta (Gould *et al* 2007b).

There was a distinct difference in the fuel hazard between the eastern and the western sections of the fire.

In the area near the origin of the fire, 3 year-old and 20 year-old fuels were rated for near-surface fuel hazard at 1.5 and 3 respectively. These hazard ratings were very close to the hazard ratings for the northern jarrah fuel type (Sneeuwjagt and Peet 1985) observed at Dee Vee block during Project Vesta (Fig. 4).

Fuel hazards in forests on the western side of the fire close to the Darling escarpment were rated for near-surface fuel hazard in two, three, and 26 year-old fuels. Hazard ratings were 2–2.5 for the two and three year-old fuels, and 4 for the 26 year-old fuel.

These hazard ratings were a full hazard class higher than the average rating for the northern jarrah fuel type at Dee Vee and slightly higher than the average fuel hazard rating for the southern jarrah fuel type at McCorkhill forest block near Nannup. This difference in fuel characteristics most likely reflects the greater productivity of the forests close to the escarpment which have an annual average rainfall of 1200mm, compared to further east within the fire area where annual rainfall is 900mm or less. Fuels closer to the escarpment had a much denser low shrub layer including a high proportion of the grass tree *Xanthorrhoea gracilis*, which supports the bark and litter in the near-surface layer to a height of 30 cm.

At the one location beside Canning Road, a forest with 10 year-old fuels had a distinct grassy-like understorey characterised by *Loxocaria sp.* The fuel load was not sampled and visually it appeared to be lighter than the average fuel load for a 10 year-old southern jarrah fuel type. However, because of fine grassy structure of the *Loxocaria sp.* fires in this fuel type would spread faster than in the litter and low shrub fuels characteristic of the northern jarrah fuel type.

In my opinion the average near-surface fuel hazards score for the jarrah forest at the Dee Vee site would be appropriate for predicting fire spread for the initial runs of the fire up to Canning Road. However, for extrapolation of fire spread west of Canning Road, fuels would need to be rated a full hazard rating class higher than the average rating based on the Dee Vee site.

The average height of the near-surface fuel for the Dee Vee and McCorkhill sites is given in Fig. 5. The fuel sampling suggested that the near-surface fuel heights of 8 cm and 12 cm observed for 3 and 20 year-old fuels respectively in the western area of the fire were lower than the standard average curves for Dee Vee which were 14 cm and 20 cm. However, there was wide variation of near-surface height in the northern jarrah fuels at Dee Vee depending on local plant associations (Fig. 5). Without a comparable fuel type over the bulk of the fire run on 15–17 January, the average near-surface fuel height for Dee Vee was assigned to fuel ages east of Canning Road.

West of Canning Road, the near-surface fuels long-unburned areas were considerably higher than the average for Dee Vee fuels with a dense layer of low shrubs supporting leaf twig and bark litter. These fuels were

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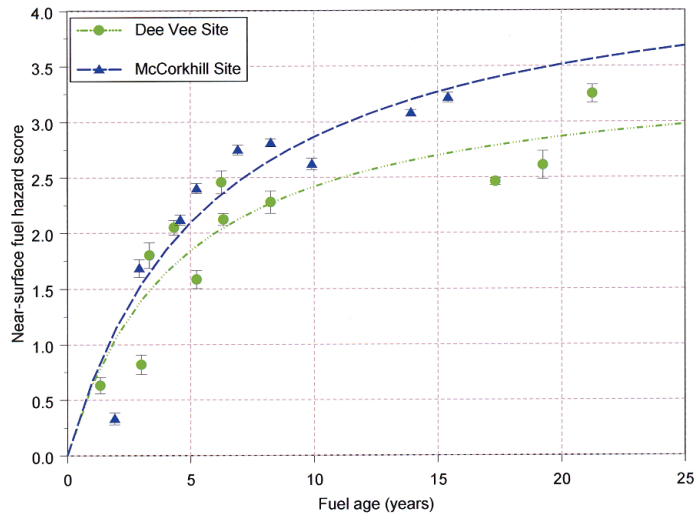


Figure 4. Change in hazard score of the near-surface fuel layer on blocks of different age after burning at Dee Vee and McCorkhill sites (bars indicate one standard error of the mean) from Project Vesta (Gould et al 2007a).

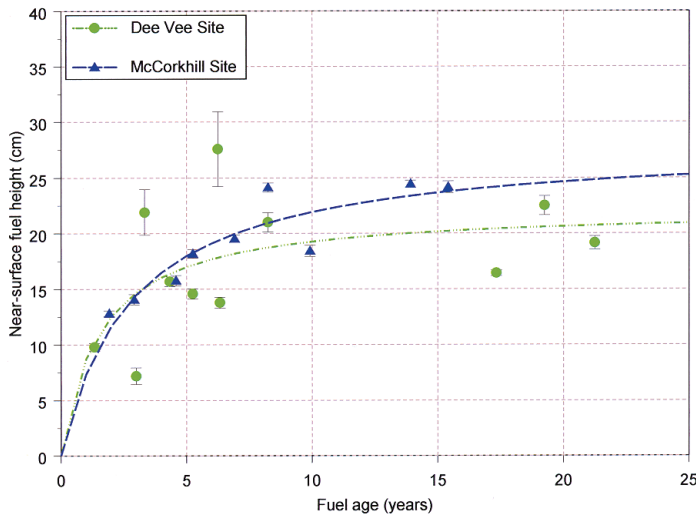


Figure 5. Accumulation of height of the near-surface layer on blocks of different age after burning at Dee Vee and McCorkhill sites (bars indicate one standard error of the mean).

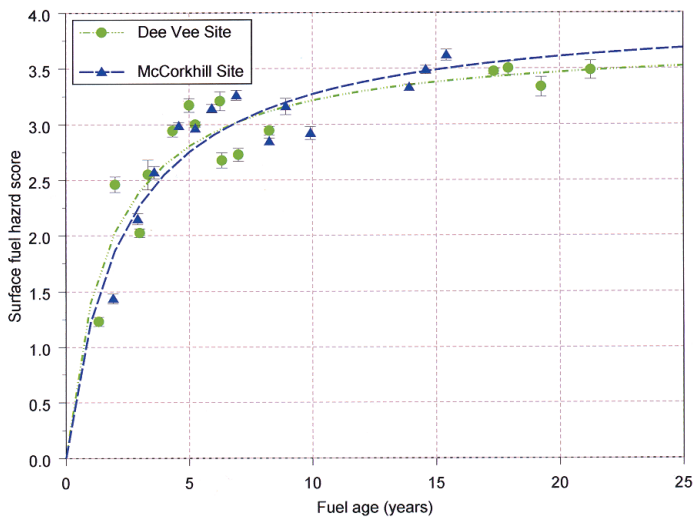


Figure 6. Change in hazard score of the surface fuel layer on blocks of different age after burning at Dee Vee and McCorkhill sites (bars indicate one standard error of the mean).

assigned a fuel height of 35 cm based on depth measurements in layers visually assessed as the mean layer when subjectively stratified into low, medium and high categories. These fuels did not burn because the fire was controlled in light fuels but the figures were used later for extrapolation of fire spread in the absence of prescribed burning.

Surface fuel characteristics varied according to time since fire, but a difference between western and eastern parts of the fire was less evident. This is consistent with the surface fuel hazard score for the Dee Vee and McCorkhill sites. Surface fuel hazard ratings were therefore estimated directly from the accumulation curve for Dee Vee developed using Project Vesta data (Fig. 6)

COMPARISON OF RATE OF SPREAD WITH FIRE PREDICTION TABLES

The emergency nature of fire suppression means that it is difficult to obtain sufficient data to accurately validate experimentally-determined fire spread equations. Fire crews have limited opportunities to make a detailed record of fire perimeter locations. Even when officers are specifically designated to record fire spread, access and visibility are limited, and it can take considerable time (sometimes hours) to negotiate forest roads and move from one location to another. Aerial observations for fire control are often more concerned about whether the fire has crossed a particular road or not, rather than the exact position or shape of the fire. Suppression action may hold up the spread of the fire, and when crews are having difficulty holding a fire the exact time of a breakaway may not be recorded.

A reconstruction of the fire spread is presented in Fig. 7. In this reconstruction, I have made the following assumptions:

- wind speed and direction recorded at the automatic weather station at Bickley could be applied at the fire area;
- fire starting at a point and spreading under a steady wind direction, would have a length to breadth ratio of 6:1;
- fire spread into the prevailing wind direction (backing spread) was constant at 30 m h⁻¹
- narrow strips of unscorched canopy, roughly parallel to the prevailing wind direction, were the result of a backing fire of low intensity resulting from a local wind shift causing the wind to blow the flames along the flank towards the burnt area. The rate of spread within these narrow strips was similar to the backing rate of spread of 30 to 50 m h⁻¹;
- narrow strips of unscorched canopy designated the shape of the perimeter of the fire in that area;
- intermediate rates of spread between confirmed observations of the head fire location were adjusted proportionately for variation in wind speed, fuel moisture and fuel load using the Vesta fire spread equations (Gould *et al.* 2007a).

This reconstruction was necessary to place point observations of fire location in context with the overall fire perimeter and to allow more a detailed evaluation of the performance of the fire spread equations.

Observed average rates of spread were determined for three periods:

- Fire 76 from origin at 1810 hours on 15 January to location at 0410 hours on the 16 January of 6km in 10 hours (600 m h⁻¹);
- combined fire spread from Ashendon Road at 1215 hours to the headfire location plotted by the air observer at 1547 hours on 16 January. Average spread was 1475 m h⁻¹. A 5-minute estimate of rate of spread at 1600 hours was 1200 m h⁻¹;
- spread of the major head of the breakaway along the southern flank on 17 January between 0400 and 0500 hours. The fire broke away near the Boddington-Forrestfield powerline, crossed Dale Road at 0630 hours and the Brookton Highway at 0951 hours, as recorded on Landsat imagery.

The predicted maximum rate of spread using the FFBT is given in Table 2. The wind ratio generally used by DEC for fire danger rating is 5:1 and this ratio was used for spread prediction calculations at the Mundaring office.

This ratio gives very low rates of spread across the range of wind speeds commonly encountered during the fire and, in my opinion, grossly under-predicts fire spread. The exposure of the anemometer at Bickley is about 8 m above the top height of the canopy and a 3:1 ratio is considered to be more appropriate for this exposure. Also, a ratio of 3:1 was found to be common for several tower sites (Neil Burrows⁴ pers. comm.) and I consider this should be used universally in dry forests for wildfire spread prediction during summer. Although a ratio of 3:1 is used for wildfire prediction by some fire behaviour officers (Lachie McCaw pers. comm.⁵), it is apparent from the documentation this was not the case for the determination of initial spread made at the Mundaring office.

The Project Vesta equation to predict fire spread from wind speed, fuel moisture and fuel characteristics is:

$$R_{ss} = [30 + 3.102(U_{10} - 5)^{0.904} \exp(0.279S_{fhs} + 0.611NS_{fhs} + 0.013NS_h)] \cdot [(M_f^{-1.495})/0.0545] \cdot [\exp^{0.069\phi}]$$

where:

- R_{ss} = the potential quasi-steady rate of spread (m h⁻¹)
- U_{10} = wind speed at 10 m in the open (km h⁻¹)
- S_{fhs} = surface fuel hazard score
- NS_{fhs} = Near-surface fuel hazard score
- NS_h = Near-surface fuel height (cm)
- M_f = fine dead fuel moisture content (%)
- ϕ = slope of the ground surface

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⁵ Principal Research Scientist, Science Division, Department of Environment and Conservation, Manjimup.

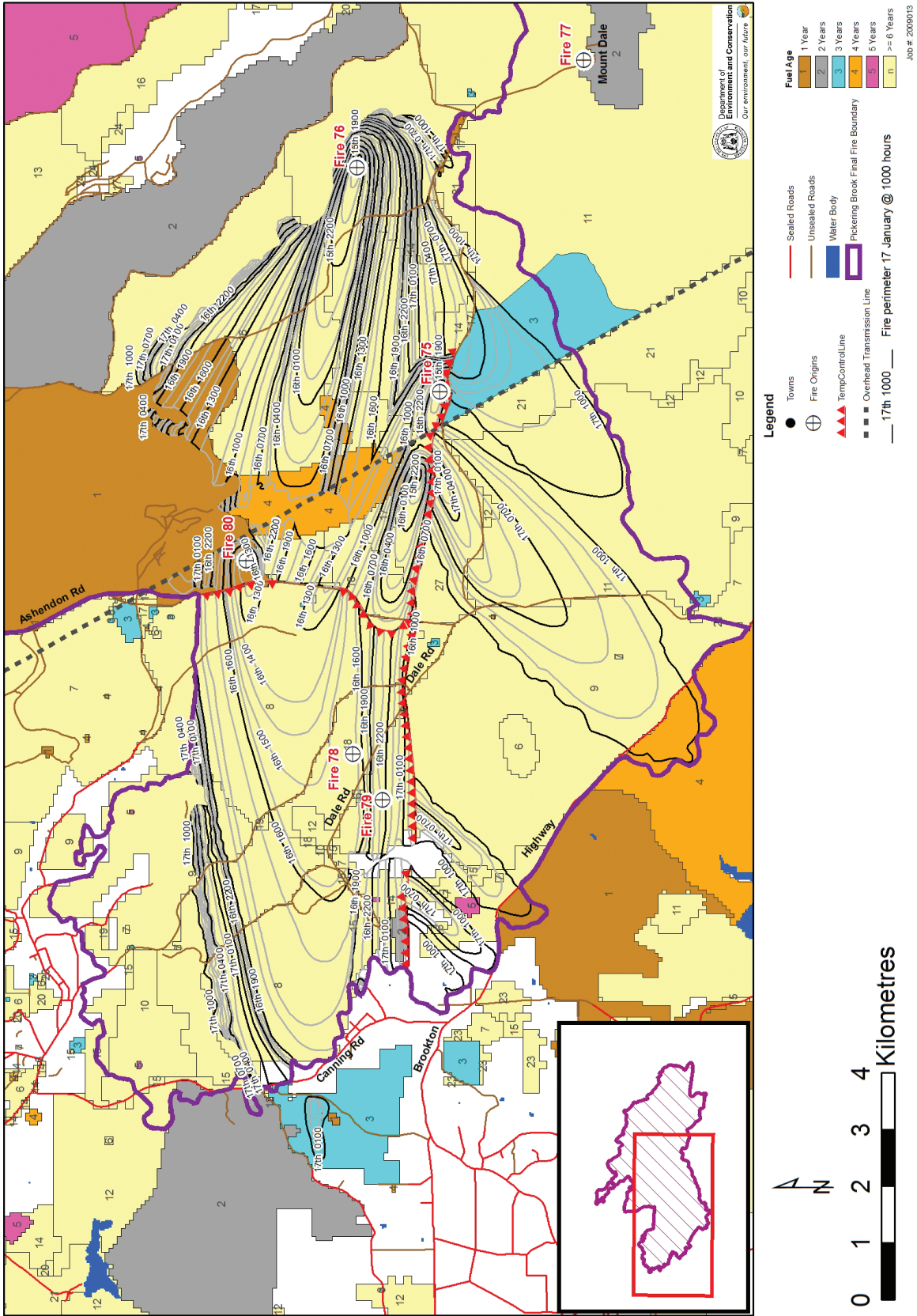


Figure 7. Reconstruction of the pattern of fire spread of the Pickering Brook fires, between 1800 15 January and 1000 17 January 2005. Isochrones show the perimeter of the fire at hourly intervals with additional isochrones at 1430 and 1545 hours 16 January.

Fuel characteristics for predicting fire spread in different fuel ages are given in Table 1.

A comparison of the rate of spread predicted by the Project Vesta equations and the FFBT using a 3:1 wind ratio with the average observed rate of spread is given in Table 3.

Both the Project Vesta equation and the FFBT for northern jarrah using a wind ratio of 3:1 predicted reasonably well for mean rate of spread on the 15 and 16 January. There were insufficient observations to directly validate rate of spread predictions for individual fuel ages. However, DEC officers observing the fire noted the increased fire behaviour in older fuel loads, and it is reasonable to accept that the relative fire spread in different fuels of different age described by the Project Vesta equation is more accurate than that predicted by the FFBT.

DISCUSSION

The function in the FFBT that describes the increase in rate of spread (R) with increasing wind speed (U) is of the form (Peet 1965):

$$R = 1/(a-bU)$$

where a and b are constants determined experimentally.

This type of function results in a very rapid increase in rate of spread at high windspeeds so that the speed of the fire eventually exceeds the wind speed, which is clearly impossible. There is now good evidence that the relationship describing the spread of a large continuously heading fire is linear (Cheney *et al.* 1998, Linn and Cunningham 2005). The curvilinear relationships described by Peet (1965), McArthur (1962; 1967) Rothermel (1972) and Burrows (1999) are inappropriate for extrapolation to strong winds beyond the range of the original data because they describe the spread of small developing fires where there is a change in spread mechanism from a backing to a heading fire. It is now accepted that two equations are needed to describe spread above and below the threshold wind speed, above which the fire changes from a predominantly backing fire to a continuously spreading headfire.

The statistical model used to form the Project Vesta equation describes rate of spread as a power function of wind speed within an exponent of 0.904, which is almost linear above a threshold wind speed of 5 km h⁻¹ at 10m in the open. For this reason, and because the Project Vesta equation used fuel structural characteristics to determine rate of spread, a further comparison of the performance of the Project Vesta equation was made for key periods of fire spread.

1800 hours 15 January – 1200 hours 16 January

Fire 76 burnt under a steady wind direction of 110°, which was confirmed by the bearing from the origin of the fire to the location of the head fire at 0500 hours. The fire burnt for 6km through 16 year-old fuel until it ran into

three year-old fuels, which effectively stopped the forward spread of the fire. If no allowance is made for the initial build-up of the fire, then the Project Vesta equation over-predicts distance travelled in six hours by 18%. However, under such a steady wind direction and under stable atmosphere at night, the time for a forest fire to develop a head fire wide enough to reflect its potential rate of spread could be as long as three hours. I have assumed a constant build-up over three hours between 1800 and 2100 hours before the fire reached its predicted potential rate of spread of 826 m h⁻¹ and it then spread at the rate predicted for the prevailing conditions over the next seven hours. On this assumption, the difference between the predicted and actual distance travelled is -3%.

Fire 75 started at around 1800 hours and spread considerably slower than the predicted rate of spread. However, it was held up by suppression forces at the Boddington-Forrestfield powerline for several hours until it spotted across the powerline break. The exact time and location of the spot fire is not known but it is assumed it originated 500 m west of the powerline along the projection of the central axis of fire at 2200 hours. After allowing three hours for the spot fire to build up to the potential rate of spread, the predicted rate of spread appeared to reasonably describe the progress of the fire until it was held up by suppression crews taking action east of Ashendon Road at around 0300 hrs. This fire crossed Ashendon Road but was contained in eight year-old fuels west of Ashendon Road.

1200 – 2400 hours 16 January

The exact time and number of breakaways across Ashendon Road after 1200 hours is uncertain. Field inspection identified two major breakaway fires. One was opposite Fire 80 in the two year-old fuel and the second breakaway fire 1.5km south. Crews tried to track the flanks of these fires before attempts at suppression were abandoned. Fires originating from these locations are consistent with later observations of fire spread and the shape of the fire as indicated by the scorch pattern interpreted from Landsat imagery.

I have assumed that these fires would individually take time to develop before they coalesced into a wide head and assumed that they spread west some 750–1000 m by 1300 hours, which is reasonably close to the rate of spread predicted by the Project Vesta equations of 769 m h⁻¹. These fires coalesced more rapidly over the next 90 minutes to form a single continuous head by 1430 hours. However, if this assumption is correct, the average rate of spread between 1430 and 1600 hours was around 2000 m h⁻¹, or twice the predicted rate of spread in 18 year-old fuels under the prevailing conditions.

Models to predict the fuel moisture content use different assumptions. The latest process model by Matthews (2006), used for these calculations, predicts the moisture content from an initial moisture value and tracks the progressive changes in moisture with changing atmospheric conditions. The empirical model used by McArthur (1967) in his forest fire danger meter assumes

there is some time-lag after a change in relative humidity before the fuel reaches the equilibrium moisture content and his tables predict an average value from temperature and relative humidity when the fuel is absorbing water. This model predicts lower fuel moisture contents during the afternoon and, if used as an input to the Project Vesta fire spread equation, results in a higher predicted rate of spread (see Table 4).

Between 1430 and 1700 hours the McArthur model predicts fuel moisture content of 4%. When used in the Vesta equations this would give a predicted rate of spread of 1743 m h^{-1} , which is closer to the rate of spread deduced from field observations.

There are other factors that may have contributed to a higher rate of spread observed during this run:

- the front created by multiple breakaways from Ashendon Road was more than 1km wide and is significantly higher than that of the experimental fires which were mostly around 100 m wide. The potential rate of spread of very wide fronts may be higher than that determined by the experimental fires;
- tall grass trees in the area may have carried substantial fuel in unburned skirts. The elevated fuel supported by the grass trees' skirts may result in a higher rate of spread than that determined using the characteristics of the surface and near surface fuel alone;
- wind speed in the fire area may have been significantly higher than that measured by the anemometer at Bickley;
- errors in observation of time and location.

Measurements during the Project Vesta experiments and observations during the Canberra bushfires in 2003 show that the spatial variation of wind in the landscape is substantial and often poorly represented by a measurement at a single location. This creates considerable uncertainty in the reconstruction of any wildfire or, for that matter, the prediction of forward spread during wildfire events. It also means that precise verification of experimental results describing the effect of fuels on rate of spread using wildfire data is very difficult, if not impossible.

In my opinion, the adjustment of rate of spread according to the ratios determined by the Project Vesta fire spread equations for fuels of different age provided a reasonable description of the fire behaviour as manifested by the spread pattern illustrated in Fig. 7, the pattern of fire behaviour illustrated by the differential burning patterns, the spot observations of fire spread, and the observational reports of changes in fire behaviour made by experienced fire officers.

0000 – 1000 hours 17 January

Analysis of the spread pattern suggests that the first breakaway on the southern flank occurred in the vicinity of Occidental plot number one between midnight and 0100 hours when the wind first shifted to an east-north-easterly direction. This breakaway was described as a long, narrow fire and was observed across Dale Road at around 1545 hours.

The rate of spread predicted from the Project Vesta equations was about 40% less than the average spread deduced from fire spread observations (Table 4). The relative humidity overnight reached a maximum value of only 52% at 0400 hours. As a result the difference in moisture content predicted by Matthews' process moisture content model and the McArthur absorption moisture content model was up to 4%.

When the absorption fuel moisture content predicted by the McArthur model was used in the Vesta equations, the predicted rate of spread is much closer to the observed rate of spread (Table 4).

It would appear from these observations that during the afternoon of 16th under windy conditions at night on the 17th January the absorption fuel moisture content model used by McArthur provides a better prediction of rate of spread than when moisture contents are derived from process fuel moisture model. However, this model too is really not appropriate because desorption conditions with rapidly falling relative humidity existed after 0400 hours. High rates of spread during the night were also observed at the January 2003 Mount Cooke fire in Perth Hills District (L. McCaw pers. comm.⁶). There appears to be a real need to develop better models to predict fuel moisture content, particularly when low humidity persists overnight.

East of the Boddington-Forrestfield powerline, the uncontained flank of Fire 76 spread southward towards Dale Road. Some edging had been carried out for about 2km east of the powerline along Dale Road. There is no record of the time that this flank crossed Dale Road, but it appears it had not crossed by 0400 hours. Landsat imagery and the shape of the final perimeter indicate that this breakaway made a south-westerly run and had crossed Permit Road by 1000 hrs. This run of the fire spread first through 3 year-old fuel east of the powerline and then through 20 year-old fuel west of the powerline. The spread rates predicted by the Vesta equations for the prevailing fuel and weather conditions using the calculated absorption moisture content are illustrated in Fig. 7 and indicate that the fire broke across Dale Road shortly after 0400 hours.

The rate of spread in the 20 year-old fuel was six times faster than the three year-old fuels and the intensity of the fire in the 20 year-old fuel was more than 20 times the intensity in the three year-old fuel (Table 5). The difference in fire intensity and the resulting impact on vegetation either side of the Boddington-Forrestfield powerline was very obvious in the fire severity map developed by Dr Li Shu^{5,7} from Landsat imagery taken after the fire (Fig. 8). Nine months after the fire some of the mature trees had been killed outright and epicormic sprouting on trees in the 20 year-old fuel was sparse in the crowns indicating that lethal heat had penetrated to the cambium on quite large branches, and sprouting was mainly confined to the

^{5,7} Dr Li Shu Fire Management Services, Department of Conservation and Environment Perth WA.

⁶ Principal Research Scientist, Science Division, Department of Environment and Conservation, Manjimup.

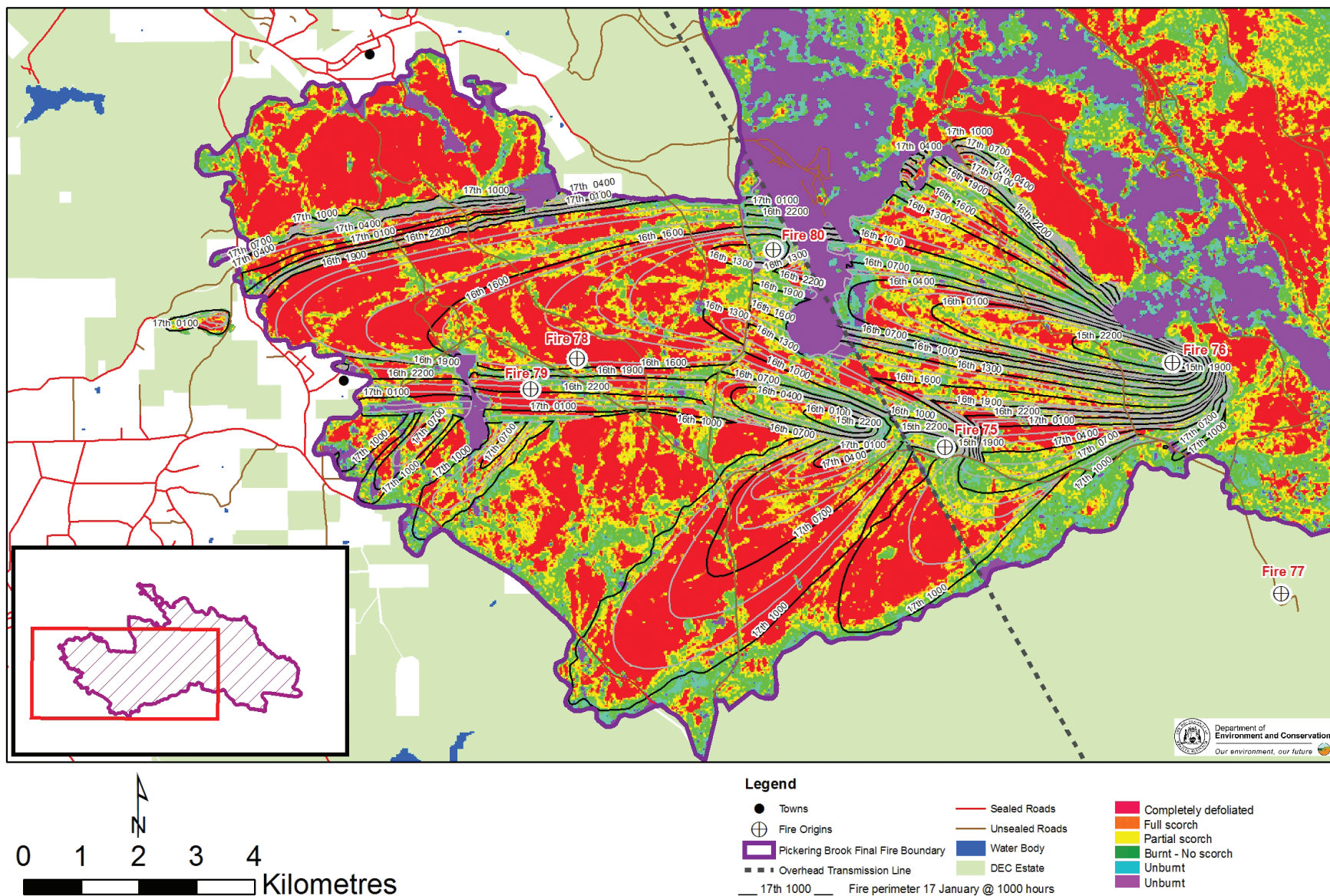


Figure 8. Enhanced satellite image showing relative change in above ground biomass following the fire. Isochrones show the perimeter of the fire at hourly intervals with additional isochrones at 1430 and 1545 hours 16 January.



Figure 9. Comparison of damage by fire in 3 year-old fuel (left) and 20 year-old fuel (right) on either side of the Boddington-Forrestfield powerline. Photographs taken nine months after the fire (Photos: Phil Cheney).

lower trunk where the bark was thickest (Fig. 9). Although the burning conditions increased in severity from the start of the spread in the 3 year-old fuels until the finish of spread in the 20 year-old fuels, the conditions at the time of crossing the powerline would be the same allowing a valid direct comparison at this location.

Projected fire threat in the absence of fuel reduction

The extent of burning in rural Western Australia, and particularly within forest areas is probably the lowest it has ever been in recent history (Ward & Sneeuwjagt 1999). However, the fuel reduction program carried out by DEC provided a mosaic of areas of low fuel load that were significant in reducing the area burnt by the Perth Hills fires, both by restricting the rate of spread and by reducing the intensity thereby making fire suppression more efficient.

If we assume that there had been no fuel reduction burning and there had been no recent wildfires in the area for at least 20 years we can construct a realistic scenario using the expected rate of spread in 20 year-old fuels (fires in fuel older than 20 years will behave in much the same way) and observations of the difficulty of suppression experienced during these fires.

15 January 1800 – 2400 hours

On the first night we can assume that with similar resources initial attack would control Fire 77 on Mount Dale and that Fire 75 and Fire 76 would burn at much the same rate and present the same suppression difficulty; i.e. Fire 75 would be checked at the Boddington-Forrestfield powerline until it spotted across the powerline around

midnight, and that Fire 76 would burn unchecked for six hours.

16 January 0000 – 0900 hours

After midnight the influence of continuous heavy fuel would become apparent. Although it is likely that there would be more spot fires, we can assume that Fires 78 and 79 that occurred near Carinyah trail around 0130 hours would also be controlled but Fire 80, which started to at 0215 hours down-wind of Fire 76, would develop rapidly and cross Ashendon Road. Fire 76 would not be held up by three year-old fuels and would also cross Ashendon Road by 0800 hours.

Whereas fire fighters were able to hold the head fire of Fire 75 in the eight year-old fuel west of Ashendon Road, they were unable to contain spot fires from burning-out operations in 16 to 17 year-old fuels east of Ashendon Road once the fire danger increased around 1200 hours. In our scenario where the fuel is 20 years old, it is highly unlikely that they would be able to check the spread of both fires, and if they did they would not have been able to hold them after 0900 hours when fuel moisture content dropped below 10%. At this level of fuel moisture content, ignition by small fire brands becomes increasingly common.

In my opinion, the net result would be that at 0900 hours the head fire would be at least 2km west of Ashendon Road and less than 4km of the southern perimeter would be controlled along Dale Road.

16 January 0900 – 2400 hours

After 0900 hours the fires would start to spread rapidly with erratic fire behaviour. At an average rate of spread of

900 m h⁻¹, the head fires would join up and burn across Westons Road and the Carinyah Trail by 1200 hours. After 1200 hours, the average rate of spread is calculated to be around 1800 m h⁻¹ over the next four hours, so that by 1600 hours the fire would have crossed the Canning Road and Springvale Road north of the Brookton Highway. If the fuel west of the Canning Road had the characteristics of 20 year-old northern jarrah fuel that has been used to estimate rate of spread up to this point, the fire would have continued to burn over the escarpment, and by 2000 hours is estimated to be west of the Kwinana Northern Terminal powerline and within 2km of the Albany Highway at Gosnells.

If however, the fuel west of Canning Road had characteristics similar to those measured at Stinton Cascades Nature Reserve where the near-surface fuel was rated a full hazard class higher than the 20 year-old fuels and elsewhere and had a near-surface depth of 35 cm, the rate of spread between 1600 and 1700 hours is estimated to be 4300 m h⁻¹. The projected fire would then burn across the Albany Highway at 1700 hours and burn into Roleystone and Gosnells by evening.

17 January 0000 – 1000 hours

The rapid spread of fire into the peri-urban built-up area would mean that all suppression forces would be direct to property protection so that by midnight of 16 January none of the southern flank would have been controlled apart, perhaps, for a stretch of 4km of flank along Dale Road west of Ashendon Road.

In continuous 20 year-old fuels it is calculated the fire would travel around 10km between midnight and 1000 hours. This means that the fire would burn through the area of Roleystone across the northern end of the Canning Dam and through the Darling Range Regional Park and reach the Albany Highway in the vicinity of Bedfordale. Again, if the fuels were given the higher rating applicable

to escarpment fuel, the fire would have continued in a south-westerly direction to the vicinity of Byford.

Although a small fire would be influenced to by the negative slopes as it burnt over the Darling escarpment, when fires are large and are burning under dangerous strong-wind conditions, spotting carries the fire across negative slopes and the overall spread appears similar to that on level ground. It is also interesting to note that the wind at Perth airport during the night was stronger than that measured at Bickley whilst the north-easterly winds were blowing, indicating that there may have been a strong katabatic effect as the north-easterly blew down the Darling Range.

The confusion associated with a high-intensity fire burning into a built-up area at night cannot be understated. It is likely that there would be a breakdown of normal communications and the suppression effort would be chaotic, leaving most individuals threatened to fend for themselves. A similar situation occurred in Victoria during Ash Wednesday 1983 when the Trentham fire burnt into the townships of Macedon and Mount Macedon after dark, causing widespread destruction of houses and other buildings.

In the absence of organised fuel reduction it is possible that high fuel loads would build up on individual properties and home gardens, as was the case in Canberra in 2003. As a result, fire would be likely to penetrate a significant distance into the continuously built-up area and cause widespread damage.

17 January 1000 – 2400 hours

After 1000 hours the wind changed to the southwest and a massive convection column developed above the fire (Fig. 10), reflecting very unstable atmospheric conditions associated with the change (Mills and McCaw 2010). At the time this photograph was taken around 1500 hours, more than 50% of the perimeter of the fire had been



Figure 10. Massive convection column development associated with unstable air, circa 1500 hours 17 January 2005 (photo from Perth airport by A Felton).

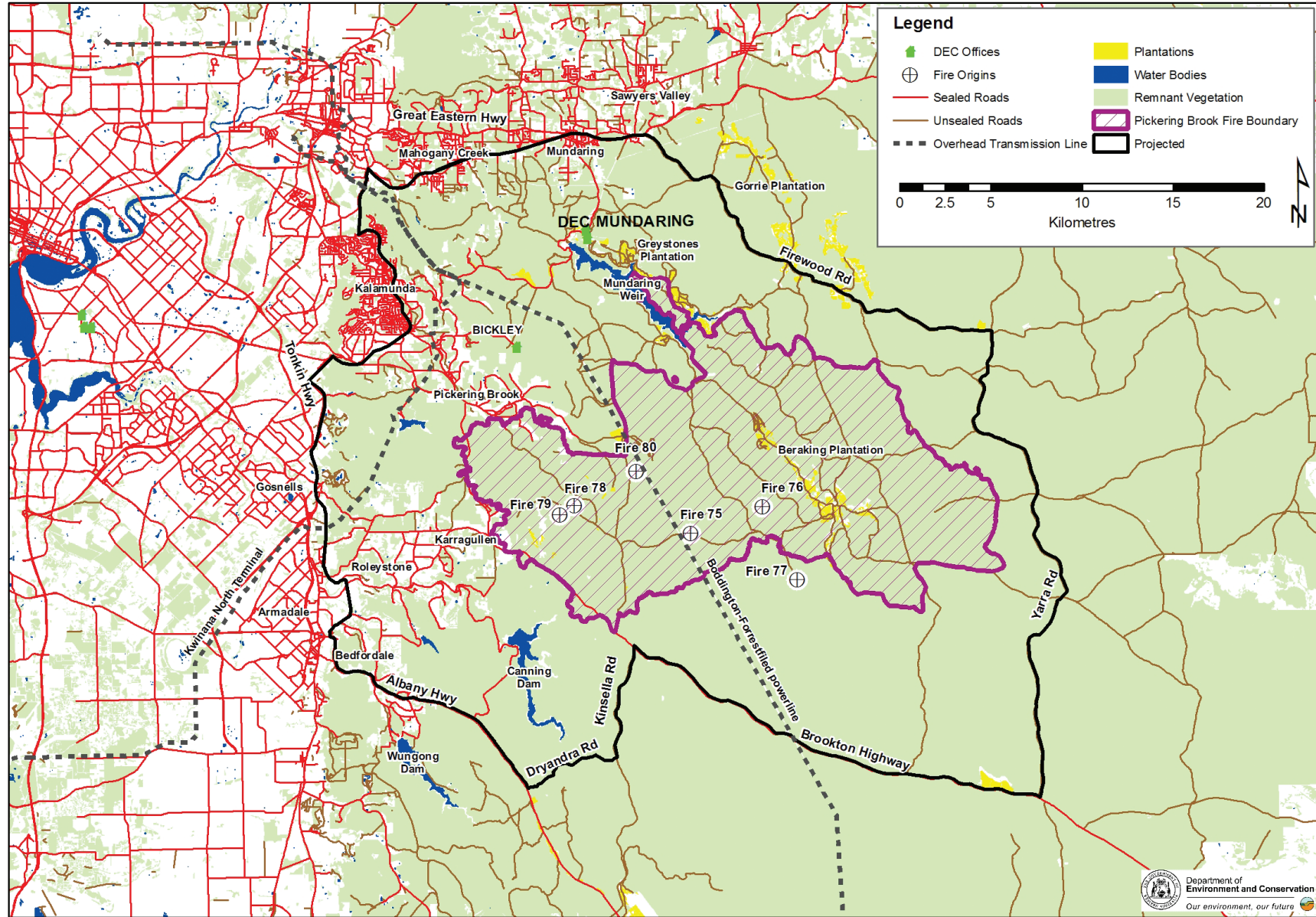


Figure 11. Comparison of the actual area burnt and the projected area that could have been burnt assuming uniform fuel age of 20 years in the absence of prescribed burning.

controlled in light fuel leaving only 30km of burning perimeter, mostly on the eastern side of the fire.

As discussed earlier, in a scenario where fuels are uniformly heavy, little of the perimeter would have been controlled at this time except where the fire had reached the western edge of continuously built-up area at Gosnells and Armadale. Under the south-westerly wind, pockets of unburnt fuel in the Roleystone area would burn rapidly upslope; the additional heat release from the heavier fuels, including that of burning houses and the total perimeter, could have created powerful convective winds due to the unstable air and resulted in a mass conflagration and widespread property damage along the Darling escarpment.

Projected fire spread after 17 January

I have not examined the spread or the development of the fire on days after 17 January in any detail. It was obvious that two year-old fuels either side of the Mundaring weir were critical in preventing rapid spread of the fire towards the north-west.

In the absence of prescribed burning to reduce fuel and in the event of the large fire, the suppression strategies available to fire control are very much reduced and are usually confined to burning-out from established roads and tracks as favourable wind directions blow the fire away from the control lines. As the fire gets larger and control becomes more urgent there is less time to open up minor tracks. The final area of the fire could well have been bounded by the Albany Highway, Dryandra Road, Kinsella Road and the Brookton Highway in the south; Yarra Road in the east and the Firewood Road connecting Yarra Road with the Great Eastern Highway in the north-east (Fig. 11). It is quite possible that under the weather conditions that prevailed over the next five days, the north-westerly run of the fire would have burnt through Greystones plantation and threatened the towns of Mundaring, Sawyers Valley, Mahogany Creek and most of the peri-urban development on the Darling escarpment between the Great Eastern Highway and Roleystone. The estimated area burnt under this scenario is 106 000 ha.

CONCLUSION

Fuel reduction by prescribed burning was a very significant factor in reducing the area burnt and the damage done to State forest, conservation reserve and private property during the Pickering Brook fire. Prescribed burning reduced both the spread and intensity of this wildfire by changing the structure of the fuel and reducing the load of fine fuel. This reduction persisted for at least eight years. Fires that ran into areas one year after being prescribed burnt were stopped and required no further suppression action. Fires will spread slowly in two and three year-old fuels in jarrah forest, but these fires are relatively easy to suppress. Wherever possible, spot fires in light fuel should not be left to slowly develop but should be suppressed as soon as possible. They are capable of throwing firebrands

across control lines under severe burning conditions and until they are mopped-up are potential sources of outbreak.

Compared to the behaviour in 20 year-old fuels, fires in 8 year-old fuels spread significantly slower and were easier to control, confirming observations made during Project Vesta experiments.

The fuel structure in higher rainfall forests along the Darling escarpment is considerably more hazardous than in fuels of the same age further east that are representative of most of the northern jarrah. Under similar weather conditions, rates of spread in these fuels will be 2–3 times faster than in the same-aged fuel elsewhere. Particular attention should be paid to changing the structure of the fuel by prescribed burning in forests and reserves along the Darling escarpment where they are close to private property and suburban development. Because of the increased hazard of these fuels, they should be burned at a shorter rotation than is normally applied in the northern jarrah and this rotation should not exceed five or six years.

Project Vesta equations satisfactorily describe the change in fire behaviour with change in fuel structure. Predictions of rate of spread using fuel moisture values predicted by a process moisture content model appeared to under-predict rate of spread compared to the observed spread rates. This was particularly evident when low humidity and low fuel moisture persisted at night. Rates of forward spread predicted by the Project Vesta equation were much closer to observed rates over a range of fuel ages and structure when fuel moistures from the McArthur (1967) absorption moisture content model were used. There is a need to better predict fuel moisture when the relative humidity is low and dry windy conditions persist overnight and examine the relationship between rate of spread and fuel moisture under these conditions.

The FFBT equations provided a reasonable estimate of the initial rate of spread using a wind ratio of 3:1 at wind speeds less than 25 km h⁻¹. The shape of the relationship describing the effect of wind on the rate of spread is such that these equations will overestimate rate of spread at high wind speeds, thus making it difficult to verify the relationship between fuel load and the rate of spread.

If the fuel reduction burning program by the Department of Environment and Conservation had not been carried out, very little effective suppression would have been possible for several days until the weather moderated and indirect suppression could be carried out from established roads. The Pickering Brook fire would have burnt over the Darling escarpment and into the areas of Roleystone and Gosnells in less than 24 hours after ignition. In my opinion this fire would have resulted in extensive damage to homes and the loss of life in the Perth Hills suburbs.

ACKNOWLEDGEMENTS

I would like to thank Lachie McCaw for his help in rating the fuel hazard, helpful comments on the manuscript and assistance with the editorial process, and DEC staff for

their assistance in providing information on fire behaviour from records in personal diaries and on visits to the field and for their cheerful help with a multitude of matters during the compilation of this report. In particular I would like to thank Claudia Marchhart for preparing maps of the fire.

Special thanks to Stuart Matthews of CSIRO for providing estimates of fuel moisture from different fuel moisture models. I am grateful for two referees who did a thorough critique of the paper which resulted in substantial improvement.

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Table 1

Fuel characteristics assigned to fuels of different ages to predict rate of spread using the FFBT and the Project Vesta equation.

Fuel age (years)	Fuel load ¹ (t/ha)	Surface fuel Hazard score	Near-surface Hazard score	Near-surface fuel height (cm)
26 (west)	25	3.5	4	35
20	22.5	3.5	2.9	20
18	21	3.5	2.8	20
16	20	3.4	2.7	20
11	15	3.3	2.5	19
9	13	3.2	2.4	18
8	13	3.1	2.2	17.5
3 (west)	5.5	2.5	1.5	15
3 (east)	5.5	2.5	1.5	15
2 (east)	4	2	1.5	10

¹ Fuel load taken from Table 6.8 FFBT (Sneeuwjagt and Peet 1985)

Table 2

Predicted rate of fire spread (ROS) using FFBT for wind ratios of 3:1, 4:1 and 5:1

Spread Period	Wind Speed ¹ (km h ⁻¹)	Estimated FMC ² (%)	Fuel Age (years)	Fuel Corr. Factor	Wind 3:1 ³ ROS (m h ⁻¹)	Wind 4:1 ROS (m h ⁻¹)	Wind 5:1 ⁴ ROS (m h ⁻¹)
January 15 – 16 1800 – 0400							
1800 – 2100	20	6	16	2.7	756	391	297
2100 – 2400	32	8	16	2.7	2052	837	351
2400 – 0400	31	12	16	2.7	715	324	183
January 16 1200 – 2000							
1200 – 1430	27	6	8	1.6	1088	448	232
1430 – 1600	21	5	18	2.7	972	499	351
1600 – 1700	21	5	8	1.6	576	296	208
1700 – 2000	16.5	7	8	1.6	192	144	105
January 17 0400 – 1000							
0500 – 0630	28	13	11	2.1	378	174	101
0630 – 0830	28	11	9	1.8	432	189	108
0830 – 1000	28	7	9	1.8	954	396	216

¹. From Bickley anemometer 8 m above top height of the canopy.

². Estimated by model of Matthews (2006).

³. Recommended wind ratio for Bickley anemometer.

⁴. Wind ratio used for fire spread prediction by DEC Mundaring.

Table 3

Comparison of Rate of Spread (ROS) predicted by the Project Vesta equations and the FFBT with mean observed rate of spread

Spread Period	Wind Speed ¹ (km h ⁻¹)	Temp. (°C)	RH (%)	FMC ² (%)	Fuel Age (years)	ROS Vesta (m h ⁻¹)	ROS FFBT ³ (m h ⁻¹)	ROS Mean (m h ⁻¹)
January 15 – 16 1810 – 0410								
1800 – 2100	20	24	23	6	16	826	756	
2100 – 2400	32	19.6	38	8	16	897	2052	600
2400 – 0400	31	13.6	63	12	16	473	715	
January 16 1200 – 2000								
1200 – 1430	27	29.4	24	6	8	769	1088	1110
1430 – 1600	21	30.3	20	5.5	18	1083	972	2000
1600 – 1700	21	30.3	20	5.5	8	1011	576	1050 ⁴
1700 – 2000	16.5	24.9	26	7	8	353	192	855 ⁵
January 17 0445 – 0951								
0445 – 0630	28	16.6	52	13	11	322	378	860
0630 – 0830	28	20.0	40	11	9	375	432	750
0830 – 0951	28	27	25	7	9	737	954	1133

¹. From automatic weather station Bickley.

². Extrapolation from model of Matthews (2006).

³. Northern jarrah; wind ratio 3:1.

⁴. 5-minute spread of 1200 m h⁻¹ observed at 1548 hours.

⁵. Spread measured from 1700 to 1900. Spread after 1900 may include back burning.

Table 4

Comparison of predicted rates of spread (ROS) using different moisture models with the observed rate of spread deduced from field observations.

Time (hrs)	Process FMC (%) (Matthews)	Predicted ROS (m h ⁻¹)	Absorption FMC (%) (McArthur)	Predicted ROS (m h ⁻¹)	Observed ROS (m h ⁻¹)
16 January					
1200 – 1430	6	769	5	1009	1110
1430 – 1600	5.5	1083	4	1743	2000
1600 – 1700	5.5	667	4	1074	1050
1700 – 2000	7	353	4.5	683	855 ¹
17 January					
0400 – 0630	13	352	9	558	860
0630 – 0830	11	382	8	603	750
0830 – 1000	7	749	5	1218	1133

¹ 1700 – 1900 hours but may include back burning after 1900 hours.

Table 5

Comparison of the head fire rate of spread and intensity in three year-old and 20 year-old fuel

Fuel age (years)	Rate of spread (m h ⁻¹)	Fuel load (t ha ⁻¹)	Head fire intensity ¹ (kW m ⁻¹)
3	300	5.5	825
20	1854	22.5	20 645

¹ Calculated using a heat yield of 18 000 kJ kg⁻¹

Fire regimes and regional biodiversity declines in north-west Australian tropical savannas? : review of knowledge and recommendations for future research

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ABSTRACT

A key conservation issue in north-western Australia is recent declines in biodiversity, especially among the nationally threatened critical weight range (35g–5kg) mammals. Changed fire regimes are implicated as a cause of these declines, but it is unclear whether declines are related to fire, or to other key threatening processes. In this review, historical and scientific evidence for fire driven declines are examined and critically evaluated. Data suggest we cannot confidently attribute biodiversity declines to fire based on available evidence. This is because historical evidence is circumstantial only, and because scientific evidence showing changes in abundance relating to fire regime may not relate to regional scale declines and range contractions. A way forward in understanding factors driving declines is investigation of key mechanisms underlying fire effects. The importance of correct diagnosis of mechanisms is emphasised as incorrect assumptions can lead to inappropriate management of declining species. Three hypotheses about key mechanisms are raised based on general conservation biology approaches for threatened species, and also on evidence gained from northern Australia ecological studies. These are 1) that declines are driven by increased predation mortality through repeated removal and simplification of vegetation cover by severe fire regimes; 2) that declines are driven by resource limitations caused by too frequent fires; and 3) that declines are driven by failure to retain sufficient source breeding populations in optimal habitats (e.g. unburnt patches) within savanna landscapes for the continued persistence of fire-sensitive species. I suggest prescribed burning operations should aim to explicitly retain long unburnt vegetation patches (>3 years, >1 ha) frequently within the landscape. Our lack of knowledge of key mechanisms driving declines, and evidence that threatened species are fire-sensitive, suggests that indiscriminate application of fire mosaics may be harmful to some threatened species.

Keywords: critical weight range mammals, Kimberley, fire intensity, mechanisms, fire response

INTRODUCTION

Considerable attention has been given to the idea that fire regimes in northern Australia are associated with recent declines in biodiversity. Fire has been invoked, particularly as a threatening agent for the critical weight range (CWR) mammals (35g–5kg) (Andersen *et al.* 2005; Woinarski *et al.* 2001), granivorous birds (Crowley and Garnett 1999; Dostine *et al.* 2001; Woinarski and Tidemann 1992), a number of fire sensitive savanna trees/shrubs (Bowman *et al.* 2001; Russell-Smith *et al.* 2002; Russell-Smith *et al.* 1998), rainforests (Bowman and Panton 1993; Bowman *et al.* 1990; Russell-Smith *et al.* 2004; Woinarski *et al.* 2004) and riparian plant species (Douglas *et al.* 2003). Evidence for fire related declines comes from the apparent historical coincidence of increasingly severe fire regimes with declines (Woinarski *et al.* 2001),

observational studies comparing populations and communities in areas with different fire regimes (e.g. Russell-Smith *et al.* 2004a; Vigilante and Bowman 2004a), and from experimental studies showing fire response (e.g. Williams *et al.* 2003; Radford *et al.* 2008).

Despite this body of evidence, considerable uncertainty remains concerning declines in various species, and the role of fire in these declines. Although it is clear that organisms do respond, sometimes negatively, to fire (Andersen *et al.* 2005; Woinarski *et al.* 2001), it is not clear whether these responses are related to regional scale declines. Many other factors, including grazing by cattle (McKenzie 1981; Franklin 1999; Franklin *et al.* 2005) and other introduced herbivores (Werner 2005), predation and other impacts by introduced animals (Burbidge and Manly 2002; Greenlees *et al.* 2007; Johnson 2006), clearing, and plant invasions (Grice 2006; Rossiter *et al.* 2003; Valentine *et al.* 2007), could all be invoked to explain plant and animal declines in northern Australia.

A key area of uncertainty concerning fire (and other threatening processes affecting northern biota) are the fundamental mechanisms underlying biotic fire responses (Williams *et al.* 2003). An understanding of these mechanisms is crucially important because without them we are blind to the real causal problem of declining biodiversity. Our lack of knowledge of mechanisms underlying fire responses is a serious issue within a land management context. This is because we don't know what outcomes we are aiming for within a prescribed burning operation to mitigate the threatening processes. For instance, should we be aiming to reduce the total area burnt annually or biennially (e.g. reducing fire rotation), to increase the diversity of fuel age structure (e.g. increase resource diversity), to maintain unburnt areas annually or perennially (e.g. for habitat refuge), or to simply reduce the overall fire intensity (but not area) by burning earlier in the year (e.g. to reduce impacts on shrubs and trees). Each of these aims may use a different management strategy to implement them, and would have potentially quite different biodiversity outcomes as their ultimate goals. Current fire management in north western Australian savannas does not explicitly frame prescribed burning objectives in relation to detailed knowledge of mechanisms underlying threatened species ecology. In the absence of this information we are applying fire management blindly.

In this review I will evaluate the evidence that fire has driven declines of biota in north western Australia. The area of focus in this review will mainly be the wetter northern parts of the tropics in the Top End of the Northern Territory and the Kimberley WA (annual rainfall >600 mm, where up until recently many threatened groups were still abundant (Woinarski *et al.* 2001). Many arid parts of northern tropical savannas had lost threatened groups many decades ago (McKenzie 1981, Johnson 2006) and are not further considered in this review. Threatened groups include the critical weight range (CWR) mammals, granivorous birds and fire sensitive plant species, though in this review I focus primarily on fauna. I will also present what I believe is the way forward to achieve a practical understanding of the key factors involved in declines of these groups. This review will first examine the nature of the evidence that fire influences populations, and whether there is sufficient evidence to attribute fire regimes as one of the key drivers. Second, given the complexity of competing threatening processes, including fire, I suggest a conceptual framework within which to view declining populations. This conceptual framework, originally proposed for conservation of endangered species, focuses on fundamental mechanisms that underlie declines (Caughley and Gunn 1996). By looking behind fire, or other threatening phenomena, this approach seeks to correctly diagnose the cause of declines, so that an effective remedy can be designed to prevent further declines and to promote recovery. Third, I present what I see as the key hypotheses relating to underlying mechanisms that enable fire to influence plant and animal populations. Finally, I recommend the use of the precautionary principal in application of prescribed

management programmes in northern Australia given our basic lack of knowledge of the mechanisms underlying fire effects.

EVIDENCE FOR FIRE INDUCED DECLINES IN NORTHERN AUSTRALIA

The causal link often drawn between biodiversity declines in north western Australia and fire regime change is essentially speculative in nature. This is not to say that fire is not an important factor, nor that fire does not influence plant and animal populations, but simply to state that no causal link between fire responses and regional scale historical declines can yet be made.

Relevance of scientific studies to regional scale declines

Studies showing the impacts of fires cannot necessarily be scaled up to regional or national declines. Evidence that fire regimes in northern Australia do affect plant and animal populations is unambiguous (Andersen *et al.* 2005; Bowman and Franklin 2005; Radford *et al.* 2008; Russell-Smith *et al.* 2003a; Vigilante and Bowman 2004a; Woinarski *et al.* 2004). Numerous experimental and post hoc observational studies have clearly shown that high fire frequency or intense fires lead to reduced abundance of small mammals, shrubs, reduced complexity of woody vegetation structure, and selective removal of obligate seeding shrubs and fire sensitive plants. There is evidence of a dichotomy between species preferring long unburnt habitat (fire-sensitive), and those preferring recently burnt habitats (fire-tolerant), with little evidence of intermediate functional groups (Andersen *et al.* 2005; Felderhoff 2006; Woinarski *et al.* 1999). However fire research in northern Australia, by necessity, has been conducted at relatively small scales or over relatively limited time periods in the context of tropical savannas (Woinarski *et al.* 2005). It is therefore unknown how representative these studies are of the greater savanna landscape. In addition, proving that fire regimes influence abundance does not prove that the same processes are involved in causing regional scale declines.

An example of fire influences not necessarily reflecting regional level dynamics was provided by the Kapalga fire experiment conducted in Kakadu National Park during the 1990's. Animal abundance was recorded across all experimental fire treatments in this study. It was found that all CWR mammal species declined across all treatments, including both high intensity late dry season fires, and in unburnt controls (Andersen *et al.* 2005; Corbett *et al.* 2003a). This suggests the possibility of another more general process operating throughout the area, irrespective of fire regime.

More evidence that fire regimes alone are not responsible for mammal declines across northern Australia is provided by continued mammal abundance in some areas which continue to have intense, extensive wildfire regimes. At the same time that trap captures at Kapalga/

Kakadu have declined to <1% (Woinarski *et al.* 2001; J Woinarski *et al.* (2010), other areas, including the north Kimberley, continue to have trap success equivalent to Kapalga in 1980's (10–30%) up to the present (Start *et al.* 2007; I.J. Radford¹ unpublished data 2009). This is despite the continued occurrence of extensive, high intensity fire regimes in the north Kimberley (Russell-Smith *et al.* 2003c).

Despite the lack of scientifically justifiable linkage between what happens at population and regional levels, it is tempting to believe that population level processes do play a role at larger regional or meta-population levels. Within the broader context, factors that tend to cause declines in population abundance in given areas will obviously have flow-on effects at the larger scale. This might be particularly so in the case of fire, where optimal “source” breeding habitats, for instance in longer unburnt fragments, may be extremely rare in the broader landscape context. Many fires cover thousands of square kilometres and can burn for months in this region (Russell-Smith *et al.* 2003b). This could potentially lead to considerable delay in site recolonisation, particularly for smaller ground based species like the CWR mammals. North Australian biotic declines have not yet been investigated at this landscape scale.

Historical evidence for fire related declines only anecdotal

There is no direct published evidence showing coincidence between historical change in fauna abundance and fire regimes. Fire regimes in northern Australia have been described (Crowley and Garnett 2000; Fensham 1997; Preece 2002; Vigilante 2001), but not systematically quantified, before the 1990s when satellite technology allowing us to measure spatial patterns in fire scars became widely available (though see Bowman *et al.* 2007 for alternative method). Aerial photography has allowed quantification of fire pattern changes prior to removal of Aboriginal occupation in only one published instance in the western desert (Burrows and Christensen 1990; Burrows *et al.* 2006). While fire regimes have been quantified in recent times, there are therefore no continuous records showing the progress of change in fire regimes from that under a traditional Aboriginal management, through Aboriginal depopulation and establishment of pastoralism, through to the periods known for declines of northern species.

There is no evidence that documented declines, such as those of small and medium mammals in Kakadu National Park (Braithwaite and Muller 1997; Woinarski *et al.* 2001), coincide with changes in fire regimes. The earliest quantified fire regime data for Kakadu in the late 1980s, already showed dominance of large scale mid to late dry season fires at that time, though a trend towards increased earlier dry season burning has occurred since

1990 (Russell-Smith *et al.* 1997). This suggests that the period of change to the current regimes, dominated by large scale late dry season fires, had already occurred by the 1990s.

The implication that breakdown of traditional Aboriginal burning practises has led directly to declines in savanna species is not supported by historical evidence. There has been considerable attention given to Aboriginal burning practises, and their role in maintaining threatened species in savanna landscapes. However, while it may be true that traditional Aboriginal burning practises were compatible with maintenance of threatened species, this does not necessarily suggest that they required this traditional burning. Irrespective of the role of Aboriginal burning in plant and animal ecology, breakdown of these regimes in most parts of the northern savannas greatly predates recent declines. While declines of CWR mammals in Kakadu occurred as late as the 1980s and 1990s, movement off country of Aboriginal populations had generally occurred decades previously prior to the 1940s. If there is a link between traditional Aboriginal fire regimes and maintenance of biodiversity, there must be an extensive lag phase. Rather I would argue that patchwork small scale fires generally described within traditional systems (Bird *et al.* 2005; Craig 1997; Haynes 1985; Preece 2002) maintained species by not burning areas or by protecting areas from fire, rather than by providing a diverse range of species specific post-fire successional habitats (see below).

In the absence of direct data linking historical species declines with changes in fire regimes, or linking of site-based fire responses to regional level dynamics, we are left with little certainty as to the causes of species declines in northern Australia. Other factors, particularly cattle grazing (Dawes-Gromadzki 2005; Franklin 1999; Franklin *et al.* 2005; McKenzie 1981; S Legge² unpublished data 2009), have also been convincingly linked with species declines or ecosystem degradation in northern Australia.

HYPOTHESIS DRIVEN RESEARCH: CAUSAL MECHANISMS UNDERLYING FIRE RESPONSES AND SPECIES DECLINES

Research into fire ecology in northern Australia has mainly focused on patterns of response in different organisms to different fire regimes (Williams *et al.* 2003). This has either been through experimental imposition of fire, or by *post hoc* comparison of biodiversity patterns in areas with different natural fire regimes. The problem with this approach is that we don't know why particular species respond to fire in the way they do. What are the fundamental mechanisms relating to fire that might be driving species declines? Are individuals killed by

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frequent, intense fires, do they starve because food resources are removed, or are they subjected to increased predation or disease due to open stressful environments? These are important questions if we hope to address the cause of reported species declines in northern Australia. Addressing the key mechanism/s causing species declines is a crucial part of any programme to promote recovery of threatened species (Caughley and Gunn 1996). Without direct knowledge of cause, prescribed management treatments, whether prescribed burning or other treatments (e.g. cattle removal, predator culls), may be completely ineffective in halting or reversing declines. Such cases are common through conservation history (Caughley and Gunn 1996).

Despite the need to investigate mechanisms underlying fire responses, few studies have yet attempted this in northern Australia (Williams *et al.* 2003). The exception is that mortality of trees and shrubs due to the effects of fire intensity and season is relatively well understood (Russell-Smith *et al.* 2003a; Williams *et al.* 1999; Williams *et al.* 1998). However, the relative importance of other mechanisms associated with fire responses and declines are poorly known.

The only effective way to address the causes of species declines in conservation biology is correct diagnosis of cause through hypothesis driven experimental testing (Caughley and Gunn 1996). Without these features of the experiment, it is impossible to attribute the effects of mechanisms measured on populations to the mechanism itself, and there will be uncertainty about what results mean (Caughley and Gunn 1996). It is crucial within this approach that experimental treatments are designed with appropriate controls and replication. It is also important, if possible, that treatments replicate practical management treatments that could be imposed to ameliorate key mechanisms causing declines. This is because for effective recovery to be achieved, it must be pragmatic. However, there is no substitute for careful, basic species level research incorporating manipulative management treatments to achieve an understanding of the dominant drivers of population fluctuations in the field.

The effects of fire (or cattle, invasive plants, invasive predators) in northern Australian landscapes are complex. Fire consumes material, changes chemical composition of soils and above ground material, removes living and structural habitat attributes and selectively removes fire sensitive species (Andersen *et al.* 2005; Bowman and Prior 2004; Edwards *et al.* 2003; Russell-Smith *et al.* 2004b; Russell-Smith *et al.* 2003a; Vigilante and Bowman 2004a; Woinarski *et al.* 2004). For this reason, to say that fire as a phenomenon causes a particular response is not very informative about the mechanisms affecting particular threatened species. There could be multiple reasons for a particular response. Evidence from a number of studies suggests that few of the impacts of fire are directly related to mortality due to the heat of the fire itself (Sutherland and Dickman 1999). The exception to this is obviously fire sensitive shrubs and trees, for which fire intensity directly affects their survivorship (Williams *et al.* 1999; Williams *et al.* 1998).

Based on previous research I would like to raise what I see as three key competing, but not mutually exclusive, hypotheses concerning mechanisms underlying fire effects on north western savanna species. These are loosely based on generalised mechanisms used in conservation of endangered species as outlined in Caughley and Gunn (1996), but also use documented literature from northern Australian fire research and elsewhere to derive specific hypotheses. Obviously mechanisms may differ among species and taxonomic groups. However classification of species into functional response groups will allow us greater potential to design management treatments (e.g. prescribed fire or feral animal control) specifically for the benefit of particular threatened species. Such information will be crucial for maintaining critically threatened species.

1) Declines caused by increased predation rates with fire-related loss of ground cover

This hypothesis relates primarily to threatened fauna in northern Australia. Threatened flora declines can be more directly related to fire patchiness and intensity due to relatively simple relationships between fire intensity and plant mortality. However this may not be the case for fauna including the CWR mammals (Clarke 2008). While fauna are subject to direct fire mortality, evidence from southern Australia suggests that abundance post-fire is little related to initial fire mortality (Sutherland and Dickman 1999). The rest of this section will address predation as a process related to post-fire abundance only for fauna.

A number of recent syntheses (Burbidge and Manly 2002; Dickman 1996; Johnson 2006) have identified impacts by the introduced predators (cats and foxes) as possibly the primary drivers of CWR mammal extinctions since European settlement. Extinctions have been most numerous in the arid zone, though they have been a national phenomenon (McKenzie *et al.* 2007). Evidence for the pivotal role of introduced predators in extinctions is provided by patterns of extinction relative to the arrival of these species compared to other influences (Johnson 2006). A number of extinctions, mostly rodents under 1 kg, that occurred in remote northern arid areas predate clearing, arrival of domestic stock or feral herbivores (e.g. rabbits, goats, horses, donkeys) and can only be attributed to the early arrival of cats or foxes (Johnson 2006). There is a significant positive correlation between mammal extinctions on offshore islands and introduction of cats or foxes (Burbidge and Manly 2002).

If historical extinctions of CWR mammals in the arid zone are related to predator pressure from introduced cats and foxes, it is plausible that recent declines in northern Australia are also related to this factor. In this region, decreased ground cover and structural simplification in recent years due to frequent large scale fires would contribute to the predator effect. Fire regime directly affects the amount of ground cover available for small and medium mammals. So even though Australian CWR mammals are adapted to a range of fire regimes which pre-date human occupation of Australia, they are not

adapted to predation by cats and foxes. Small mammal species in Australia are known to respond positively to increasing vegetation structural complexity and cover (Law and Dickman 1998; Spencer *et al.* 2005; Sutherland and Dickman 1999). It has been shown that small mammal abundance can be influenced by structural habitat attributes protecting them from predators (Arthur *et al.* 2005). It is clear that fire can affect ground vegetation cover and vegetation structure (Andersen *et al.* 2005; Edwards *et al.* 2003; Russell-Smith *et al.* 2003a; Vigilante and Bowman 2004a; Woinarski *et al.* 2004). Fire regimes of high frequency, extensive coverage, lack of habitat refuge and extended periods before vegetation recovery would be most likely to cause declines in species requiring cover from predators.

Evidence of the primary importance of introduced predators relative to fire per se was provided by Short and Turner (1994). They documented no effect of burning regime on CWR mammals of Barrow Island where there are no feral cats. None of these CWR mammals are found on mainland sites where cats are present. Similarly, extinctions of CWR mammals on many north western offshore islands are most directly related to presence of introduced predators, particularly cats.

Although few studies have explicitly compared causes of fauna mortality (predation, starvation) or factors affecting mortality (predator populations, structural shelter from predators provided by vegetation), between burnt and unburnt habitats in north west Australia, increases in many predator species are well documented in recently burnt habitats. It is known that many predator species increase in recently burnt, or actively burning habitats (Corbett *et al.* 2003b). Increase in predatory bird species such as black kites, or insectivorous species such as magpie larks, has been documented in recently burnt habitats in several northern Australia studies (Braithwaite and Estbergs 1987–88; Corbett *et al.* 2003b; Woinarski *et al.* 1999; Woinarski *et al.* 2004), though this has not been directly tested in northern Australia in relation to fire. There is a varied fire response among reptile predators, with some species including the frilled neck lizard preferring recently burnt country, while others do not (Andersen *et al.* 2005; Corbett *et al.* 2003b). It is not known how feral cats and foxes respond to fire in northern Australia.

It is currently unknown whether the mechanism of cat predation and removal of vegetation cover (through frequent fires or by cattle) is an important mechanism driving declines in north western tropical savannas. Cats are known to be present throughout the Kimberley and to have been present as naturalised populations since as early as 1890 (Abbott 2002). Foxes periodically invade this region from the south in favourable seasons. Nothing is published of population dynamics of introduced predators in relation to the fire cycle in tropical Australia, nor the impacts they have on associated mammal populations. This should be an important area of future research into declines in northern CWR mammals, either through use of predator shelter, or more directly through cat baiting/culling treatments. Given the weight of

evidence for a strong predator effect this would be a priority for future research.

An obvious objective of fire management for savanna species susceptible to predation (e.g. CWR mammals), would be to provide sufficient vegetation cover for them to avoid predators. Unlike many other groups, CWR mammal species require relatively large areas of habitat in order to persist (>1ha). It will therefore be critical within fire management treatments, to provide for this explicitly. Random ignitions are unlikely to provide this habitat structure due to the deterministic nature of fuel removal by fire (van Wilgen *et al.* 2004). Systematic and targeted effort may be required to provide significant late seral stage, high biomass/ground cover vegetation within burnt areas, particularly if optimal habitat for mammals have >2 years growth. There may be a need to include some suppression activities in northern land management agency repertoires in order to protect such patches against wildfire.

The hypothesis that threatened savanna species have undergone declines due to removal of ground vegetation cover is consistent not only with increased fire activity, but also with cattle impacts. The intensity of grazing enterprises has been positively correlated with declines in small mammals and a number of bird groups (Franklin 1999; Franklin *et al.* 2005; McKenzie 1981). Although environmental impacts by cattle presumably differ from fire impacts in some respects (e.g. species specific selective pressures, differing effects on woody plant species), both processes remove and alter herbaceous vegetation structure and thereby alter habitat cover attributes relevant to prey species. In this respect both processes might contribute to declines of CWR mammals and some bird species through removal of cover. Although removal of herbaceous cover has not been postulated as a mechanism underlying declines in birds (e.g. threatened finch species), widespread removal of shrub layer vegetation under severe fire regimes, may have a similar impact on birds through increased predation (e.g. by raptor species), to those postulated for mammal species by cat and fox predation.

Other mortality factors related to fire regime

I have focused here primarily on the hypothesis that loss of protection from predators is a key mechanism underlying possible increases in mortality rates in burnt landscapes. There could be other sources of increased mortality in burnt landscapes. Parasitism and disease, along with predation, is a major mortality factor in ecological communities. The role of an increasingly stressful environment due to extensive fire may have effects on plant and animal fitness in burnt (or long unburnt) landscapes. This mechanism has been little investigated in northern Australian biota in relation to fire, though some research into the role of parasitism in threatened finch species has been undertaken (Tidemann *et al.* 1999). In this case parasitism was thought to be secondary to other factors driving declines in these threatened finch species (Dostine *et al.* 2001; Franklin *et al.* 2005).

Tests of the predation (herbivory)/ground cover hypothesis

There are a number of ways of testing the predation-ground cover hypothesis. An initial step is to gather evidence that there are increased numbers of predators, or predator activity in areas with lower vegetation cover and structural complexity (i.e. due to recent fires). The next step is to document the relative impact of predation on prey populations at sites with differing vegetation cover. This will involve detailed demographic study and analysis of the fate of individuals from prey populations (predation or not, which species of predator). Finally, to fully demonstrate the importance of predation and habitat cover on populations, we need to design studies which experimentally manipulate habitat cover and predation levels (preferably within a factorial experiment) in order to test for their relative importance. For the latter to be successful such experimentation should include appropriate experimental controls where no habitat or predator manipulations are imposed, and also should be done at sites where data on pre-treatment population dynamics is available. Only in this way can responses be confidently attributed to experimental treatments within spatially and temporally variable savanna ecosystems.

2) Declines caused by fire-related change in resource availability

The resource limitation hypothesis is perhaps the key alternative hypothesis to the predation-fire hypothesis for declines among northern savanna species. This hypothesis has been raised to explain declines in tropical granivorous birds, including a number of finch species. The hypothesis is that a shortage of grass seeds, particularly during the wet season, is a major factor leading to declines (Dostine *et al.* 2001; Garnett and Crowley 1994). Frequent fires are thought to reduce or stop perennial grasses, including *Triodia* spp. and *Alloteropsis* spp., from producing seeds for a year or more. This hypothesis is currently being tested in a major study across northern Australia (S. Garnett³ & S. Legge⁴ pers. comm. 2007). A similar mechanism may operate to reduce the extent and abundance of many granivorous native rodent species in northern savannas (Start *et al.* 2007).

Fruiting and flowering of a number of tree species has been shown to be affected by fire (Vigilante and Bowman 2004b). This could have impacts not only on recruitment of the trees themselves, but also on populations of organisms that depend on these resources. Species known to feed on fruits and flowers and also thought to be threatened, include possums (e.g. *Petropseudes dahlia* & *Wyulda squamicaudata*) and arboreal rodent species (e.g. *Conilurus penicillatus* & *Mesembriomys macrurus*)

(Thompson 1996). The importance of this factor in causing declines populations has not been investigated.

Frequent high intensity fire regimes may reduce total ecosystem productivity and therefore the levels of multiple savanna resources. Frequent fire has been shown to have important effects on soil nutrient levels, including nitrogen reserves in tropical Australian savannas (Cook 1994; Cook 2003). Fire is also known to influence soil microbial communities, which in turn can influence resources available to and survival of tropical plant species, including a number of rainforest species (Bowman and Panton 1993). The influence of these key resources, not only for particular species, but for overall ecosystem functioning and productivity, is a key area of future research in regard to fire regime impacts in savannas.

Tests of fire-resource limitation hypothesis

There are a number of ways of testing the resource limitation-fire hypothesis. Initial work needs to be done documenting the key resources used by the target species. Some of this information can be gained through faecal analysis, field observations and isotope analyses of animal tissue. The dynamics of resources then needs to be documented, particularly with respect to fire succession. The relationship between dynamics of the target species and the resources can then be assessed. Relationships between resources, and the factors that potentially affect their dynamics (rainfall, nutrient flushes, fire) will begin to allow an ecosystem level understanding of regulation of populations. If patterns are similar among different trophic levels in the ecosystem, even with a lag phase, this might be circumstantial evidence that the resource partially determines the dynamics of the target species. If resources do not relate to species dynamics, it may be that resource fluctuations are independent of species numbers and demographic variables. This would indicate that some other feature in the ecosystem is driving populations. The final definitive test for the role of resources in population fluctuations is use of resource supplementation or removal experiments, both in the presence and absence of recent fire.

3) Declines caused by post-fire recolonisation failure in frequently burnt landscapes

Research into landscape scale functioning of species in northern savannas has not been undertaken and is likely to be a major challenge to ecologists. Conceptualisation of population processes within the larger landscape scale context, however, may be beneficial for an understanding of the role of fire and underlying mechanisms in the vast northern savanna landscapes.

One area of theory that may be applicable to fire regimes in northern savannas is metapopulation theory (Hanski 1994; Hanski and Gilpin 1991). Briefly this theory focuses on populations as functioning within a matrix of habitats across a landscape which vary in their quality or benefit to particular species (e.g. due to resource,

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predator or disease distribution). This is a useful concept in terms of fire regime effects in northern savannas because recently burnt and longer unburnt habitat will differ in quality for different species depending on whether they are early or late fire succession species. Fire sensitive species (those responding negatively to recent fire) are likely to require long unburnt habitats as “source” or breeding habitats within the landscape. A “source” habitat is one in which a species can maintain populations and/or increase in numbers to provide excess individuals to allow dispersal and colonisation of other habitats. Source populations will be required for each species within a landscape to provide individuals for establishment of populations in “sink” habitats or newly available suitable source habitats. In a fire context this would include habitats that had temporarily become unsuitable for breeding populations due to some effect of fire (e.g. increased predation or resource limitation). In the context of burnt landscapes “sink” habitats may be areas that are unable to support populations of the species.

Although populations of threatened species in northern savanna landscapes have not been investigated in this way, there are a number of studies which at least support the notion that some species use patches of unburnt habitat within burnt landscapes as refuges. *Pseudomys desertor* and *Pseudomys nanus* at Purnululu National Park (Partridge *et al.* unpublished), and *Rattus tunneyi* and *Pseudomys nanus* at Mornington Station in the Kimberley (Legge *et al.* 2008) are both largely restricted to areas within burnt landscapes of higher vegetation biomass where recent fire had been excluded. While other mammal species are apparently unaffected by fire patchiness (e.g. *Pseudomys delicatulus*) this indicates the possibility that populations of some species will use these patches as source habitats for recolonisation into surrounding areas.

In a metapopulation context, biodiversity declines and extinctions in northern Australia may occur where source populations and recolonisation rates are insufficient to allow for re-establishment of fire sensitive species (e.g. CWR mammals) in frequently burnt landscapes. If CWR mammals require >2 years between fires for habitat to be suitable, there may be insufficient source habitats and dispersal opportunities to allow persistence across much of the savanna landscape.

One approach to testing the effect of differing source sink patterns in allowing persistence of populations would simply be to compare post-fire re-establishment/colonisation rates under differing fire regimes. This would involve gathering baseline data on population dynamics of target species, and then applying management fire regimes to those areas. Such work would best be applied to fire-sensitive species such as CWR mammals or threatened finches. There are three primary fire regime patterns that should be compared based on the above discussion and previous literature. These are (i) fire regimes where patches of long unburnt vegetation (>2 years) are deliberately protected (1ha–1km² scale) as habitat refuges within burnt areas, (ii) landscapes with a diverse but more or less random patch mosaic burning (frequent broad-

scale burning at low fire danger periods) to reduce the intensity and size of wildfires, and (iii) landscapes under ambient fire regimes consisting of extensive and intense dry season fires, typically with few unburnt patches or shelter refuges (few, scattered unburnt patches). It would be expected that recolonisation rates would be greater where there is greater fire patchiness (greater diversity of vegetation structure) and more unburnt patches retained. Given the sparseness of dispersing individuals in extensive savanna landscapes this type of study would require substantial trapping or sampling effort.

MOSAIC THEORY AND APPLICATION OF PRESCRIBED BURNING AMIDST UNCERTAINTY ABOUT MECHANISMS

Given the level of uncertainty concerning the role of fire in regional declines of fauna, and the lack of a clear understanding of fire-related mechanisms underlying declines, what should fire management should land owners be applying? Anecdotal evidence of increased instances of dry season fires, and the number of uncontrolled ignition sources, suggests that some form of protective burning should be attempted. However, what should this prescribed burning be trying to achieve as a target?

One approach to fire management put forward in northern Australia and elsewhere is the patch mosaic burning approach. In extensive landscapes such mosaics of different post-fire seral stages are designed not so much to provide barriers to fire, as regrowth is rapid enough not to allow fire breaks to be established for long, but to reduce overall fuel loads and therefore reduce fire intensity and increase patchiness of wildfires. In terms of goals relating to threatened fauna, this is a bet-hedging approach that aims to provide a range of post-fire habitats. This approach is argued to provide a range of habitat types, structures and resources in the hope that animals will benefit. Diversity in habitat structure and seral stage is argued generally to be beneficial to both flora and fauna (Law and Dickman 1998).

However, the benefit that flora and fauna will derive from a fire mosaic will vary according to the specific requirements of the species concerned. If, as I argue, many of the CWR mammals require longer term unburnt patches (>2 years), a randomly applied fire mosaic may not provide this. This is because areas of high fuel beneficial to these species will selectively burn under a random ignition approach. Achieving several years without fire in significant patches throughout the landscape may require considerable targeted burning, probably similar to traditional Aboriginal burning. It also may require fires to be put out. This is seldom done in northern landscapes due to lack of personnel, available resources and the remoteness of the country. Land management agencies in northern Australia do not have the resources available which would allow them to apply fine scale mosaic burning to large areas, or to undertake suppression of wildfires.

I believe that a key aim in applying mosaics in north western savannas should be to provide late seral stage or high biomass/cover vegetation patches, or longer unburnt fuels, for maintenance of threatened species. As discussed above there is considerable evidence that many species, including the CWR mammals, will benefit directly through retention of longer unburnt habitat areas (>3 years or >5 years in more arid areas) (Andersen *et al.* 2005; Corbett *et al.* 2003a; Pardon *et al.* 2003). It appears that too much fire, not too little, is the main problem facing most of the threatened species in north western savannas (Andersen 1999). In contrast to north eastern savannas, where intensive management has allowed effective fire suppression and associated environmental problems including exotic plant invasion (Grice 2006; Radford *et al.* 2008) and land degradation due to overgrazing (Ash *et al.* 1997; Cook *et al.* 2004), there appears to be little evidence that threats to ecosystems in north western Australia result from a lack of fire. In this context, and with abundant ignition sources (both natural and anthropogenic), it is difficult to make the argument that land managers need to burn specifically to provide recently burnt habitat for wildlife. Evidence showing that most of the threatened species in northern savannas are, if anything, fire sensitive (need access to long unburnt areas), suggests that burning in this region should be aimed at protecting or promoting retention of patches of long term unburnt vegetation (3–5 years) (Andersen 1999).

It is often implied that milder, patch mosaic burning regimes would benefit biodiversity in northern Australia by buffering the effects of the severe regimes currently underway. Indeed for plants the application of low intensity early season broad-scale fires could be argued to facilitate the survival and recovery of fire sensitive species, as mortality of these species is directly related to fire intensity (Russell-Smith *et al.* 1998). However, the same may not be effective for maintaining other fire sensitive species such as the CWR mammals, within savannas, as these species may need long unburnt areas, not just reduced intensity fires. These fauna species will only benefit from regimes where vegetation cover from grasses and shrubs are retained in significant areas (>1ha) throughout the landscape. Extensive early dry season burning to reduce later wildfire intensities, as advocated in many published papers, may not benefit species like the CWR mammals if dense vegetation patches are removed.

ACKNOWLEDGEMENTS

I'd like to thank Lachie McCaw, Neil Burrows, Keith Claymore, Rick Sneeuwjagt, Roger Armstrong, Norm McKenzie and Tony Start for helpful discussions and comments during the development of the paper. I also thank Lachlan McCaw, John Woinarski, Kate Parr, Alan Andersen, Lynda Prior and an anonymous reviewer for critical review of drafts of this paper.

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Vascular Flora of the Margaret River Plateau National Parks, Conservation Parks and State Forest, south-western Western Australia

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ABSTRACT

Lists of the vascular flora of the Yelverton and Witchcliffe State Forests and the Bramley and Forest Grove National Parks from the Margaret River Plateau of south-west Western Australia are provided for the first time. A combined list of 731 taxa (87 weeds) was recorded from these areas. A total of 520 vascular plant taxa (490 native and 30 weeds) have been recorded from Yelverton Conservation Parks, 448 vascular plant taxa (388 native and 60 weeds) from Bramley National Park, 351 vascular plant taxa (315 native and 36 weeds) from Witchcliffe State Forest and 363 vascular plant taxa (307 native and 56 weeds) from Forest Grove National Park.

No native species appear to be endemic to the Plateau. No declared rare species were found, although 23 priority taxa were recorded from these reserves. Numerous disjunct and geographically significant populations are known from these parks.

INTRODUCTION

The Busselton-Augusta area contains four major physiographic regions: The Swan and Scott Coastal Plains, the Blackwood Plateau and the Leeuwin-Naturaliste Ridge. These regions are separated and defined by the Darling and Dunsborough series of faults (Lowry, 1967). These regions are further subdivided as outlined below (Figure 1).

The Leeuwin-Naturaliste Ridge occurs west of the Dunsborough fault and is composed of pre-Cambrian crystalline granitic and gneissic rocks of the Leeuwin Block, often overlain with laterite and sand. The ridge is further divided into two major landform units; the Margaret River Plateau, which stretches approximately 90km from Dunsborough to Augusta, and the Leeuwin-Naturaliste Coast stretching from Cape Naturaliste to islands off Cape Leeuwin (Tille and Lantzke, 1990). The Leeuwin-Naturaliste Coast is a discontinuous ridge of Tamala limestone and sands with underlying and occasionally outcropping Leeuwin block granite. This unit contains the Leeuwin-Naturaliste National Park, which meets the plateau in the south through the Boranup Forest (now part of the Leeuwin-Naturaliste National Park).

The Margaret River Plateau is 5–15 kilometres wide, approximately 740km² in area and is bounded on the east by the Blackwood Plateau (the Whicher Scarp is part of the Blackwood Plateau) and to the west by the Leeuwin-Naturaliste Coast (Tille and Lantzke, 1990). The area is

subject to a moderate Mediterranean climate with an annual rainfall varying from 850–1100 mm, north to south. Much of the plateau has been cleared for agriculture, but was previously dominated by jarrah (*Eucalyptus marginata*) and marri (*E. calophylla* or *Corymbia calophylla*) woodlands on the uplands with patches of karri (*E. diversicolor*) forest, woodlands on deep sands and a complex mosaic of wetland plant communities along rivers, creeks and ephemeral wetlands (Smith, 1973).

There are four major areas of natural bushland left on the plateau; the Yelverton and Witchcliffe State Forests and the Bramley and Forest Grove National Parks (Figure 2). The western two-thirds of the Yelverton State Forest is a National Park and this area straddles the transition between the Blackwood Plateau and the Margaret River Plateau. The western State Forest portion straddles the Blackwood Plateau and the Whicher Scarp.

Smaller conservation reserves (from north to south) on the Margaret River Plateau include Nature Reserves 26065, 22996, 35451, 4661, Reserve 20258 and Reserve 22996. These are generally less than 100 hectares in area. Reserve 14779 (West Bay, Augusta) at the southern tip of the Plateau, is part of Leeuwin-Naturaliste National Park.

None of the larger reserves has previously had a vascular flora list compiled. Currently the Department of Environment and Conservation (DEC) is preparing management plans for the new and existing national parks along the Leeuwin-Naturaliste Ridge and the Scott Coastal Plain. This paper provides information on the composition and conservation status of the vascular floras of the parks of the Margaret River Plateau. A previous publication detailed the vascular flora of the reserves of the Scott

Coastal Plain (Gibson *et al.*, 2001) and a further paper in preparation deals with the Leeuwin-Naturaliste National Park (Vascular flora of the Leeuwin-Naturaliste National Park, Western Australia by GJ Keighery, N Gibson and MN Lyons MN).

MATERIALS AND METHODS

Data on species distributions for the four areas were extracted from the database developed by Lyons *et al.* (2000), an unpublished survey of the then Yelverton State Forest and adjacent bushland (Keighery, 1990) and additional surveys undertaken on an ad hoc basis between 2000 to 2003 chiefly by G.J. and B.J. Keighery.

The database of Lyons *et al.* (2000) was compiled from survey data and herbarium records as detailed in that publication. In all, over 30,000 records were used to compile the flora lists, of which approximately 30% were derived from collections held in the Western Australian Herbarium and 70% from field survey. Many of the herbarium records were vouchers from these field surveys. Nomenclature generally follows Paczkowska and Chapman (2000).

RESULTS

Seven hundred and thirty one vascular plant taxa were recorded from these areas combined, composed of 644 natives and 87 weeds. The largest families were the Orchidaceae (52 native, 1 weed), Papilionaceae (55 native, 12 weeds), Cyperaceae (42 native, 3 weeds), Asteraceae (31 native, 13 weeds), Proteaceae (37) and Myrtaceae (33 native, 3 weeds). The largest genera were *Stylidium* (23), *Acacia* (19 natives, 2 weeds), *Leucopogon* (17), *Hibbertia* (14), *Caladenia* (14) *Drosera* (13) and *Thysanotus* (12).

The overall composition of the flora is typical of that of the high rainfall zone of south-west Australia (Hopper, 1979, Lyons *et al.*, 2000). There is a predominance of herbaceous elements, such as the families Cyperaceae, Orchidaceae, Asteraceae, Anthericaceae and Restionaceae.

Yelverton Reserves

The Yelverton Reserves surveyed include the Yelverton State Forest, a reserve for Sand and Gravel (Class C Reserve 29192) and the area of the Parkland Reserve (Class C Reserve 36715) abutting these two areas. This is hereafter referred to as Yelverton Reserves. The Yelverton State Forest includes two areas of bushland reserve, a larger area to the north and smaller area to the south (Figure 2). The western two thirds of both areas of the Yelverton State Forest is the Yelverton National Park (Class A Reserve 47672) and the western third is Timber Reserve (Class C Reserve 0 129 25). In the south east corner of the northern Yelverton State Forest area (in the Timber Reserve) a drainage line expands into a large wet swamp. This swamp has been named Poole Swamp for the farm to the east, and the road (Poole Road) to this farm.

A total of 520 vascular plant taxa (490 native and 30

weeds) have been recorded from the Yelverton Reserves (Appendix 1).

The largest families are the Papilionaceae (41 natives, 4 weeds), Orchidaceae (38 native, 1 weed), Cyperaceae (31 native, 2 weeds), Myrtaceae (30 native, 1 weed) and Asteraceae (23 native, 7 weeds). The largest genera are *Stylidium* (18), *Acacia* (12), *Thysanotus* (12), *Drosera* (12) and *Hibbertia* (9).

Yelverton Reserves contain a particularly diverse range of vegetation types, though the majority of the reserve is open jarrah/marri forest to woodland on laterites or sand over laterites. Deeper sands support low woodlands of *Agonis flexuosa* and *Allocasuarina fraseriana* or on dunes on the eastern side low open woodlands of *Banksia attenuata* and *Allocasuarina fraseriana*. Creek lines are edged with *Banksia littoralis* and/or *Eucalyptus patens*. Swampy flats have a heathland of *Pericalymma ellipticum* with Poole Swamp dominated by a shrub-land of *Homalospermum firmum*.

The banksia woodlands are mainly within a series of miscellaneous reserves (rail, road, townsite and local government) abutting the national park along its eastern margin. They represent the only substantial vegetated portion of the Yelverton Land System (Tille and Lantske, 1990) of the Whicher Scarp (Figure 2) which is present in government reserves.

These woodlands contain numerous elements of the flora of the Whicher Scarp. These include the only known populations of *Johnsonia inconspicua* on reserved land in the region. This species is also highly disjunct with a cluster of populations around Yelverton and the next north-east of Bindoon (Keighery, 2001). The western most population of the rare *Laxmannia jamesii* (itself composed of a series of populations on the Whicher Scarp, then disjunct to Albany) and the southern most populations of sandy soil taxa such as *Lepyrodia heleocharoides*, *Thysanotus glaucus* and *Phlebocarya filifolia*.

Poole Swamp is of exceedingly high conservation value with very disjunct populations of *Actinotus laxus*, *Comesperma nudiuscula*, *Cosmelia rubra*, *Gahnia sclerioides*, *Gonocarpus pusillus*, *Gymnoschoenus anceps*, *Empodisma gracillima* and *Sporadanthus rivularis*. These species are characteristic of swamps in the Warren Bioregion (Department of the Environment and Water Resources 2007).

Creeklines and swamps contain other species of conservation interest including *Cyathochaeta teretifolia*, *Gonocarpus hexandrus* and the priority species *Pultenaea pinifolia*.

The lateritic sands support the geographically restricted species *Calothamnus pallidiflorus*, *Acacia inops* (largely confined to the Margaret River Plateau) and *Pimelea ciliata* subsp. *longituba*.

Bramley National Park

Bramley National Park is a portion of a larger series of forest lands, much of which have been converted to pine or eucalypt plantations and were excluded from the National Park. A vascular plant list of the entire forest

totalling over 550 taxa was prepared and will be deposited in the Wildlife Science Library, Woodvale. The majority of the reserve is open jarrah/marri forest to woodland either on laterite or sands over laterite. Sandy areas support low woodlands of *A. flexuosa* and *Allocasuarina fraseriana*. River valleys have tall forests of karri (*E. diversicolor*) in favourable sites or are edged with *Banksia seminuda*, *A. flexuosa* or *E. patens* woodlands.

A total of 448 vascular plant taxa (388 native and 60 weeds) has been recorded from Bramley National Park (Appendix 1).

The largest families are the Papilionaceae (30 natives, 8 weeds), Orchidaceae (35 native, 1 weed), Asteraceae (20 native, 10 weeds), Cyperaceae (19 native, 3 weeds) and Myrtaceae (16 native, 3 weeds). The largest genera are *Styliidium* (13), *Hibbertia* (10), *Leucopogon* (10), *Drosera* (8) and *Acacia* (8).

Priority flora recorded are *Acacia semitrullata* (P3), *Astroloma* sp. Nannup (R.D. Royce 3978) P4, *Caladenia attingens* subsp. *attingens* (P4), *Bossiaea disticha* (P3) and *Jansonia formosa* (P3). The latter two species are at their north eastern margins.

A rarely recorded semi-aquatic herb is *Centrolepis fascicularis*, the only perennial species of this genus in Western Australia (Keighery, 2005) found in seeps edging creeks, here at its northern limit. Karri (*E. diversicolor*) itself is here at its north western margin.

The vegetated creeklines and associated seeps contain a variety of geographically significant populations (*Boronia molloyae*, *Centrolepis fascicularis*, *E. diversicolor* and *Jansonia formosa*) and should be protected from disturbance or alteration under the management plan.

Because of the past disturbance (roads, gravel, sand pits and plantations), the park contains a large number of weeds. Some of the most significant are largely outside the Park but still require urgent management. A very significant population of the woody weed *Pittosporum undulatum* occurs in the Margaret River adjacent to the National Park, and large populations of Arum Lily (*Zantedeschia aethiopica*) occur under the Pine Plantations. These species have the potential to form dense populations displacing the native understorey and limiting regeneration of the overstorey and hence threatening the integrity of the vegetation and floristics of the uplands and creeklines of the National Park.

Areas around the dam on Ten Mile Creek have numerous weeds which were introduced as past amenity plantings. A separate list of these plantings has been compiled but only those which have established are listed in Appendix 1 as naturalised. Along the eastern boundary an old disturbed settlement site contains populations of *Agapanthus praecox* and *Roldana pentasites*. The former is serious weed in the Porongurup National Park and the latter in eastern Australia, both should be eradicated.

Witchcliffe State Forest

The Witchcliffe State Forest is largely covered by tall open jarrah-marri woodlands on laterite over a diverse shrub layer on lower sandy slopes the understorey is dominated

by *Taxandria parviceps*. Along loamy valley floors there are small pockets of karri forest in marri - dominated woodlands to forest.

Along creek lines and swamps there are tall shrublands of *Taxandria linearifolia*, often associated with *Taxandria parviceps* tall shrubland. These can be mixed with *Astartea* species and *Homalospermum firmum* (which is occasionally locally dominant).

A total of 351 vascular plant taxa (315 native and 36 weeds) has been recorded from Witchcliffe State Forest (Appendix 1).

The largest families are the Papilionaceae (29 natives, 6 weeds), Orchidaceae (28 native, 1 weed), Cyperaceae (21 native, 2 weeds) and Asteraceae (11 native, 6 weeds). The largest genera are *Acacia* (8), *Drosera* (8), *Leucopogon* (7), *Styliidium* (6), *Thysanotus* (6) and *Hibbertia* (5).

Priority flora recorded are *Astroloma* sp. Nannup (R.D. Royce 3978) P4 and *Hybanthus volubilis*, P2.

Witchcliffe State Forest provides a very important vegetated link to the forested Blackwood Plateau, east of the Margaret River Plateau.

Forest Grove National Park

This National Park supports very similar vegetation and flora to Witchcliffe State Forest. Upland areas of Forest Grove are largely covered by jarrah-marri tall open woodlands on laterite over a diverse shrub layer, on the lower sandy slopes the understorey is dominated by *Taxandria parviceps*. Areas of deep grey sands have jarrah woodland over *A. flexuosa* low woodlands. Along loamy valley floors are small pockets small areas of karri forest in marri - dominated woodlands to forest.

Creek lines and swamps are dominated by the same species as in Witchcliffe State Forest.

A total of 363 vascular plant taxa (307 native and 56 weeds) has been recorded from Forest Grove National Park (Appendix 1).

The largest families are the Papilionaceae (26 natives, 8 weeds), Orchidaceae (26 native, 1 weed), Cyperaceae (23 native, 2 weeds) and Asteraceae (13 native, 9 weeds). The largest genera are *Acacia* (11), *Drosera* (8), *Leucopogon* (8), *Hibbertia* (8), *Thysanotus* (7) and *Styliidium* (6).

Priority flora recorded are: *Actinotus prostrata* (P3), *Astroloma* sp. Nannup (R.D. Royce 3978) P4, *Acacia subracemosa* (P2), *Acacia semitrullata* (P3) and *Bossiaea disticha* (P3). *A. subracemosa* and *Bossiaea disticha*, both largely confined to the karri of the Leeuwin – Naturaliste Coast, are here at their eastern margins.

Several very large gravel pits in the park are the focus of dumping garden waste and hence are becoming foci of numerous weeds (including *Dolichos* pea (*Dolichos lignosus*), Broome (*Genista monspessulana*) and even a stand of Bushy Yate (*Eucalyptus conferruminata*)), these areas require urgent remedial action.

Forest Grove provides the opportunity for a vegetated link to the Leeuwin – Naturaliste Coast, since the Boranup Forest nearly abuts the park.

DISCUSSION

No vascular plant taxa appear to be endemic to the Margaret River Plateau, although there are numerous endemics in the Busselton to Augusta region. These endemics are found in four major regions: the Scott Coastal Plain (Gibson *et al.*, 2001), the Swan Coastal Plain (Gibson *et al.*, 1994), sections of the Leeuwin - Naturaliste Ridge, the Blackwood Plateau and the Whicher Scarp.

A few species with ranges centred on the Margaret River Plateau extend to the western margins of the Blackwood Plateau. For example one of the most restricted species, *Acacia inops*, is currently only known from Yelverton to east of Witchcliffe.

Previously, *Hybanthus volubilis* was considered confined to the Leeuwin-Naturaliste Ridge when described, but field work for the Scott National Park (Robinson and Keighery, 1997) located this species on the Scott Coastal Plain. *Pimelea ciliata* subsp. *longituba* is also centred on the plateau, but extends north to Ambergate on the Swan Coastal Plain and east of Witchcliffe (Rye, 1999).

However, the plateau reserves have high species richness (over 500 taxa in Yelverton), which is the result of soil and habitat diversity. Because of the steep climatic gradients experienced along the ridge there are numerous disjunct and geographically significant flora populations present in the parks.

There are also very significant differences in species composition compared to reserves on the Scott Coastal Plain. The reserves of Margaret River Plateau and Scott National Park share only 51 % of their flora (Gibson *et al.*, 2001). These differences relate primarily to the diverse wetlands of the latter, which include riverine/estuarine margins (characterised by species such as *Apium prostratum*, *Bolboschoenus caldwellii*, *Ottelia ovalifolia*, *Ruppia megacarpa*, *Samolus repens*, *Sarcocornia quinqueflora*, *Suaeda australis* and *Villarsia violifolia*), clay flats (*Aphelia nutans*, *Meeboldina denmarkica*, *Trithuria submersa* and *Utricularia menziesii*), Scott Wet Ironstones (*Loxocarya magna*, *Dryandra nivea* subsp. *uliginosa*, *Chordiflex isomorphus*, *Hakea tuberculata* and *Grevillea manglesioides* subsp. *ferricola*) which are not present on the Plateau.

Other differences are in the large number of species which range from Albany to Augusta area (e.g. *Lysinema conspicuum*, *Taxandria floribunda*, *Eremosyne pectinata*, *Banksia occidentalis* and *Leucopogon tenuicaulis*) and a series of Scott Coastal Plain endemics (eg: *Adenanthos detmoldii*, *Calothamnus* aff. *crassus* and *Grevillea brachystylis* subsp. *australis*).

The parks of the Margaret River Plateau in contrast are rich in Busselton to Augusta endemics which are centred on the Blackwood Plateau (e.g. *Pultenaea brachytrypis* and *Pultenaea pinifolia*). They also contain species of deep sands (*Conospermum teretifolium*, *A. mooreana*, *Phlebocarya filifolia*, *Stirlingia latifolia*) and laterised uplands (*Calothamnus sanguineus*, *Melaleuca trichophylla*, *Marianthus candidus*, *Bossiaea aquifolium*).

These latter groups are often at or near their southern margins and are not found on the Scott Coastal Plain.

The Margaret River Plateau Parks contain many restricted or rare habitats, for example the only vegetated examples of the upland sections of the Yelverton Land System (Whicher Scarp) are found in Yelverton National Park and associated reserves.

Yelverton National Park also contains intact and very diverse wetlands. These are apparently surface expressions of a surficial aquifer intersected by the Whicher Scarp System [which is composed of the Yelverton Land System in the west and the Whicher Land System in the east (Tille, 1996), see Figure 2], rather than rainfall dependent. These wetlands are, as noted previously, nodes of Priority Flora and numerous range ends. There are few other examples of such wetlands; most are altered for water use, cleared or undocumented on private lands. The only other reserved examples we are aware of are:

- Haag Nature Reserve on the Whicher Scarp north - east of Yelverton. Here a very similar spring - fed swamp has a disjunct population of Albany Pitcher Plant (*Cephalotus follicularis*).
- At the base of the Whicher Scarp, in a newly acquired nature reserve.

The major management planning requirements for these reserves from this report are listed below.

- Consolidation of the Yelverton reserves under a single - purpose reserve.
- Protection of the values of Poole Swamp and dieback management in Yelverton.
- Prevention of rubbish dumping by rehabilitation of gravel/sand pits in all areas.
- Weed control, especially in Bramley National Park, but also in old gravel pits in other parks.
- Consideration of ecological linkages to the west and east in Forest Grove.
- Protection of riverine corridors in all parks.

ACKNOWLEDGEMENTS

We would like to thank staff of the Western Australian Herbarium for access to the WAHERB database.

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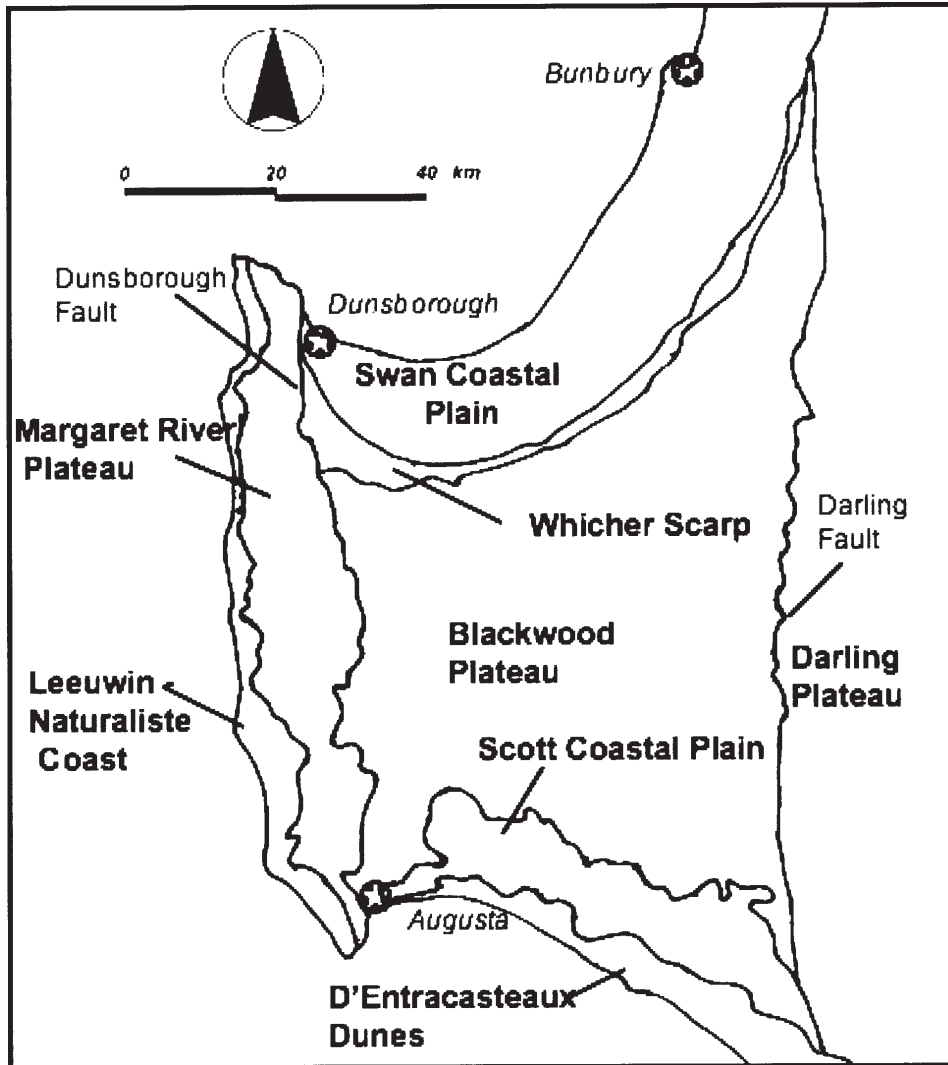


Figure 1: Physiographic regions/Major landform units of the Bunbury/Leeuwin – Naturaliste Area (approximate boundaries)

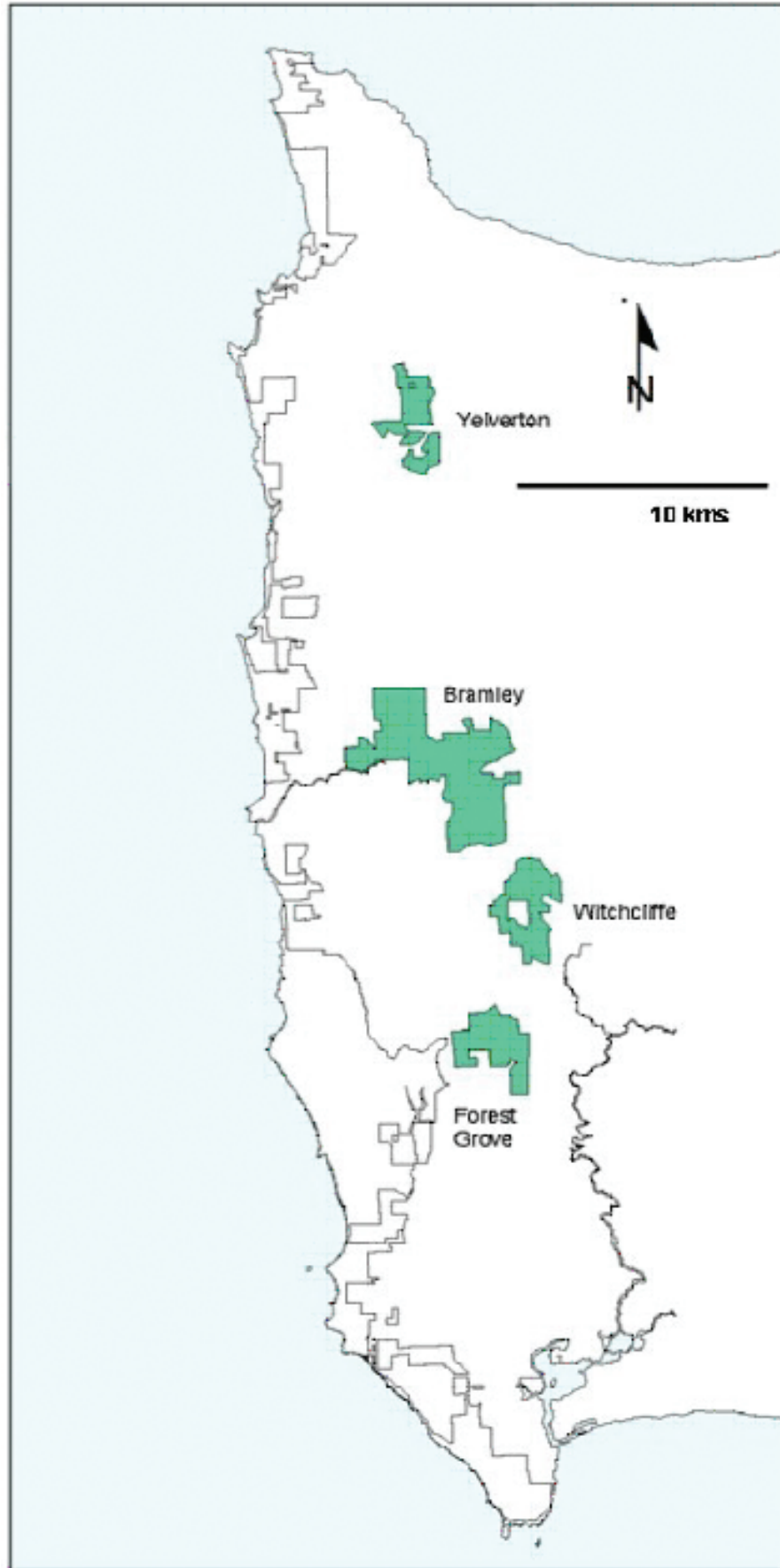


Figure 2: Margaret River Plateau National Parks, Conservation Parks and State Forest areas.

APPENDIX 1

Vascular Flora of the Margaret River Plateau Conservation Areas

Key:

Column 1: Plant Names ordered alphabetically in family, genus and species

Column 2:- 5: Bushland Area – B = Bramley, F = Forest Grove, W = Witchcliffe, Y = Yelverton

Column 6: Con = Conservation Code (Atkins, 2006).

*Naturalised/ Name	B	F	W	Y	Con
Adiantaceae					
<i>Adiantum aethiopicum</i>	+	+			
<i>Cheilanthes austrotenuifolia</i>	+			+	
Agavaceae					
* <i>Yucca filamentosa</i>	+				
Amaryllidaceae					
* <i>Agapanthus praecox</i> subsp. <i>praecox</i>	+				
* <i>Amaryllis belladonna</i>	+			+	
Aspleniaceae					
<i>Asplenium aethiopicum</i>				+	
Amaranthaceae					
<i>Alternanthera nodiflora</i>	+	+	+	+	
<i>Ptilotus manglesii</i>					
<i>Ptilotus stirlingii</i>			+		
Anthericaceae					
<i>Agrostocrinum hirsutum</i>	+	+	+	+	
<i>Arthropodium capillipes</i>	+	+	+	+	
<i>Caesia micrantha</i>	+	+	+	+	
<i>Caesia occidentalis</i>			+	+	
<i>Chamaescilla corymbosa</i> var. <i>corymbosa</i>	+	+	+	+	
<i>Johnsonia acaulis</i>				+	
<i>Johnsonia inconspicua</i>				+	P1
<i>Johnsonia lupulina</i>	+	+	+	+	
<i>Laxmannia jamesii</i>				+	P4
<i>Laxmannia ramosa</i>				+	
<i>Laxmannia sessiliflora</i> subsp. <i>australis</i>	+	+			
<i>Sowerbaea laxiflora</i>	+	+	+	+	
<i>Thysanotus asper</i>				+	P4
<i>Thysanotus glaucus</i>				+	P4
<i>Thysanotus gracilis</i>	+	+	+	+	
<i>Thysanotus manglesianus</i>	+	+	+	+	
<i>Thysanotus multiflorus</i>	+	+	+	+	
<i>Thysanotus patersonii</i>	+	+	+	+	
<i>Thysanotus pseudojunceus</i>				+	
<i>Thysanotus sparteus</i>	+	+	+	+	
<i>Thysanotus tenellus</i>				+	
<i>Thysanotus thyrsoides</i>	+	+	+	+	
<i>Thysanotus triandrus</i>		+		+	
<i>Tricoryne elatior</i>	+	+	+	+	
<i>Tricoryne humilis</i>	+	+	+	+	
Apiaceae					
<i>Actinotus glomeratus</i>	+	+	+		
<i>Actinotus laxus</i>				+	
<i>Actinotus omnifertilis</i>		+	+	+	
<i>Actinotus prostratus</i>			+		P3
<i>Centella asiatica</i>	+				
<i>Daucus glochidiatus</i>	+	+	+	+	
<i>Homalosciadium homalocarpum</i>	+	+	+	+	
<i>Hydrocotyle alata</i>	+		+	+	

*Naturalised/ Name	B	F	W	Y	Con
Hydrocotyle callicarpa	+		+	+	
Hydrocotyle pilifera var. glabrata	+			+	
Pentapeltis peltigera	+	+	+	+	
Platysace filiformis	+	+	+	+	
Platysace haplosciadia				+	
Platysace pendula		+			
Platysace tenuissima	+	+	+	+	
Trachymene pilosa	+	+	+	+	
Xanthosia candida	+	+	+	+	
Xanthosia ciliata	+		+	+	
Xanthosia huegelii	+	+		+	
Xanthosia tasmanica	+	+	+		
Araceae					
* Zantedeschia aethiopica	+	+			
Asteraceae					
Angianthus preissianus		+		+	
* Arctotheca calendula	+	+		+	
Asteridea pulverulenta	+			+	
Brachycome iberidifolia	+			+	
* Carduus pycnocephalus	+				
Centipeda cunninghamii	+				
* Conyza sumatrensis	+	+	+	+	
* Chrysanthemum segetum		+			
Cotula australis	+	+			
* Dittrichia graveolens	+				
Euchiton sphaericus	+			+	
Craspedia variabilis			+	+	
* Filago gallica	+		+		
Gnaphalium gymnocephalum	+	+	+		
Gnephosis drummondii				+	
* Hypochaeris glabra	+	+	+	+	
Ixiolaena viscosa				+	
Lagenophora huegelii	+	+	+	+	
* Leontodon saxatilis	+	+	+		
Millotia tenuifolia	+		+	+	
Olearia axillaris				+	
Olearia ciliata			+	+	
Olearia paucidentata	+	+		+	
Pithocarpa pulchella var. melanostigma	+	+	+	+	
Podolepis gracilis				+	
Podotrochea angustifolia				+	
* Pseudognaphalium luteo-album	+	+	+		
Pterochaeta paniculata	+	+	+	+	
Quinetia urvillei	+	+	+	+	
Rhodanthe citrina	+			+	
* Roldana pentasites	+				
Senecio hispidulus	+			+	
Senecio minimus var. minimus		+			
Senecio multicaulis subsp. multicaulis	+	+	+	+	
Senecio quadridentatus	+				
Siloxerus humifusus	+	+	+	+	
* Siegsbeckia orientalis	+				
* Soliva sessilis	+				
* Sonchus asper	+	+		+	
Sonchus hydrophilus	+				
* Sonchus oleraceus	+	+	+	+	
* Symphotrichum subulatum	+	+		+	
* Tolpis barbata	+				
Trichocline spathulata	+	+	+	+	
Trichocline spathulata	+	+	+	+	
* Ursinia anthemoides	+	+		+	

*Naturalised/ Name	B	F	W	Y	Con
Waitzia nitida	+			+	
Waitzia suaveolens	+			+	
Boryaceae					
Borya constricta	+				
Borya sphaerocephala				+	
Brassicaceae					
* Raphanus raphanistrum	+	+			
Caesalpiniaceae					
Labichea punctata	+		+		
Campanulaceae					
* Wahlenbergia capensis				+	
Wahlenbergia preissii	+		+	+	
Wahlenbergia multicaulis	+				
Caryophyllaceae					
* Petrorrhagia velutina	+		+		
* Silene gallica	+	+	+		
Casuarinaceae					
Allocasuarina fraseriana	+		+	+	
Allocasuarina humilis	+		+	+	
Centrolepidaceae					
Aphelia cyperoides	+		+	+	
Aphelia drummondii	+			+	
Centrolepis aristata	+	+	+	+	
Centrolepis drummondiana	+	+	+	+	
Centrolepis fascicularis	+				
Centrolepis pilosa				+	
Chenopodiaceae					
Chenopodium pumilio	+				
Clusiaceae					
* Hypericum perforatum var. angustifolium	+	+	+		
Colchicaceae					
Burchardia congesta	+	+	+	+	
Burchardia multiflora	+	+	+	+	
Wurmbea dioica				+	
Crassulaceae					
Crassula colorata var. colorata	+	+	+	+	
Crassula colorata var. tuberculata			+		
* Crassula decumbens				+	
* Crassula natans var. minus				+	
Cuscutaceae					
* Cuscuta epithymum	+				
Cyatheaceae					
* Cyathea cooperi	+				
Cyperaceae					
Baumea juncea		+		+	
Baumea vaginalis	+	+	+	+	
Carex appressa				+	
Carex fascicularis	+				
Chorizandra cymbaria			+	+	

*Naturalised/ Name	B	F	W	Y	Con
Chorizandra enodis	+		+	+	
Cyathochaeta avenacea	+	+	+	+	
Cyathochaeta clandestina			+		
Cyathochaeta teretifolia	+			+	P3
* Cyperus congestus	+		+	+	
* Cyperus tenellus	+	+	+	+	
Gahnia decomposita		+	+	+	
Gahnia sclerioides	+			+	P3
Gahnia trifida		+			
Gymnoschoenus anceps		+	+	+	
Isolepis cyperoides		+	+	+	
Isolepis marginata	+	+		+	
* Isolepis prolifer	+				
Isolepis setiformis			+	+	
Isolepis stellata				+	
Lepidosperma costale	+	+			
Lepidosperma effusum	+		+	+	
Lepidosperma leptostachyum	+	+	+	+	
Lepidosperma pubisquameum	+	+	+	+	
Lepidosperma squamatum	+	+	+	+	
Lepidosperma striatum				+	
Lepidosperma tenue	+	+	+	+	
Lepidosperma tetraquetrum	+	+	+	+	
Mesomelaena graciliceps	+	+	+	+	
Mesomelaena stygia				+	
Mesomelaena tetragona	+	+	+	+	
Schoenus caespititius				+	
Schoenus curvifolius	+	+	+	+	
Schoenus discifer	+	+			
Schoenus efoliatus	+	+	+		
Schoenus grandiflorus		+			
Schoenus maschalinus				+	
Schoenus subbulbosus		+		+	
Schoenus subflavus	+	+		+	
Schoenus sublateralis				+	
Schoenus sp. (GK 10830)				+	
Tetraria capillaris	+	+	+	+	
Tetraria octandra	+	+	+	+	
Tricostularia neesii var. neesii	+	+		+	
Dasyogonaceae					
Calectasia narragara				+	
Dasyogon bromeliifolius	+	+	+	+	
Dasyogon hookeri				+	
Kingia australis	+	+	+	+	
Lomandra caespitosa	+	+	+	+	
Lomandra drummondii		+			
Lomandra hermaphrodita	+		+	+	
Lomandra integra	+	+	+	+	
Lomandra nigricans	+	+	+	+	
Lomandra pauciflora	+	+	+	+	
Lomandra preissii	+			+	
Lomandra purpurea	+	+		+	
Lomandra sericea	+	+	+	+	
Lomandra sonderi		+	+	+	
Dennstaedtiaceae					
Histiopteris incisa	+				
Pteridium esculentum	+	+	+	+	
Dilleniaceae					
Hibbertia amplexicaulis	+	+	+	+	
Hibbertia commutata	+	+	+		

*Naturalised/ Name	B	F	W	Y	Con
<i>Hibbertia cuneiformis</i>	+	+			
<i>Hibbertia cunninghamii</i>	+	+	+	+	
<i>Hibbertia ferruginea</i>				+	
<i>Hibbertia furfuracea</i>	+			+	
<i>Hibbertia huegelii</i>	+				
<i>Hibbertia hypericoides</i>	+	+	+	+	
<i>Hibbertia inconspicua</i>	+	+		+	
<i>Hibbertia perfoliata</i>				+	
<i>Hibbertia pilosa</i>		+			
<i>Hibbertia rhadinopoda</i>	+		+		
<i>Hibbertia serrata</i>	+			+	
<i>Hibbertia notibractea</i>		+		+	
Droseraceae					
<i>Drosera erythrorhiza</i>	+	+	+	+	
<i>Drosera gigantea</i>				+	
<i>Drosera glanduligera</i>	+	+	+	+	
<i>Drosera huegelii</i>		+			
<i>Drosera leucoblasta</i>	+	+	+	+	
<i>Drosera macrantha</i> subsp. <i>macrantha</i>	+	+	+	+	
<i>Drosera menziesii</i> subsp. <i>menziesii</i>	+		+	+	
<i>Drosera microphylla</i>				+	
<i>Drosera neesii</i> subsp. <i>neesii</i>				+	
<i>Drosera pallida</i>	+	+	+	+	
<i>Drosera platystigma</i>				+	
<i>Drosera pulchella</i>	+	+	+	+	
<i>Drosera stolonifera</i>	+	+	+	+	
Epacridaceae					
<i>Andersonia caerulea</i>	+	+	+	+	
<i>Andersonia micrantha</i>	+			+	
<i>Astroloma ciliatum</i>	+		+	+	
<i>Astroloma epacridis</i>		+			
<i>Astroloma pallidum</i>	+	+	+	+	
<i>Astroloma</i> sp. Nannup(R.D.Royce 3978)	+	+	+		P4
<i>Brachyloma preissii</i>		+			
<i>Conostephium pendulum</i>				+	
<i>Leucopogon assimilis</i>	+		+		
<i>Leucopogon australis</i>	+		+	+	
<i>Leucopogon capitellatus</i>	+	+	+	+	
<i>Leucopogon conostephioides</i>	+			+	
<i>Leucopogon cordatus</i>				+	
<i>Leucopogon cymbiformis</i>	+			+	
<i>Leucopogon distans</i>		+			
<i>Leucopogon glabellus</i>				+	
<i>Leucopogon hirsutus</i>		+	+	+	
<i>Leucopogon obovatus</i>	+				
<i>Leucopogon oxycedrus</i>				+	
<i>Leucopogon parviflorus</i>	+				
<i>Leucopogon pendulus</i>	+	+	+	+	
<i>Leucopogon propinquus</i>	+	+	+		
<i>Leucopogon racemulosus</i>		+			
<i>Leucopogon unilateralis</i>		+			
<i>Leucopogon verticillatus</i>	+	+	+		
<i>Lysinema ciliatum</i>				+	
<i>Sphenotoma capitatum</i>	+			+	
<i>Sphenotoma gracile</i>		+	+		
<i>Styphelia tenuiflora</i>	+	+	+	+	
Euphorbiaceae					
<i>Amperea ericoides</i>	+	+	+	+	
<i>Amperea simulans</i>	+				

*Naturalised/ Name	B	F	W	Y	Con
* Euphorbia peplus	+				
Monotaxis grandiflora		+		+	
Monotaxis occidentalis				+	
Phyllanthus calycinus	+		+		
Poranthera microphylla	+	+	+	+	
Ricinocarpus glaucus	+	+		+	
Fumariaceae					
* Fumaria capreolata	+	+	+		
* Fumaria muralis	+	+			
Gentianaceae					
* Centaurium erythraea	+	+	+	+	
Geraniaceae					
Geranium solanderi	+		+	+	
Goodeniaceae					
Dampiera alata	+	+	+		
Dampiera hederacea	+	+	+	+	
Dampiera leptoclada		+			
Dampiera linearis	+	+	+	+	
Goodenia caerulea	+			+	
Goodenia eatoniana				+	
Goodenia pulchella		+			
Goodenia pusilla		+			
Lechenaultia biloba	+			+	
Lechenaultia expansa		+		+	
Scaevola auriculata	+	+	+	+	
Scaevola calliptera	+	+	+	+	
Scaevola glandulifera		+		+	
Scaevola microphylla	+	+	+	+	
Velleia trinervis	+	+	+	+	
Haemodoraceae					
Anigozanthos flavidus	+	+	+	+	
Anigozanthos manglesii subsp. manglesii				+	
Anigozanthos viridis subsp. viridis				+	
Conostylis aculeata subsp. aculeata	+	+	+	+	
Conostylis juncea	+				
Conostylis laxiflora			+	+	
Conostylis serrulata	+	+	+	+	
Conostylis setigera subsp. setigera	+		+	+	
Haemodorum laxum	+	+	+	+	
Haemodorum simplex				+	
Haemodorum sparsiflorum				+	
Haemodorum spicatum	+	+	+	+	
Phlebocarya ciliatum	+	+	+	+	
Phlebocarya filifolia				+	
Tribonanthes australis				+	
Tribonanthes longipetala				+	
Haloragaceae					
Gonocarpus benthamii subsp. benthamii	+	+		+	
Gonocarpus diffusus		+	+	+	
Gonocarpus hexandrus subsp. hexandrus			+	+	
Gonocarpus hexandrus subsp. serratus	+		+	+	
Gonocarpus pusillus				+	
Haloragis brownii			+	+	P4
Hydatellaceae					
Trithuria bibracteata				+	

*Naturalised/ Name	B	F	W	Y	Con
Hypoxidaceae					
Hypoxis glabella var. glabella		+		+	
Hypoxis occidentalis	+			+	
Iridaceae					
* Gladiolus cardinalis		+			
* Gladiolus undulatus	+	+	+	+	
Orthrosanthus laxus var. laxus	+				
Patersonia babianoides				+	
Patersonia juncea				+	
Patersonia maxwellii				+	
Patersonia occidentalis	+	+	+	+	
Patersonia pygmaea				+	
Patersonia umbrosa var. umbrosa	+			+	
Patersonia umbrosa var. xanthina	+	+	+	+	
* Romulea rosea	+	+	+	+	
* Watsonia meriana var. bulbillifera	+				
* Watsonia versfeldii	+	+		+	
Juncaceae					
* Juncus bufonius	+	+		+	
* Juncus capitatus	+		+	+	
Juncus holoschoenus	+		+		
* Juncus microcephalus	+		+		
Juncus pauciflorus		+			
Juncus pallidus	+	+	+		
* Juncus usitatus	+				
Luzula meridionalis	+	+		+	
Lamiaceae					
Hemiandra pungens var. pungens				+	
Hemigenia rigida				+	
Hemigenia sp. Albany (G.J. Keighery 8712)	+		+		
* Mentha pulegium	+	+	+		
* Prunella vulgaris		+			
* Stachys arvensis	+	+	+	+	
Lauraceae					
Cassytha flava				+	
Cassytha glabella	+	+	+	+	
Cassytha racemosa forma racemosa	+	+	+	+	
Lentibulariaceae					
Utricularia violacea		+			
Utricularia tenella				+	
Linaceae					
Linum marginale	+			+	
* Linum trigynum	+	+	+		
Lindsaeaceae					
Lindsaea linearis	+	+	+	+	
Lobeliaceae					
Isotoma hypocrateriformis	+	+	+	+	
Lobelia alata	+	+	+		
Lobelia rarifolia	+			+	
Lobelia rhytidosperma	+			+	
Lobelia tenuior		+			
* Monopsis debilis				+	

*Naturalised/ Name	B	F	W	Y	Con
Loganiaceae					
Logania campanulata		+	+	+	
Logania serpyllifolia subsp. angustifolia		+		+	
Logania serpyllifolia subsp. serpyllifolia	+	+	+	+	
Logania vaginalis	+	+	+	+	
Phyllangium paradoxum	+	+		+	
Lycopodiaceae					
Phylloglossum drummondii				+	
Menyanthaceae					
Villarsia albiflora	+				
Villarsia parnassifolia	+	+			
Mimosaceae					
Acacia alata	+	+	+	+	
Acacia browniana var. browniana	+	+			
* Acacia dealbata		+		+	
Acacia divergens	+	+	+	+	
Acacia extensa			+	+	
Acacia gilbertii		+	+		
Acacia inops				+	P3
Acacia latericola	+				
* Acacia melanoxydon	+				
Acacia mooreana	+			+	
Acacia myrtifolia	+	+	+	+	
Acacia nervosa				+	
Acacia obovata				+	
Acacia pulchella var. pulchella	+	+	+	+	
Acacia scalpelliformis			+		
Acacia semitrullata	+	+		+	P3
Acacia stenoptera				+	
Acacia subracemosa		+			P2
Acacia uliginosa		+			
Acacia urophylla	+	+	+		
Acacia varia	+				
Paraserianthes lophantha				+	
Myoporaceae					
Myoporum capparoides	+				
Myrtaceae					
Agonis flexuosa	+	+	+	+	
Agonis linearifolia	+	+	+	+	
Agonis parviceps	+	+	+	+	
Astartea scoparia	+	+	+	+	
Astartea laricifolia				+	
Astartea leptophylla	+		+		
Beaufortia sparsa				+	
Calothamnus lateralis			+	+	
Calothamnus pallidiflorus				+	P4
* Calothamnus rupestris	+				
Calothamnus sanguineus				+	
Calytrix flavescens				+	
Calytrix leschenaultii				+	
Eucalyptus calophylla	+	+	+	+	
Eucalyptus diversicolor	+	+	+		
Eucalyptus marginata subsp. marginata	+	+	+	+	
Eucalyptus megacarpa	+			+	
* Eucalyptus microcorys	+				

*Naturalised/ Name	B	F	W	Y	Con
<i>Eucalyptus patens</i>	+	+	+	+	
<i>Eucalyptus rudis</i>				+	
<i>Homalospermum firmum</i>		+	+	+	
<i>Hypocalymma angustifolium</i>				+	
<i>Hypocalymma cordifolium</i> subsp. <i>cordifolium</i>			+	+	
<i>Hypocalymma cordifolium</i> subsp. <i>minus</i>	+				
<i>Hypocalymma ericifolium</i>				+	
<i>Hypocalymma strictum</i>				+	
<i>Hypocalymma robustum</i>	+	+		+	
* <i>Kunzea baxteri</i>	+				
<i>Kunzea glabrescens</i>	+			+	
<i>Kunzea rostrata</i>				+	
<i>Melaleuca incana</i> subsp. <i>incana</i>	+		+	+	
<i>Melaleuca systema</i>	+			+	
<i>Melaleuca thymoides</i>	+		+	+	
<i>Melaleuca trichophylla</i>				+	
<i>Pericalymma ellipticum</i>				+	
<i>Verticordia plumosa</i> var. <i>plumosa</i>	+			+	
Olacaceae					
<i>Olax benthamiana</i>	+				
Onagraceae					
<i>Epilobium billardierianum</i> subsp. <i>cinereum</i>	+	+	+	+	
<i>Epilobium hirtigerum</i>			+		
Ophioglossaceae					
<i>Ophioglossum lusitanicum</i>	+			+	
Orchidaceae					
<i>Caladenia arrecta</i>	+				P4
<i>Caladenia attingens</i> subsp. <i>atingens</i>	+				
<i>Caladenia cairnsiana</i>				+	
<i>Caladenia citrina</i>	+	+			
<i>Caladenia flava</i> subsp. <i>flava</i>	+	+	+	+	
<i>Caladenia georgei</i>	+		+		
<i>Caladenia hirta</i> subsp. <i>hirta</i>	+	+	+		
<i>Caladenia infundibularis</i>	+		+		
<i>Caladenia longicauda</i>	+				
<i>Caladenia longiclavata</i>			+	+	
<i>Caladenia macrostylis</i>		+			
<i>Caladenia magniclavata</i>				+	
<i>Caladenia reptans</i> subsp. <i>reptans</i>		+		+	
<i>Caladenia rhomboidiformis</i>				+	
<i>Corybas recurvus</i>				+	
<i>Cryptostylis ovata</i>			+		
<i>Cyanicula gemmata</i>		+	+	+	
<i>Cyanicula sericea</i>	+	+	+	+	
<i>Cyrtostylis huegelii</i>	+	+	+	+	
<i>Diuris ?amplissima</i>	+			+	
<i>Diuris corymbosa</i>	+	+			
<i>Diuris longifolia</i>	+			+	
<i>Drakaea glyptodon</i>		+		+	
<i>Elythranthera brunonis</i>		+	+	+	
<i>Elythranthera emarginata</i>		+		+	
<i>Eriochilus dilatatus</i> subsp. <i>dilatatus</i>	+		+	+	
<i>Eriochilus dilatatus</i> subsp. <i>multiflorus</i>	+	+			
<i>Leptoceras menziesii</i>	+	+	+	+	
<i>Leporella fimbriata</i>	+	+	+	+	
<i>Lyperanthus serratus</i>	+		+	+	
<i>Microtis atrata</i>				+	
<i>Microtis media</i>	+	+	+	+	
* <i>Disa bracteata</i>	+	+	+	+	

*Naturalised/ Name	B	F	W	Y	Con
Paracaleana nigrita				+	
Præcoxanthus aphyllus	+			+	
Prasophyllum cyphochilum	+			+	
Prasophyllum fimbria	+		+	+	
Prasophyllum parvifolium	+	+	+	+	
Prasophyllum regium	+		+	+	
Pterostylis barbata	+	+	+	+	
Pterostylis ?nana	+	+	+	+	
Pterostylis pyramidalis	+				
Pterostylis recurva	+	+	+	+	
Pterostylis vittata	+	+	+	+	
Pyrorchis nigricans	+	+	+		
Thelymitra cornicina	+			+	
Thelymitra crinita	+	+	+	+	
Thelymitra flexuosa				+	
Thelymitra fuscolutea	+		+	+	
Thelymitra graminea		+			
Thelymitra macrophylla	+		+	+	
Thelymitra mucida			+	+	
Thelymitra paludosa	+		+	+	
Orobanchaceae					
* Orobanche minor	+	+	+	+	
Oxalidaceae					
* Oxalis glabra	+	+	+		
* Oxalis incarnata	+				
Oxalis perennans	+				
Papilionaceae					
Aotus gracillima			+	+	
Bossiaea aquifolium subsp. aquifolium	+		+	+	
Bossiaea disticha	+	+			P3
Bossiaea eriocarpa				+	
Bossiaea linophylla	+	+	+	+	
Bossiaea ornata	+	+	+	+	
Bossiaea praetermissa		+			
Bossiaea rufa	+	+	+		
Callistachys lanceolata	+	+	+	+	
* Chamaecytisus pal mensis	+				
Chorizema cordatum		+			
Chorizema glycinifolium				+	
Chorizema ilicifolium	+	+	+		
Chorizema nanum			+	+	
Chorizema rhombeum	+	+	+	+	
Daviesia cordata				+	
Daviesia decurrens	+	+	+	+	
Daviesia horrida	+			+	
Daviesia inflata	+	+	+	+	
Dillwynia uncinata				+	
* Dipogon lignosus	+	+			
Eutaxia virgata	+		+	+	
* Genista canariensis	+		+		
Gastrolobium bilobum		+			
Gompholobium capitatum				+	
Gompholobium confertum			+	+	
Gompholobium knightianum	+	+	+	+	
Gompholobium marginatum	+	+	+	+	
Gompholobium ovatum	+	+			
Gompholobium polymorphum		+	+	+	
Gompholobium preissii	+		+	+	
Gompholobium scabrum				+	
Hardenbergia comptoniana	+	+	+	+	

*Naturalised/ Name	B	F	W	Y	Con
Hovea chorizemifolia	+	+	+	+	
Hovea elliptica	+	+	+	+	
Hovea stricta				+	
Hovea trisperma	+	+	+	+	
Isotropis cuneifolia	+	+	+	+	
Jacksonia furcellata				+	
Jacksonia horrida				+	
Jacksonia sparsa				+	P4
Jansonia formosa	+				P3
Kennedia carinata	+			+	
Kennedia coccinea	+	+	+	+	
Kennedia prostrata	+			+	
* Lathyrus tingitanus		+	+		
* Lotus angustissimus	+	+	+	+	
* Lotus suaveolens		+			
Mirbelia dilatata	+	+	+	+	
Nemcia capitata	+		+	+	
* Ornithopus compressus	+	+	+		
* Ornithopus pinnatus		+			
* Podalyria sericea				+	
* Psoralea pinnata	+	+			
Pultenaea brachytropis				+	
Pultenaea pinifolia				+	P3
Pultenaea reticulata	+		+	+	
Sphaerolobium hygrophilum			+		
Sphaerolobium macranthum	+		+		
Sphaerolobium medium	+	+	+	+	
Sphaerolobium nudiflorum				+	
Sphaerolobium racemulosum	+		+	+	
Templetonia retusa	+				
* Trifolium campestre var. campestre	+	+	+	+	
* Vicia sativa subsp. nigra	+	+			
Viminaria juncea	+	+			
Philydraceae					
Philydrella pygmaea				+	
Phormiaceae					
Dianella revoluta var. revoluta	+			+	
Pittosporaceae					
Billardiera fusiformis	+			+	
Billardiera laxiflora	+				
Billardiera parviflora var. parviflora				+	
Billardiera variifolia	+	+	+	+	
Cheiranthra preissiana			+	+	
Marianthus candidus	+	+	+	+	
Marianthus coerulea-punctatus		+			
Marianthus tenuis	+				
Pronaya sericea				+	
Plantaginaceae					
* Plantago lanceolata	+	+	+		
Poaceae					
Agrostis avenacea				+	
* Aira caryophyllea	+	+	+	+	
Amphipogon amphipogonoides	+	+	+	+	
Amphipogon laguroides subsp. laguroides	+	+	+	+	
Amphipogon setaceus			+		
Amphipogon turbinatus	+			+	
* Anthoxanthum odoratum	+	+	+		
Austrodanthonia caespitosa	+		+		

*Naturalised/ Name	B	F	W	Y	Con
<i>Austrodanthonia occidentalis</i>	+		+	+	
<i>Austrodanthonia setacea</i>					
<i>Austrostipa campylachne</i>	+	+	+	+	
<i>Austrostipa compressa</i>		+			
<i>Austrostipa semibarbata</i>	+			+	
* <i>Avena barbata</i>	+	+	+	+	
* <i>Briza maxima</i>	+	+	+	+	
* <i>Bromus hordeaceus</i>	+	+		+	
<i>Deyeuxia quadriseta</i>	+	+	+	+	
<i>Dichelachne crinita</i>	+	+	+	+	
<i>Echinopogon ovatus</i>	+	+			
* <i>Glyceria declinata</i>		+			
<i>Hemarthria uncinata</i>	+				
* <i>Holcus lanatus</i>	+	+		+	
* <i>Hyparrhenia hirta</i>	+		+		
* <i>Lolium multiflorum</i>	+	+	+	+	
<i>Microlaena stipoides</i>	+	+	+	+	
<i>Neurachne alopecuroidea</i>		+	+	+	
* <i>Pennisetum clandestinum</i>	+	+	+		
* <i>Pennisetum purpureum</i>				+	
* <i>Poa annua</i>	+	+		+	
<i>Poa serpentum</i>	+				
<i>Tetrarrhena laevis</i>	+	+	+	+	
* <i>Vulpia myuros</i>	+	+		+	
Podocarpaceae					
<i>Podocarpus drouynianus</i>	+	+	+		
Polygalaceae					
<i>Comesperma calymega</i>	+			+	
<i>Comesperma confertum</i>		+	+		
<i>Comesperma nudiusculum</i>				+	
<i>Comesperma virgatum</i>	+		+	+	
<i>Comesperma volubile</i>				+	
Polygonaceae					
* <i>Rumex acetosella</i>	+	+	+		
* <i>Rumex conglomeratus</i>				+	
Portulacaceae					
<i>Calandrinia corrigioloides</i>		+			
Primulaceae					
* <i>Anagallis arvensis</i> var. <i>arvensis</i>	+	+			
* <i>Anagallis arvensis</i> var. <i>caerulea</i>	+	+		+	
* <i>Anagallis minima</i>	+				
Proteaceae					
<i>Adenanthos barbiger</i> subsp. <i>barbiger</i>	+			+	
<i>Adenanthos meisneri</i>				+	
<i>Adenanthos obovatus</i>		+		+	
<i>Banksia attenuata</i>		+		+	
<i>Banksia grandis</i>	+	+	+	+	
<i>Banksia illicifolia</i>				+	
<i>Banksia littoralis</i>	+	+	+	+	
<i>Banksia seminuda</i>	+				
<i>Conospermum capitatum</i> subsp. <i>capitatum</i>	+	+			
<i>Conospermum capitatum</i> subsp. <i>glabratum</i>				+	
<i>Conospermum flexuosum</i>				+	
<i>Conospermum teretifolium</i>				+	
<i>Dryandra bipinnatifida</i>	+			+	
<i>Dryandra lindleyana</i>	+	+	+	+	
<i>Grevillea brachystylis</i> subsp. <i>brachystylis</i>				+	P3

*Naturalised/ Name	B	F	W	Y	Con
<i>Grevillea quercifolia</i>		+	+	+	
<i>Grevillea trifida</i>	+			+	
<i>Hakea amplexicaulis</i>	+	+	+	+	
<i>Hakea ceratophylla</i>			+	+	
<i>Hakea falcata</i>	+				
<i>Hakea lasianthoides</i>	+	+	+	+	
<i>Hakea linearis</i>	+			+	
<i>Hakea lissocarpha</i>	+	+	+	+	
<i>Hakea ruscifolia</i>	+	+	+	+	
<i>Hakea trifurcata</i>	+				
<i>Isopogon sphaerocephalus</i>				+	
<i>Persoonia elliptica</i>			+	+	
<i>Persoonia longifolia</i>	+	+	+	+	
<i>Persoonia saccata</i>		+		+	
<i>Petrophile diversifolia</i>	+	+	+	+	
<i>Petrophile linearis</i>				+	
<i>Stirlingia latifolia</i>				+	
<i>Stirlingia tenuifolia</i>				+	
<i>Synaphea favosa</i>	+			+	
<i>Synaphea gracillima</i>				+	
<i>Synaphea petiolaris</i>	+	+	+	+	
<i>Xylomelum occidentale</i>		+	+	+	
Pteridaceae					
<i>Pteris vittata</i>			+	+	
Rafflesiaceae					
<i>Pilostyles hamiltonii</i>	+				
Ranunculaceae					
<i>Clematis pubescens</i>	+	+	+	+	
<i>Ranunculus colonorum</i>	+				
Restionaceae					
<i>Anarthria gracilis</i>	+			+	
<i>Anarthria prolifera</i>		+	+	+	
<i>Anarthria scabra</i>	+	+	+		
<i>Chaetanthus tenellus</i>				+	
<i>Cytogonidium leptocarpoides</i>				+	
<i>Desmocladius fasciculatus</i>	+	+	+	+	
<i>Desmocladius flexuosus</i>	+	+	+		
<i>Empodisma gracillimum</i>		+	+	+	
<i>Hypolaena exsulca</i>	+	+	+	+	
<i>Hypolaena macrotepala</i>				+	
<i>Hypolaena viridis</i>	+				
<i>Leptocarpus tenax</i>				+	
<i>Lepyrodia glauca</i>	+				
<i>Lepyrodia heleocharoides</i>				+	P3
<i>Lepyrodia muirii</i>	+				
<i>Lepyrodia porterae</i>			+		
<i>Loxocarya cinerea</i>	+	+	+	+	
<i>Lyginia barbata</i>	+		+	+	
<i>Meeboldina coangustata</i>	+				
<i>Meeboldina roycei</i>	+		+		
<i>Meeboldina scariosa</i>	+				
<i>Meeboldina thysananthus</i>			+		
<i>Melanostachya ustulata</i>		+		+	
<i>Sporadanthus rivularis</i>			+	+	
<i>Sporadanthus strictus</i>	+		+		
<i>Taraxis grossa</i>	+	+			
Rhamnaceae					
<i>Cryptandra arbutiflora</i>	+			+	

*Naturalised/ Name	B	F	W	Y	Con
Trymalium floribundum subsp. tridum	+	+		+	
Trymalium ledifolium var. rosmarinifolium	+	+	+	+	
Rosaceae					
* Rubus ulmifolius	+				
Rubiaceae					
* Galium aparine	+			+	
* Galium divaricatum	+				
Opercularia apiciflora	+	+	+	+	
Opercularia echinocephala	+	+	+	+	
Opercularia hispidula	+	+	+	+	
Opercularia volubilis	+		+		
* Sherardia arvensis	+			+	
Rutaceae					
Boronia crenulata subsp. gracilis				+	P2
Boronia crenulata subsp. pubescens	+	+	+	+	
Boronia defoliata				+	
Boronia denticulata				+	
Boronia dichotoma		+	+		
Boronia gracilipes	+	+	+	+	
Boronia megastigma			+	+	
Boronia molloyae	+	+	+		
Boronia ramosa subsp. anethifolia				+	
Boronia stricta				+	
Chorilaena quercifolia	+	+			
* Coleonema album	+				
Philothea spicata	+	+	+	+	
Santalaceae					
Leptomeria cunninghamii	+			+	
Leptomeria squarrulosa	+	+	+	+	
Sapindaceae					
Dodonaea viscosa				+	
Scrophulariaceae					
Gratiola pubescens	+		+		
* Parentucellia viscosa	+		+		
Veronica plebeia	+		+		
Selaginellaceae					
Selaginella gracillima				+	
Solanaceae					
* Solanum nigrum		+		+	
Stackhousiaceae					
Stackhousia huegelii			+	+	
Tripterococcus brachylobus				+	
Tripterococcus brunonis	+	+	+	+	
Tripterococcus panniculatus				+	
Sterculiaceae					
Lasiopetalum floribundum	+	+	+	+	
Thomasia heterophylla		+			
Thomasia macrocarpa				+	
Thomasia pauciflora	+	+	+	+	
Stylidiaceae					
Levenhookia preissii	+		+	+	
Levenhookia pusilla	+	+	+	+	

*Naturalised/ Name	B	F	W	Y	Con
<i>Levenhookia stipitata</i>	+			+	
<i>Stylidium adnatum</i>	+	+	+	+	
<i>Stylidium amoenum</i>		+	+	+	
<i>Stylidium bulbiferum</i>				+	
<i>Stylidium caespitosum</i>	+		+		
<i>Stylidium calcaratum</i>	+	+	+	+	
<i>Stylidium crassifolium</i>	+				
<i>Stylidium eriopodium</i>	+			+	
<i>Stylidium fasciculatum</i>	+				
<i>Stylidium guttatum</i>				+	
<i>Stylidium hispidum</i>	+			+	
<i>Stylidium junceum</i>	+			+	
<i>Stylidium leeuwinense</i>		+			
<i>Stylidium luteum</i>				+	
<i>Stylidium maitlandianum</i>				+	
<i>Stylidium neurophyllum</i>	+			+	
<i>Stylidium piliferum</i>				+	
<i>Stylidium repens</i> var. <i>repens</i>	+		+	+	
<i>Stylidium rhynchocarpum</i>	+			+	
<i>Stylidium scandens</i>	+			+	
<i>Stylidium schoenoides</i>		+		+	
<i>Stylidium spathulatum</i>	+	+	+	+	
<i>Stylidium squamotuberosum</i>			+		
<i>Stylidium violaceum</i>				+	
Thymelaeaceae					
<i>Pimelea ciliata</i> subsp. <i>longituba</i>				+	P3
<i>Pimelea hispida</i>	+	+	+	+	
<i>Pimelea lehmanniana</i> subsp. <i>nervosa</i>				+	
<i>Pimelea preissii</i>				+	
<i>Pimelea rosea</i>	+				
<i>Pimelea spectabilis</i>	+	+	+	+	
<i>Pimelea suaveolens</i> subsp. <i>suaveolens</i>	+			+	
<i>Pimelea sylvestris</i>	+	+	+	+	
Tremandraceae					
<i>Platytheca galioides</i>					
<i>Tetratheca filiformis</i>			+	+	
<i>Tetratheca hirsuta</i>			+		
<i>Tremandra diffusa</i>	+	+	+		
<i>Tremandra stelligera</i>	+	+	+	+	
Valeriaceae					
* <i>Centranthus rubra</i>	+				
Violaceae					
<i>Hybanthus debilissimus</i>	+	+	+	+	
<i>Hybanthus volubilis</i>			+		P2
Xanthorrhoeaceae					
<i>Xanthorrhoea gracilis</i>		+	+	+	
<i>Xanthorrhoea preissii</i>	+	+	+	+	
Xyridaceae					
<i>Xyris gracillima</i>		+	+	+	
<i>Xyris inaequalis</i>	+				
Zamiaceae					
<i>Macrozamia fraseri</i>	+	+	+	+	

Flora and vegetation of the Banded Iron Formations of the Yilgarn Craton: the Booylgoo Range

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ABSTRACT

A quadrat-based survey was undertaken of the vascular flora and plant communities on the Booylgoo Range, 65 km east of Sandstone in the arid Murchison bioregion. The Range is an outcropping of the Booylgoo greenstone belt, which consists of diverse lithologies that includes Archaean banded iron formation (BIF), metabasalt, mafics, and Tertiary laterites. Quadrats were strategically placed to cover these broad geologies and the topographic profile of this range. This survey identified a total of 207 taxa (species, subspecies, varieties and forms) and nine putative hybrids from 47 families of vascular plants. This includes six species of conservation significance, five of these being new records for the area. Range extensions exceeding 100 km are reported for nine species, but no endemic taxa were found. Classification analysis of presence/absence data on perennial taxa at 51 sites resolved six floristic community types, one of these with two subtypes. These are described in terms of structure, dominant taxa, indicator species and associated soil and environmental attributes. There is a strong association of community types with edaphic factors (topology, rock substrate and soil chemistry). The greatest floristic dissimilarity among communities is between those on banded iron formation and those on mafic substrates, which is associated with marked differences in soil chemical characteristics. Within BIF sites, the greatest floristic differences are between upland and lowland communities. This is associated with the extremes along a topo-edaphic gradient. The Booylgoo Range is an isolated, arid-zone landform whose different communities are tightly linked to landform element, topography and substrate. Mining and exploration tenements cover all of the survey area and the Booylgoo Range lies on two active pastoral leases. None of the range occurs within the secure conservation estate.

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

INTRODUCTION

The Booylgoo Range is a notable topographical feature in that it is one of very few ranges of significant elevation in the greater Sandstone region, in the northern Yilgarn region of Western Australia. Underlying the range is the Booylgoo greenstone belt, which consists of metamorphosed volcanics and metasedimentary rocks of great antiquity (Tingey 1985; Wyche 2004). It is one of many located within the granitoids of the northern Yilgarn Craton (Cassidy *et al.* 2006; Groenewald & Riganti 2004). This outcropping of bedrock forms a series of rises, hills and ridges that attain elevations of up to 100 m above the surrounding plains of sediments. These and other greenstone belts in the Murchison Mineral Field have been subject to exploitation over the past century for base and precious metals. A significant component of the Booylgoo greenstone belt is banded iron formation (BIF), and a renewed expansion of the iron ore industry in Western Australia has targeted these BIF landforms as highly prospective for iron ore.

Massive outcrops and ranges of ironstones and volcanics provide a challenging environment for plants because of a variety of conditions, including skeletal, acidic, low nutrient and metal-enriched soils with a low water holding capacity and high runoff, hard substrates, excessive UV irradiation, wind exposure and high temperatures (de Castro Vincent & Meguro 2008; Jacobi *et al.* 2007). Nonetheless, these landforms have been found to support diverse floras, distinctive communities and uncommon, endemic or unusual species (Butler & Fensham 2008; van Etten & Fox 2004; Gibson *et al.* 2007; Jacobi *et al.* 2007). Previous surveys have characterised the floristic communities on discrete, isolated greenstone and BIF ranges in the Eastern Goldfields of the Yilgarn Craton (Gibson & Lyons 1998a, 1998b, 2001a, 2001b; Gibson 2004a, 2004b). These floras have been found to be species-rich, have high species turnover among ranges (?-diversity), and can harbour new, rare and poorly known taxa and regional endemics. These studies have also established that the floristic communities are varied both within an individual range and among ranges, and some communities are geographically restricted. Given the deficiency of detailed flora surveys for BIF ranges in the

Northern Yilgarn, this current work is part of an ongoing series of floristic surveys on banded iron formation and greenstone landforms within the northern Murchison geological region of the Yilgarn Craton (Department of Environment 2007; Gibson *et al.* 2007). These surveys aim to provide description of the flora and vegetation communities, which will assist in strategic conservation planning and management for these highly prospective BIF and greenstone ranges (Department of Environment 2007; Department of Industry and Resources 2007). This particular study specifically aims to describe the flora and floristic communities on the Booylgoo Range.

Study Site

The Booylgoo Range is a significant outcropping of Archaean bedrock in the general Sandstone region that is located approximately 65 km east of the township of Sandstone and 125 km south of Wiluna, in the Murchison region of Western Australia (Fig. 1). It is a north-south trending greenstone belt occurring over a latitudinal range of 27.68° S – 28.01° S and a longitudinal range of 119.87° E – 119.99° E, which is c. 40 km long and c. 4–5 km wide along much of its length. It extends over the Booylgoo Spring and Depot Spring Stations, within the shire of Sandstone.

Land Use History

As with much of the Murchison region, pastoralism and mining historically have been the economic mainstays in the greater Sandstone region (Hennig 1998a; Tingey 1985). Although the general Sandstone region is marginal grazing land, pastoral leases were initiated within the first decade of the 20th century, and firmly established by the 1920s (Tingey 1985). Both the Booylgoo Spring and Depot Spring stations are active pastoral leases and currently stock cattle.

Gold deposits were located in the greater Black Range district area of the East Murchison Goldfields in the 1890s, leading to the establishment of Sandstone and Youanmi townships (Hennig 1998a; Tingey 1985). Gold production and the population in the Sandstone township and surrounds peaked around 1912, only to decline after the late 1920s (Hennig 1998a; Tingey 1985). Interest in gold, base metals and iron-ore was renewed in the 1960s and again from late 1970s onwards, such that mining continues on the Sandstone and Gum Creek belts (Tingey 1985; Wyche *et al.* 2004). Owing to little evidence of gold mineralisation, the Booylgoo Range itself has only been subjected to mineral exploration and has not been subject to the same intensive mining that has occurred on surrounding areas (Wyche *et al.* 2004). Economically viable deposits of iron-ore have been identified in the BIF ridges of the Booylgoo Range (Flint *et al.* 2000).

Climate

Booylgoo Spring and Depot Spring stations are on the western border of the north-eastern Goldfields and Sandstone – Paynes Find regions, where the climate is

described as arid (Gilligan 1994) or a desert with a limited, bimodal rainfall (Beard 1976, 1990). The closest meteorological centre to the study area is at Booylgoo Spring Station (Fig. 1), which records an average annual mean rainfall of 236 mm (Australian Bureau of Meteorology 1908–). The wettest months are February and March, while the driest is September. Sporadic summer rainfall occurs when the remnants of tropical cyclones pass into the Eremaean region, while irregular winter and spring rainfall arrives with moist, south-westerly cold fronts (Leighton 1998). The Booylgoo Range lies within a region with a high drought susceptibility, where annual evaporation range for the region (approaching 3600 mm) greatly exceeds the annual rainfall (Gilligan 1994; Leighton 1998). The temperature regime for Booylgoo Spring is for hot summers and cool winters (Australian Bureau of Meteorology 1908–). The average winter (June–August) daily maximum and minimum temperatures are 18.5 °C and 5.2 °C, while the average summer (December–February) daily maximum and minimum temperatures are 35.3 °C and 20.7 °C respectively.

Geology

The geology of the Booylgoo Range and surrounding areas has been described and mapped on the Sandstone 1:250 000 geological sheet (SG/50-16) (Tingey 1985) and Lake Mason 1:100 000 (Sheet 2842) (Wyche 2004). The wider area around the Booylgoo Range, as depicted on the Sandstone sheet, predominately consists of gently undulating plains of Cainozoic sediments. A small proportion of this area of low relief is interrupted by outcropping ranges of Archaean bedrock, which provides the only topographical relief to an otherwise flat landscape. The Booylgoo Range varies in elevation from 470 m above sea level on the lowest slopes and surrounding flats to between 520 and 560 m on the taller ridges. Mt Anderson (576 m) and Mt St Michael (564 m) are the two tallest named peaks for the range (Fig. 1).

The Booylgoo Range is formed by outcropping of the Booylgoo greenstone belt, which consists of a succession of metamorphosed sedimentary deposits and volcanic intrusions laid down during the Archaean eon. The metamorphosed igneous rocks include mafic (basalts and gabbro) and ultramafic intrusions, while banded iron formation (BIF) is a significant component of the metasediments (Tingey 1985; Wyche 2004). BIF itself consists of a series of alternating fine layers of shales, siltstone, cherts and iron oxide rich sediments, and can host mineral deposits (Page 2001). The Booylgoo greenstone belt occurs within the Southern Cross Domain of the Youanmi Terrane (Cassidy *et al.* 2006); previously referred to as the South Cross Granite Greenstone Terrane (Tyler & Hocking 2001a, 2001b). Similar greenstone belts in the Youanmi Terranes have been dated at c. 3.0–2.7 Ga (Cassidy *et al.* 2006). The Booylgoo greenstone belt is a syncline, with the north and south ends dipping towards the centre (Tingey 1985; Wyche 2004). Since the BIF occurs at the lower levels in the sequence, deformations

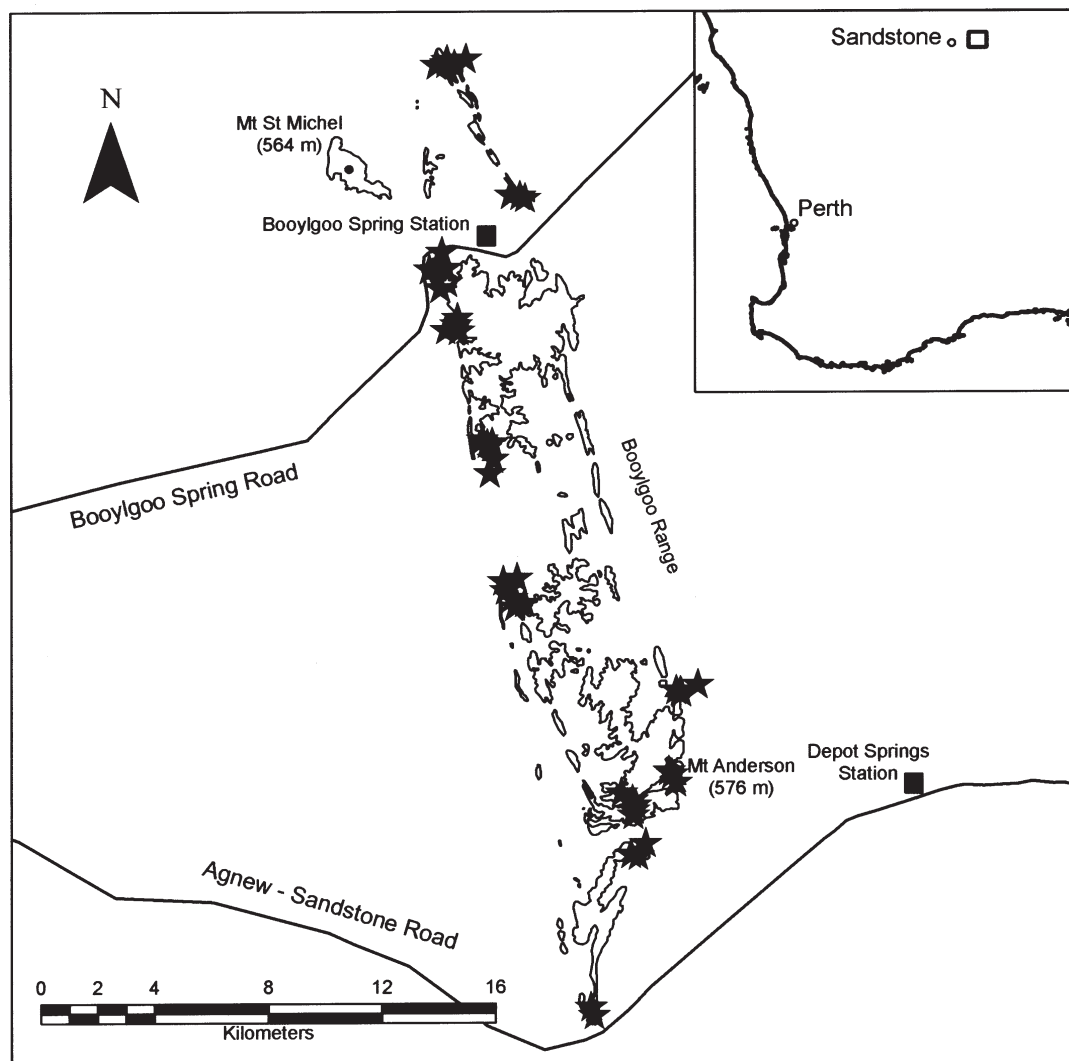


Figure 1. Map depicting the general location of the Booylgoo Range within Western Australia (insert). The major ridges of the range are outlined and associated significant landmarks are labelled. The positions of the 51 floristic quadrats are demarcated by star symbols (★).

have resulted in the protrusion of prominent ridges of BIF on the outer margins of the range. Therefore, this BIF is exposed as two major north-south trending, near parallel ridges that border central ridges of massive to foliate mafic rocks, including metabasalts, komatiitic basalt (metamorphosed), fine-medium grained mafic rock (strongly foliate to schistose), ultramafics (peridotite), tremolite-chlorite-(magnetite) schist and metagabbro (Wyche 2004). The tallest and most extensive outcroppings of BIF occur in the southern half of the range.

There are three main discontinuities within the latitudinal extent of the range, where the bedrock has been extensively dissected by the larger drainage systems and covered by alluvial and colluvial deposits (*cf.* Wyche 2004). The northernmost gap is where the Booylgoo Spring homestead is located and where the Booylgoo Spring Road crosses the range (Fig. 1). In the centre of the range a large area has been eroded by drainage and this partially

interrupts the range. The third main discontinuity occurs south of Mt Anderson and the associated east-west oriented band of BIF. South of this point, the range becomes a series of narrow, north-south trending, arcuate ridges of BIF and metabasalt which form a series of low hills of massive BIF that terminate immediately north of the Agnew–Sandstone Road.

Cainozoic deposits, which are derived from weathering of the exposed bedrock, overlie the lower slopes, flats and outwashes of the Booylgoo Range. Scree of predominately eroded chert and banded iron formation lines the flanks of BIF ridges, while an alluvium of clay, silt and gravel has accumulated in drainage lines. Colluvial deposits and alluvial sheetwash of clay, silt and ferruginous gravels overlie the plains further from the range (*cf.* Wyche 2004). Relatively small areas of ferruginous lateritic duricrust overlie the pediment of BIF ridges along the eastern flanks of the BIF ridges, which often erodes into breakaways. Abutting onto the western flanks of Booylgoo Range is a

distinct sandplain of aeolian deposits which overlie weathered regolith.

Soils of greenstone landforms in the eastern Murchison region are derived from weathering of parent rock (mafic metavolcanics and BIF), and as such these soils are typically shallow to skeletal (< 50cm) rudosols (lithosols) or stony red earths becoming progressively shallow stony red earths on the lower slopes, flatsand outwashes (Churchward 1977; Hennig 1998b; van Vreeswyk 1994). Texturally, these soils are fine sandy loam – clay loams, and often contain an abundance of rock fragments. Fine ironstone gravels can be found in weathered soil profiles on pediments, plains and outwashes (Hennig 1998b). The soils are relatively poorly developed, infertile and characteristically acidic (pH 5.0–7.0) (Churchward 1977; Hennig 1998b; van Vreeswyk 1994). Being derived from metalliferous rock, soil concentrations of metal elements are higher than those derived from granitoids (Cole 1973; Churchward 1977; Gray and Murphy 2002).

Vegetation

Using the current Interim Biogeographic Region (IRBA) classification (Environment Australia 2000; Thackway & Creswell 1995), the Booylgoo Range is located within the Murchison IBRA bioregion which has been adopted from the Austin Botanical District and Eremaean Botanical Province of Beard (1976, 1990). The vegetation of this district is dominated by mulga (*Acacia aneura*) low woodlands on plains and mixed *Acacia* stands on rocky outcrops. Beard (1976, 1990) further described the Wiluna subregion of the Austin Botanical District, within which the Booylgoo Range is located, where the vegetation on rocky ranges are described as essentially a shrubby cover of *Acacia aneura*, *Acacia quadrimarginea*, *Acacia grasbyi* and *Hakea suberosus* (= *H. lorea*) over *Cassia* (*Senna*), *Eremophila clarkei* and *Eremophila latrobei* undershrubs, over *Ptilotus obovatus* and annual herbs. This brief description applies to both greenstone and granite hills, as Beard considered the vegetation as similar. Beard (1976) mapped these as uniform physiognomic units on a scale of 1:1 000 000.

To date, there have been no fine scale surveys on the Booylgoo Range per se, and the closest vegetation community descriptions are those by Pringle (1994a, 1998a), which are inclusive in the wider rangeland surveys of the north-eastern goldfields (Pringle & van Vreeswyk (1994) and the Paynes Find – Sandstone region (Payne *et al.* 1998). These surveys have adopted the land system approach, where a land system is a catenary sequence of vegetation communities linked to geological and topographic features. The ridges of BIF and associated metasediments of the Booylgoo Range have been mapped as the Brooking land system (Payne *et al.* 1998; Pringle & van Vreeswyk 1994), which has up to five community types, one to two of these occurring on these uplands (Pringle 1994a, 1998a). Hills of mafic rocks have been mapped as the Gabanintha and Laverton land systems by Payne *et al.* (1998) and Pringle and van Vreeswyk (1994), respectively, and these support five community types, two

or three of these occurring on ridges, hill crests and hill slopes. Vegetation communities are common to both land systems, including the main upland stony ironstone mulga shrublands unit and the greenstone hill acacia shrublands (Pringle 1994a, 1998a). Several other mulga shrubland and saltbush communities characteristic of stony plains, lateritic hard pans and drainage tracts occur on the lowlands around these land systems.

METHODS

The methodology employed in this survey follows the standard procedure that has been used in previous vegetation community surveys of other BIF and greenstone ranges in Western Australia (Gibson and Lyons 1998a, 1998b, 2001a, 2001b; Gibson 2004a, 2004b; Markey & Dillon 2006a, 2006b; Meissner & Caruso 2008a, 2008b, 2008c). Fifty one 20 x 20 m permanent quadrats were established over the survey area in spring during a two week period of September 2006. Quadrats were established over both the longitudinal and latitudinal extent of the range and placed strategically in vegetation communities on BIF and adjacent geologies to cover the broad toposequence, from hill crests and slopes of exposed bedrock and scree to colluvial deposits on pediments and plains. Only vegetation in good, undisturbed condition was sampled, thereby avoiding burnt, heavily grazed and cleared areas. The vegetation on the adjoining sandplain on the south-western side of the range was not sampled as the substrate was not derived directly from the range bedrock and had been burnt within the past five years.

Quadrats were marked with four steel fence droppers, photographed and both location and altitude recorded with a GPS receiver (Garmin 76, Garmin Ltd). Vegetation structure using dominant taxa was described according to McDonald *et al.* (1998). Cover class estimates of all vascular plant species (spermatophytes and pteridophytes) were recorded, and material was collected for identification at the Western Australian Herbarium. Data on topographical position, aspect, slope, altitude, percentage litter, percentage bare ground, percentage rock cover class of both surface deposits and exposed bedrock, shape of surface rock fragments, soil colour and soil texture were collected according to McDonald *et al.* (1998). Leaf litter and bare ground were visual estimates of percentage cover (bare ground cover including litter and rock cover), and slope readings were obtained from a clinometer. Topographic position (Tp) was coded as semi-quantitative, five point scale (flat / outwash = 1, lower slope = 2, mid slope = 3, upper slope or low ridge = 4, crest = 5). Both surface rock fragment (Rock Frag) and exposed bedrock outcrop (% rock) cover classes were scored on seven point cover scale; 0% cover (0); < 2% cover (1); 2–10% (2); 10–20% (3); 20–50% (4); 50–90% (5); > 90% (6). Maximum rock fragment size (MxR) was classed on a seven point size scale; 2–6mm (1); 6–20mm (2); 20–60mm (3); 60–200mm (4); 200–600mm (5); 600mm–2m (6); > 2m (7).

A bulked topsoil sample (10cm depth) was compiled

from 20 subsamples collected over the area of the quadrat. Soil colour was gauged in the field and soil texture was estimated manually according to McDonald *et al.* (1998). Particles over 2mm in size were removed by sieving before soil chemical composition was analysed at the Chemistry Centre of Western Australia. Mineral concentrations were determined by inductively coupled plasma atomic emission spectrometry (ICP AES) for the simultaneous determination of a suite of 16 elements (Al, B, Ca, Cd, Co, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, S and Zn), using the Mehlich No. 3 soil test procedure (Mehlich 1984, Walton & Allen 2004). Soil pH was determined in 0.01M CaCl₂ (method S3, Rayment & Higginson 1992). The effective Cation Exchange Capacity (eCEC) (cmol(+)/kg) was calculated as the sum total of individual Na, Ca, K and Mg charge equivalents, which were calculated from their respective cation concentrations from ICP AES (Rayment & Higginson 1992; Soil and Plant Council 1999). Electrical conductivity (EC) was determined by method S2 (using a conductivity meter on a 1:5 solution of soil extract:deionised water at 25 °C (Rayment & Higginson 1992). Soil organic carbon (%) was determined using Metson's colorimetric modification of the Walkley and Black wet oxidation method S09 (Metson 1956, method 6A1 of Rayment & Higginson 1992). Total soil nitrogen (%) was determined by a modified kjeldahl digest (method S10) (Rayment & Higginson 1992).

Floristic communities were determined from simultaneous classification and ordination analyses on dissimilarity matrices (Bray-Curtis coefficient), which had been derived from site by species data matrices, using the PATN (V3.03) (Belbin 1989). For final analyses, annual taxa and perennial singletons (a taxon known from a single quadrat) were omitted, following the protocol employed in previous surveys on Western Australian ironstone and greenstone ranges (e.g. Gibson 2004a, 2004b). This was after the dissimilarity matrices with sets of taxa were compared using the '2 Stage' algorithm in Primer (Clark & Gorley 2006), and found to be highly correlated. Species and site classifications was undertaken using the flexible 'unweighted pair group method using arithmetic averages' (UPGMA) algorithm, which is agglomerative, hierarchical clustering method ($\lambda = -0.1$) (Belbin 1992; Sneath & Sokal 1973). A two-way table was generated from these site and species classifications. Indicator species analysis (Dufrene & Legendre (1997) was employed to determine the significant indicator species for each floristic community type, using the INDVAL routine in PC-Ord (McCune & Mefford 1999) and a Monte Carlo permutation test (10 000 simulations) to evaluate the statistical significance of each taxon.

Semi-strong hybrid (SSH) nonmetric multidimensional scaling (MDS) was used to resolve spatial relationships in three dimensions among the sites from the floristic data, using 1000 random starts and 50 iterations (Belbin 1991). Principal Component Correlation (PCC) was used to determine the linear relationship between environmental variables on the site ordination coordinates (Belbin 1989). A Monte-Carlo permutation test (MCAO) was employed to evaluate the

significance of the PCC correlation coefficients, using 10000 iterations of this procedure (Belbin 1989). Kruskal-Wallis nonparametric analysis of variance and Dunns' posthoc multiple comparisons were employed to determine differences in environmental variables among the community types (Zar 1984).

Representative specimens of all taxa have been lodged at the Western Australian Herbarium. Collection details and geographical distributions of taxa were obtained from online records (Western Australian Herbarium 1998–). The conservation status of taxa, according to the Western Australian Department of Conservation (DEC) codes, was obtained from Atkins (2008).

RESULTS

Flora

The survey flora list was compiled from the 51 quadrats and opportunistic collections around the Booylgoo Range (Appendix 1). From this, a total of 207 taxa (species, subspecies, varieties and forms) and nine putative hybrids were recorded. Four of the 207 taxa were introduced weeds. No regionally endemic taxa (defined as having a distribution restricted to within a 100km radius) were found during this survey. Taxa were from 47 families, of which the most common were the Poaceae (21 introduced taxa), Asteraceae (19 taxa), Mimosaceae (all taxa of *Acacia*, 17 taxa and 1 hybrid), Myoporaceae (all *Eremophila*, 15 taxa), Chenopodiaceae (15 taxa and 1 hybrid), Caesalpiniaceae (all *Senna*, 8 taxa and 6 hybrid entities) Malvaceae (11 taxa, *Sida* 6 taxa), Goodeniaceae (8 taxa), Amaranthaceae (all *Ptilotus*, 8 taxa), Myrtaceae (8 taxa) and Solanaceae (7 taxa) (Appendix 1). Low cover values for herbaceous annuals and geophytes in the quadrats were attributed to dry winter conditions, while summer rains had promoted an abundant cover of annual grasses (*Aristida contorta* and *Eriachne pulchella*).

Priority taxa

Six species of conservation significance were collected in this survey (Table 1), all being recognised under DEC conservation codes (Atkins 2008) as uncommon or data deficient. Five species were new records for the Booylgoo Range, but none of these species can be considered as endemic to the range or wider Sandstone region (Table 1). With the exception of *Grevillea inconspicua* and *Calytrix eriosipetala*, these species were found to be largely restricted to banded iron formation substrates when collected from the Booylgoo Range. *Grevillea inconspicua* tended to be associated with mafic and ultramafic lithologies downslope from exposed BIF seams, and was most common in the central part of the range. *Calytrix eriosipetala* was associated with laterites, either on pediments flanking ironstone hills or on laterite breakaways located away from the main range.

For both *Baeckea* sp. Melita Station (H. Pringle 2738) and *Calytrix eriosipetala*, the Booylgoo Range populations

were a minor range extension of < 50km east of previously known occurrences. *Baeckea* sp. Melita Station (H. Pringle 2738) has a narrow distribution within the eastern Murchison and Yalgoo regions, while *Calytrix crosipetala* is known from approximately 20 locations scattered throughout the wider Murchison bioregion. The ranges of three priority species were extended by over 100km. *Acacia balsamea* has a distribution which extends from north-east Murchison to central and north-west Western Australia, and this latest collection is a range extension of c. 100km west from the nearest known population. The collection of *Homalocalyx echinulatus* at Booylgoo Range extends the southern limit of this species by c. 125km. Although *Calytrix uncinata* is recorded from the Booylgoo Range for the first time, the nearest populations being 100 and 150km north-east and north-west respectively, this new population is within its known range. It was found to be uncommon, being located at a single location on a low ridge of weathered ironstone at the northern end of the range.

Putative new taxa

Two taxa were identified in this survey that have affinities to known taxa but were sufficiently morphologically distinct to consider as putative new entities. *Acacia* aff. *siberica* (PERTH 07556969) belongs to the Juliflora species complex of the Eremaean (flat, multi-nerved phyllodes with cylindrical flowers), and is most closely allied to *A. siberica*, which was also collected from the Booylgoo Range. Although mature pods are lacking from collections, it is suspected that this collection is different enough from *Acacia siberica sensu stricto* to be considered a separate entity (B. Maslin, pers. comm¹). *Acacia* aff. *siberica* differs from *Acacia siberica* by having adpressed hairs on the phyllodes (versus glabrous phyllodes in *A. siberica*), and united calyx lobes for half their length whilst they are united for less than half their length in *Acacia siberica*.

A previously unrecognised variant of *Acacia xanthocarpa* was collected from this survey. This variant possesses flat phyllodes, as opposed to the terete phyllodes of the more typical form. Further investigation may show this to be a new taxon, possibly even a new species (B. Maslin, pers. comm.¹). Subsequent examination of the herbarium collections has located other specimens from near Booylgoo Springs Station and Lake Mason Station, c. 50km north-west of the Booylgoo Range. Where parent rock type has been noted, this species has been collected mainly from hills of metavolcanics and gabbro.

Putative hybrids

Although interspecific hybrids and intergrades of *Senna*, *Maireana* and *Acacia* were collected, no new putative hybrid combinations were found in this survey. Six putative

hybrids of *Senna* taxa were identified, although there was a continuum of intermediate forms (intergrades) between *Senna glaucifolia* and *Senna* sp. Meekatharra (E. Bailey 1–26), and between *Senna glaucifolia* and *Senna artemisioides* subsp. *helmsii* (see Appendix 1). Other *Senna* hybrids were relatively more distinct and discrete entities, including the putative hybrid *Senna glutinosa* subsp. *chatelainiana* x *charlesiana*. This entity matches collections lodged at the Western Australian Herbarium under the name *Senna artemisioides* subsp. *filifolia* x *glutinosa* subsp. *chatelainiana* so the entities are probably synonymous. Preference is given to the former hybrid combination because the *S. artemisioides* complex does not hybridise with the *S. glutinosa* complex, but hybrids can occur within each complex (Randall & Barlow 1998).

Range extensions

Seven other species without a priority conservation listing had their known range limits extended by c. 100–200km from the closest known collection (Western Australian Herbarium 1998–). *Indigofera monophylla* is widespread in northern Western Australia, and the population at Booylgoo Range was a 200km south-east range extension from its southern limit. The range of *Sida* sp. spiciform panicles (E. Leyland s.n. 14/8/90) was extended 350km south-east of its previously known limit. The south-eastern limit of *Cheilanthes brownii* was moved further into the Murchison region, 100km south of populations on the Herbert Lukin Ridge, near Wiluna.

Hibiscus solanifolius (sensu lato) has a disjunct distribution in the Great Sandy Desert and Coolgardie-Murchison regions. Recent collections from the Booylgoo Range, the Herbert Lukin Ridge (c. 125km north of Booylgoo) (Markey & Dillon, in press), and the Robinson Range (c. 290km northwest) (Meissner *et al*, in press²) have extended the range of this entity into the northern Murchison region. It may eventuate that *Hibiscus solanifolius* is a complex of several entities (L. Craven, pers. comm²). Similar to *Hibiscus solanifolius*, *Hibiscus sturtii* var. *truncatus* has a disjunct distribution in central and coastal northern Western Australia. The Booylgoo Range collections push the south-western range limit of this latter species west into the central Murchison by c. 200km. The status of *Hibiscus* taxa will be verified during the current revision of the genus (L. Craven, pers. comm³).

The perennial sedge, *Cyperus vaginatus*, was located at the southern end of Booylgoo Range, where it was common in a creekline associated with a permanent spring near Mt Anderson. This location pushes its range south-east into central Murchison by c. 225km, which is at the south-eastern limit of a range that extends north into the Pilbara and has disjunctions occurring in the Great Sandy Desert bioregion.

Acacia sp. Peak Hill (R. Gibson 0003) is an informally named entity of which there are seven known populations

¹ Bruce Maslin: Research Associate. Department of Environment and Conservation. Western Australian Herbarium, Kensington.

^{2,3} Lyn Craven: Research Scientist, Centre for Plant Biodiversity Research, Australian National Herbarium, Canberra, ACT

scattered in the Murchison and Gascoyne bioregions (Western Australia Herbarium 1998–). Most occurrences are on the tops and slopes of greenstone and laterite hills. The Booylgoo Range population is therefore a significant southern range extension c. 200–280km south of other known populations. Superficially, *Acacia* sp. Peak Hill (R. Gibson 0003) resembles *A. coolgardiensis* or *Acacia ramulosa*, and is part of the Juliflora species complex (flat, multi-nerved phyllodes and cylindrical flowers) (B. Maslin, pers. comm.⁴). This tall shrub (2–3 m) was found only in one small area on BIF at the south-east of the Booylgoo Range, where it was locally common.

Floristic Communities

Twelve taxa were amalgamated into six species complexes for floristic analyses. Among these were hybrid intergrades of *Senna glaucifolia* x sp. Meekatharra (E. Bailey 1–26), which were amalgamated with the one parental taxon to which they were the most morphologically similar. Closely related taxa were amalgamated when this grouping was more informative than when taxa were separate (e.g. four forms of *Haloragis odontocarpa*, and *Eriachne mucronata* and *E. helmsii*), or when they could distinguished due to poor quality of flowering material (e.g. subspecies of *Eremophila forrestii*). The *Acacia aneura* species complex is so variable that it could only be resolved into morphotypes which approximated the varieties described by Pedley (2001), which are consistent with the morphotypes used in previous ironstone surveys (Markey & Dillon 2008a, 2008b; Meissner & Caruso 2008a, 2008b, 2008c).

For classification and ordination analysis, the site by species matrix consisted of 189 taxa from 51 quadrats within the survey area, of which 62 were annuals and 36 perennial singletons. The average species richness per quadrat was 23.2 ± 1.9 (s.e.) taxa per quadrat, and ranged from 15 to 43 taxa per quadrat. Preliminary analyses verified that singletons and annuals had little overall effect on the classification, and the ‘2-Stage’ comparison of resemblance matrices found 92% correlation between the data matrix with all taxa (singletons and annuals) and the shared perennial dataset used in final analyses. The final shared perennial data matrix consisted of 91 taxa from 51 quadrats, which was 48% of total number of taxa. The average species richness of this final dataset was 16.0 ± 1.3 (s.e.) taxa per quadrat, with a range of between 11 and 32 taxa per quadrat.

The floristic classification of the shared perennial dataset simultaneously resolved the sites and species into a hierarchal set of groupings for their respective site and species classifications. From the species classification, the 91 taxa were resolved into nine species groups, which are listed in a sorted two-way table of the site and species classification (Appendix 2). The primary division in the site classification separated floristic communities on mafic-

influenced sites (Community types 5 and 6) from those on landforms of banded iron formation (Community types 1–4) (Fig. 2). This split is associated with differences across several species groups (Appendix 2), notably the species groups that contain the more common taxa (A, G and H). Within this latter grouping of banded ironstone sites, there was a further major division which separated sites on lower slopes, pediments and alluvial outwash / colluvial plains from those located generally higher in the landscape, particularly on hill slopes and crests. This division is also discernable on the sorted two-way table, where it is

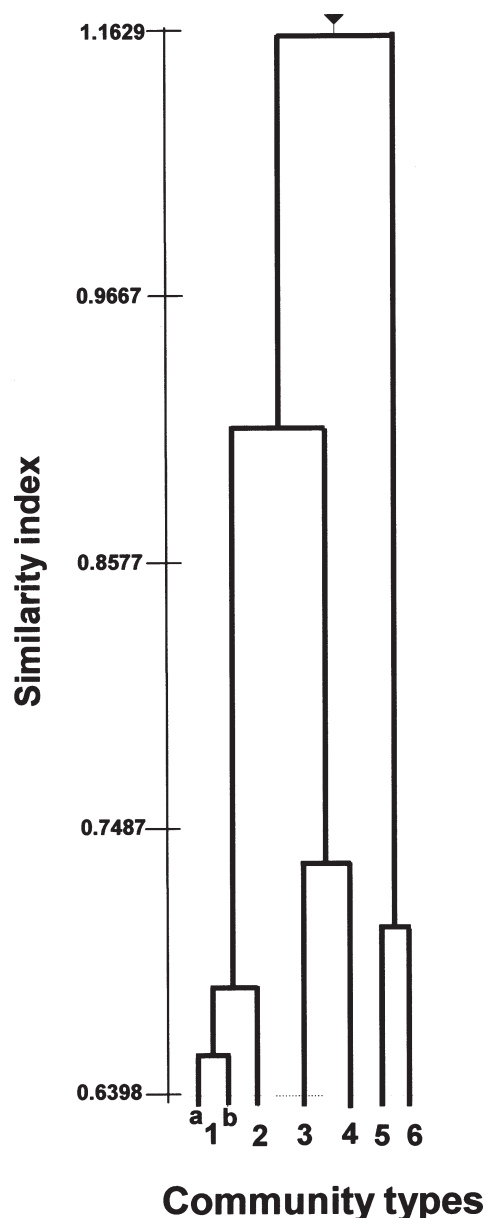


Figure 2. Summary dendrogram of six floristic community types of the Booylgoo Range from classification analysis of a presence / absence dataset of 189 perennial taxa from 51 quadrats, based on UPGMA (flexible) clustering and Bray-Curtis co-efficient of dissimilarity. The dendrogram is resolved to the six group level, with a further two subtypes resolved in Community type 1.

⁴ Bruce Maslin: Research Associate. Department of Environment and Conservation. Western Australian Herbarium, Kensington.

particularly evident in species groups D–F and G (Appendix 2). At the six group level in the site classification, the 51 quadrats are grouped into six main community types, with one of these communities (Community type 1) further subdivided in two subtypes (Fig. 2).

Community type 1 is a grouping of sites on rocky hill slopes and crests of ridges of banded iron formation. It has good representation in Species group H. Community type 1a is a structurally heterogeneous unit on gentle to moderately steep hill slopes and crests. Typically this floristic community consists of tall open - sparse *Acacia aneura* shrubland where *Acacia aneura* var. cf. *microcarpa* is a significant indicator species, and often with additional *Acacia* species such as *A. quadrimarginea* or *A. thoma*. The sparse mid-stratum consists of various shrubs, including significant indicator species *Eremophila latrobei* subsp. *latrobei*, *Solanum ashbyae* and *Sida* sp. Golden calyces glabrous fruit (H.N. Foote 32) (Table 2). Other common taxa include *Ptilotus schwartzii* and the perennial grasses *Cymbopogon ambiguus* and *Eriachne helmsii*, the latter of which is a significant indicator species. Notable taxa include *Prostanthera campbellii*, *Eriachne helmsii* and *Psydrax suaveolens* on rocky crests, *Homalocalyx echinulatus* and *Eremophila jucunda* subsp. *jucunda*, which form low shrublands on shallow colluvium over sheets of bedrock on mid – lower slopes, and *Senna artemisioides* subsp. *helmsii* and *Eremophila forrestii*, which are also found on mid – lower slopes. Many taxa from Species group I occur in this community type, with limited representation from Species group E–H, otherwise this community type is more poorly represented across the other Species groups A–D, particularly in comparison to Community type 1b (Appendix 2). Species richness is moderately low, with an average number of total taxa of 23.2 ± 1.9 (s.e.) per quadrat (Table 3).

There is some suggestion of further groupings within this heterogeneous community type, particularly among crests versus mid-lower slopes. Sites on low ridge crests / hillocks have both clear floristic affinities to Community type 2 and are influenced by adjacent, lower slope communities (see Community type 2 description). More sampling may provide enough floristic information to further subdivide Community type 1a into an upper slope - crest community and a low crests and lower slope community.

Community type 1b is marginally more species rich than Community type 1a (Table 3), with an average total number of taxa being 28.1 ± 1.7 (s.e.) per quadrat (Table 3). Found on gently – moderately inclined mid-upper hill slopes and crests of weathered BIF, this community consists of a more structurally homogeneous community than Community type 1a. This community consists of *Acacia aneura* var. cf. *microcarpa* and *Thryptomene decussata* tall open - sparse shrubland, with *Acacia ramulosa* var. *ramulosa* as an occasional co-dominant. Common and distinctive mid-stratum shrubs include *Eremophila latrobei* subsp. *latrobei*, *Solanum ashbyae*, *Eremophila georgii*, *Dodonaea petiolaris*, *Dodonaea rigida*, *Sida* sp. Golden calyces glabrous fruit (H.N. Foote 32), *Ptilotus*

obovatus, *Cheilanthes sieberi*, *Ptilotus schwartzii*, and, less frequently, *Scaevola spinescens* (Table 2). The perennial grass *Thyridolepis multiculmis* is noted as a significant indicator species for the ground layer. Relative to Community type 1a, there is more representation in type 1b from across all species groups, especially A, C and G, but reduced in part of group I.

Community type 2 is the characteristic community type of the steeper, rocky crests and upper slopes of BIF. The majority of sites were located in the southern half of the range, where there are taller and more substantial outcroppings of BIF. It is described as sparse shrublands of *Acacia aneura* and *Thryptomene decussata* over mid-stratum shrubs of *Eremophila latrobei* subsp. *latrobei*, *Prostanthera campbellii*, *Philotheca brucei* subsp. *brucei*, *Eremophila georgei*, *Olearia humilis*, *Sida* sp. Golden calyces glabrous fruit (H.N. Foote 32) and *Dodonaea petiolaris*, over a ground layer that includes *Cheilanthes brownii* and perennial grasses such as *Eragrostis lacunaria* (Table 2). One site of this community consisted of a woodland of *Callitris columellaris* on very steep escarpment near the crest of the range. Taxa from species group I are absent (*Eriachne helmsii*, *Psydrax* spp. and *Cymbopogon ambiguus*), which distinguishes this community from upland sites in type 1a (Appendix 2). This community has representation in Species groups F and I, and is distinguished from Community type 1a and 1b by good representation in Species group G, whilst there is very limited representation in species group H (Appendix 2). The species richness of this community is on par with Community type 1b, with an average number of total taxa of 27.1 ± 1.4 (s.e.) per quadrat (Table 3).

There is a subset of Community type 1a which shares taxa from Species group G with Community type 2. However, this subtype differs from Community type 2 in that there is an absence of *Thyridolepis multiculmis*, *Eremophila georgei* and *Cheilanthes sieberi*, the presence of *Eriachne helmsii*, *Psydrax* spp. and *Cymbopogon ambiguus*, and distinctive representation in Species groups H and I (Appendix 2). This sites occur on exposed seams of BIF bedrock on mid-lower slopes, and which may be too narrow and low to support all taxa associated with Community type 2.

Community type 3 is closely allied to Community type 4 (Fig. 2), both having generally poor representation in Species groups E–G (Fig. 2, Appendix 2). Sites grouped in this community type are typically shrublands on lower slopes, pediments, valley flats or plains adjacent to BIF landforms. These are shrublands of *Acacia aneura* (var. cf. *microcarpa* and var. cf. *tenuis*), often with *Acacia ramulosa* var. *ramulosa* as co-dominant, over a shrub stratum over *Senna* spp. (particularly *Senna glaucifolia*), *Eremophila jucunda* subsp. *jucunda*, *Solanum lasiophyllum*, *Eremophila latrobei* subsp. *latrobei*, *Eremophila galeata*, *Ptilotus obovatus* and *Ptilotus schwartzii*. Most of these listed taxa are significant indicator species for this community, and other taxa have relatively high indicator values (Table 2). This is a comparatively more speciose community, with an average number of total taxa of 31.1 ± 2.5 (s.e.) per quadrat (Table 3). There is some

representation from across Species groups A to G, with most taxa in the community occurring in Species groups H and I, whilst there is poor representation from Species groups E, F, and G. There are some floristic similarities between Community type 1b and 3, although the latter community has a notably reduced representation in group I and a far more constant and wider representation from group H (Appendix 2).

Community type 4 is the community typical of pediments and valley flats at the base of the Booylgoo Range, which consists typically of tall, sparse – open shrublands of *Acacia aneura*, *Acacia ramulosa* var. *ramulosa* and *Acacia craspedocarpa*, with isolated trees of *Brachychiton gregorii*, over a sparse or open shrubland of *Solanum lasiophyllum*, *Senna glaucifolia*, *Senna* sp. Meekatharra (E. Bailey 1–26), *Senna artemisioides* subsp. *helmsii*, *Eremophila galeata* and *Ptilotus obovatus*, over perennial grasses such as *Enneapogon caeruleus* and *Monachather paradoxa*. The main indicator species are *Brachychiton gregorii*, *Senna glaucifolia*, *Acacia craspedocarpa*, *Eremophila galeata*, and the hybrid, *Senna artemisioides* subsp. *helmsii* x *glaucifolia* (Table 2). There was also an unusual variant of *Eremophila latrobei* subsp. *latrobei* which has a distinctive lax, open branched, taller growth form and more densely hirsute, white-coloured leaves. Community type 4 is allied to type 3, but has relatively little representation in Species groups B–G and far more restricted representation in group I. There is good presentation in Species group H, which has high constancy across the sites in Community type 4 and differential representation of taxa within this group relative to Community type 3 (Appendix 2). The average number of total taxa is 31.5 ± 3.9 (s.e.) per quadrat, which is similar to that of Community type 3 (Table 3).

As previously mentioned, **Community types 5 and 6** were the first communities to be separated by the classification analyses. **Community type 5** consists entirely of sites located on mafic bedrock and colluvium in the basalt hills adjacent to the BIF ridges. Sampling of mafic sites was limited and these sites were somewhat heterogeneous as they were spread over the toposequence of the basalt hills. This general basalt community consisted of tall, sparse – open shrublands of *Acacia xanthocarpa* and *Acacia ramulosa* subsp. *ramulosa*, over a sparse shrub layer which included to varying degrees the indicator species *Dodonaea rigida*, *Eremophila exilifolia*, *Senna manicula*, *Eremophila granitica*, *Eremophila forrestii*, *Grevillea inconspicua*, *Solanum ashbyae* and *Cheilanthes lasiophylla* (Table 2). Other common components include *Acacia tetragonophylla*, *Ptilotus obovatus* and *Scaevola spinescens*. The average species richness is 32.0 ± 1.9 (s.e.) taxa per quadrat (Table 3). Taxa which are common within and constant to Community type 5 are Species group A, and a central portion of Species group H (Appendix 2). Otherwise, there is poor representation in Species groups B–G and I. This combination of representation among the Species groups highlights the distinctiveness of this community type from those on adjacent BIF substrates.

Community type 6 is a heterogenous grouping of only three sites which were allied most closely to Community type 5 and still had some floristic affinities to Community type 3 (*Solanum lasiophyllum*, *Senna* sp. Meekatharra (E. Bailey 1–26) and *Acacia aneura* var. cf. *aneura* from Species group H) (Appendix 2). These sites were located downslope from outcropping ridges of BIF, in shallow gullies and where there was some influence of associated ultramafics, mafics, cherts, shale and other metasediments. The general community consisted of tall shrublands of *Acacia aneura* and *Acacia ramulosa* var. *ramulosa*, over various shrubs, including *Grevillea inconspicua*, *Senna manicula*, and *Eremophila platycalyx* subsp. *platycalyx*. The main indicator species are *Senna* sp. Meekatharra (E. Bailey 1–26), *Austrostipa trichophylla*, *Eremophila oldfieldii* subsp. *angustifolia*, *Dodonaea petiolaris* and *Ptilotus exaltatus*. These sites had an average species richness of 33.3 ± 3.5 (s.e.) taxa per quadrat.

Communities not in classification

An interesting spring community was observed which was not sampled in this survey. Located near Mt Anderson, the valley flat had been impacted from historical use as a stockyard, but there was a distinct community associated with the permanent spring and associated creekline. The surrounding creekline and valley vegetation consisted of a tall shrubland of *Hakea lorea* subsp. *lorea*, *Acacia aneura* and *A. craspedocarpa* over a sparse shrub layer of *Eremophila serrulata*, *Solanum lasiophyllum* and occasional saplings of *Santalum lanceolatum*. The herb layer consisted of subshrubs and tall herbs of *Trichodesma zeylanicum*, *Pluchea dentax*, *Haloragis trigonocarpa*, *Nicotiana occidentalis* and a dense cover of *Cymbopogon ambiguus*, *Cyperus vaginatus* and *Typha domingensis* were the dominant aquatic plants growing in the spring. Elements of this community occur in ephemeral creeklines, but the spring community itself would be expected to be uncommon on the range as there are only three permanent springs.

SSH MDS Ordination

Semi-strong hybrid multidimensional scaling of the floristic data was used to reduce floristic relationships among sites into a three dimensional solution (Fig. 3). At a value of 0.20, the ordination procedure was not at a satisfactory level (Seber 1984) but indicates moderate distortion in solving the ordination in three dimensions. Nonetheless, the SSH MDS ordination was informative, and is presented in Fig. 3. The two groups identified from the primary division in the classification were evident in ordination, with a BIF associated group (Community types 1a, 1b, 2, 3, 4) distinct from a group of mafic sites (Community types 5 and 6). At the seven group level, sites are generally clustered by community type, although some of these are relatively dispersed clusters and there is some overlap of different community types. This overlap is most noticeable among the subtypes, 1a and 1b. The greatest floristic dissimilarity is between the Community

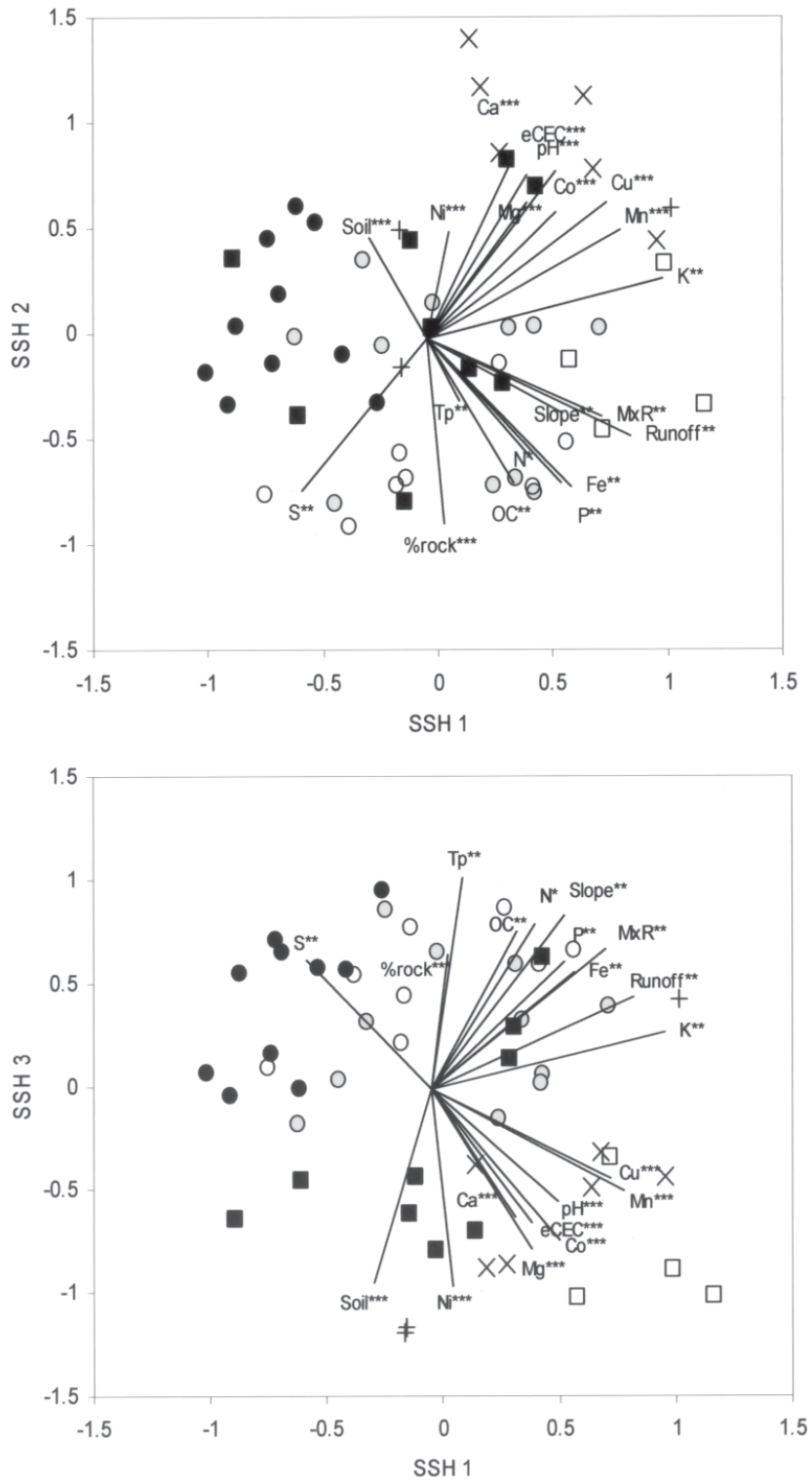


Figure 3. Ordination diagrams from three dimensional ordination (SSH MDS) using Bray-Curtis dissimilarities in Booylgoo Range floristic data (stress value = 0.20). Sites are labelled by Community type (1a ○, 1b ○, 2 ●, 3 ■, 4 □, 5 ×, 6 +). Vectors of best linear fit are drawn in positive direction for each significant environmental variable. Levels of significant correlations (from MCAO) are indicated by asterisks (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$). Abbreviations for environmental variable are given in the methods section.

types 2 and 5. The sites classified as Group 6 are a loose, floristically heterogenous cluster.

Environmental Correlates

The topsoils from the Booylgoo Range sites were found to be strongly acidic, averaging pH 4.7. Soil acidity ranged from pH 3.9 to pH 6.6, which is can be described as ranging from strongly to slightly acidic (*cf.* Slattery *et al.* 1999). Soils were generally classed as shallow (5–50cm), red, stony silty clay loams or silty clay sands, and observed to be firm-setting or forming a crust over loose soil. For most sites the ground was usually bare of vegetation ($86.5\% \pm 1.1$ (s.e.)), had only a very sparse cover of leaf litter ($13.5\% \pm 1.2$ (s.e.)) and an extensive mantle of loose rock fragments (> 90%). Surface fragments derived from BIF outcrops were typically angular platy or tabular in shape, while mafic colluvium was more angular – subangular. Surface rock sizes ranged from 2mm to 2 m, but the average maximum size class was 4.7 (which equates to a size range of 20–60cm). These general soil characters close match descriptions for lithosols on greenstone hills and rises through the Mid West region (Hennig 1998b; van Vreeswyk 1994).

Four elements B, Cd, Mo and Na were undetected in over half of the samples and omitted from analysis. The remaining soil chemical and site physical parameters were compared for inter-correlation (Table 4). Among the soil parameters, there was one highly inter-correlated set of trace elements (Ca, Ni, Co, Mg, Mn, eCEC and pH). Another set consisted of Fe, organic C, P and N. Among the geomorphological variables, there was one main set of inter-correlated variables (topographic position, slope, maximum rock fragment size, outcrop cover, runoff, altitude and soil depth), where soil depth was negatively correlated with the others. These parameters (especially slope) are all positively correlated with the set of Fe, P, organic C, and N (Table 4).

There were too few samples from Community types 4 and 6 to permit statistical comparison with the other community types. However, non-parametric analysis of variance found significant differences in average soil and site physical parameters among the remaining community types (Kruskal-Wallis non-parametric ANOVA) (Table 3). Among the inter-correlated suite of trace elements (Ca, Co, Cu, Mg, Mn and Ni) and eCEC, significantly highest values were associated with Community type 5. These were sites on mafic bedrock substrates, which suggests the metalliferous bedrock is having a strong influence on soil composition. Conversely, values were relatively lower in the communities were associated with massive banded iron formation. Trace element values were relatively moderate in Community type 3, while generally lowest among Community types 1a, 1b and, in particular, Community type 2. The trace element concentrations in Community type 4 were comparable to type 3 (Table 3), which suggests that both these communities are on lowland sites which are receiving trace element enrichment. Levels of exchangeable cations were of intermediate levels in Community types 1b and 3, and lowest in types 1a and

2. Although not tested, soils from Community type 6 tended to have a moderately high but variable eCEC, and trace elements were within the ranges of values for Community types 1, 2 and 3. Despite differences in eCEC and trace elements concentrations, soil salinity (as estimated by EC) was not significantly different among the community types (Table 3).

Soils were most acidic in the upland BIF communities, types 1a and 2, while weakly acidic in Community type 5 (Table 3). Organic C, N, P and Fe were also significantly the highest within Community type 2 and, to a lesser degree, among types 1a and 1b. These values were generally lower for Community type 5 and the lowest for sites associated with Community type 3. Although not tested, Community type 4 tended to have relatively low N, organic C, higher pH, higher trace elements on par with Community type 3 and 5. Leaf litter was observed to accumulate in rocky crevices in upland BIF outcrops, which may account for the elevated soil N and organic C observed in upland BIF communities. Both P and S were also significantly lower in Type 5 than in the other communities, which suggest that soils derived from banded iron formation have higher P and S levels than those associated with mafic bedrock.

With the exception of runoff, bare ground and litter cover, there were significant differences in site physical attributes among the community types (Table 3). There was a tendency for Community type 2 to occupy the highest topographic positions in the landscape, while type 3 occurred at the lowest altitudes and types 1 and 5 were variable (although this was not significant in multiple range tests) (Table 3). In conjunction with occupying the highest upland positions, sites from Community type 2 had the steepest slopes, greatest cover of massive outcrop, the largest surface rock fragments (corresponding to a size range from 60cm to 2m), lowest cover of surface rock fragments and the shallowest soil depths (being skeletal (> 5cm) on average). Community types 1a, 1b and 5 had middle range values for slope angle, outcrop and rock fragment sizes, and generally shallow (5–50cm) soil depths. At the other extreme, Community type 3 occupied sites at the lowest topographic positions, with the lowest gradients, lowest outcrop cover (no outcrop), deepest average soil depth class (> 50cm) and smallest surface rock fragments (Table 3). Although not verified statistically, slope angles tended to be also very low in Community type 4, where sites also had relatively small surface rock fragments and minimal or no outcropping bedrock. Community type 6 was comprised of only three sites, all which generally occupied steep, rocky mid-slopes of BIF colluvium and with a moderate amount of BIF outcrop and mafic and ultramafic influence.

There is some suggestion of a geographical segregation of floristic community types, notably where sites of Community type 2 were concentrated towards the southern end of the range among the relatively tall ridges (Table 3). There is also a trend for a more northern distribution of Community type 3, but recent fires and accessibility precluded sampling at the southern sites which may be suitable terrain for this community. Differences in

longitude are minor (Table 3) because the range is narrow and the central-eastern margin of the range was inaccessible (Fig. 1).

Principal Component Correlation (PCC)

Principal component correlation (PCC) of environmental variables with the ordination coordinates found significant linear relationships for most environmental parameters, and the fitted linear vectors are shown in Fig. 3. There are two major enviro-floristic gradients, and the observed trends mirror results from the univariate analyses. One main gradient consists of collinear vectors for a set soil variables (Ni, Ca, eCEC, Mg, Co, Cu, Mn and pH). Sulphur runs parallel but negative in direction to this first main gradient. This gradient is linked to geological substrate, with the main separation of the mafic-associated Community type 5 at the high extreme of this gradient from the BIF ridge-associated Community types 1a, 1b and 2 at the low extremes. This reinforces previous findings that Community 5 is associated with relatively high soil concentrations of trace elements, soil pH and eCEC, while Community types 2 and 1b, and 1a (to lesser extent), are associated with low soil pH and trace element concentrations. Community types 3 and 4 coincide with the middle range of this gradient, again suggesting elemental enrichment in lowland soils.

Orthogonal to this first main gradient are two near-collinear gradients, one of gradient of mainly soil trace elements and macronutrients (Fe, N, P, organic C, runoff) and another gradient of geomorphology (topographic position, maximum surface rock size, and slope). Soil depth is nearly parallel but opposite in direction to this gradient. This gradient is associated with the separation of Community types 2, 1b and 1a from types 3, 4 and 5, which corresponds to the segregation of BIF lowland and outwash sites on deeper soils from sites on hill slopes and crests with skeletal soils, massive exposed rock outcrops and large rock fragments. Community type 2 is at the highest extreme of this gradient, while Community types 1a and 1b are closely adjacent. The vector for outcrop cover is somewhat distant from these other two main gradients, but the pattern is similar; Community type 2 is at the high extreme of rock outcrop cover, whilst types 3, 4 and 5 are at the low end of rock outcrop cover.

DISCUSSION

Flora

A total 207 taxa were recorded from this survey, which is in excess of double the number of taxa (84) previously known from herbarium records for the the range and surrounding plains (Western Australian Herbarium 1998–). The spring survey had been preceded by a good summer rainfall and a poor winter, which had promoted the abundant growth of annual grasses (*Eriachne pulchella*, *Aristida contorta*) but herbaceous winter annuals and geophytes were largely absent from sites. It is likely that

numbers of these lifeforms have been underestimated, and it is assumed further sampling during a relatively wet winter will increase the total species count for the range.

Similar ironstone surveys conducted during the same field season in 2006 recorded 191 taxa for the Herbert Lukin Ridge (c. 125km north of Booylgoo Range) (Markey & Dillon 2009), and 144 and 116 taxa for the Cashmere Downs and Mt Forrest – Mt Richardson Ranges, respectively (c. 100km south) (Meissner *et al.* 2009c). This suggests that the Booylgoo Range supports a relatively rich flora for an arid-zone greenstone range in the Murchison region. A variety of habitats associated with tall peaks, steep escarpments and permanent springs may account, in part, for this species richness. Had the survey been extended to the sandplains at the base of the range, this number of taxa would have been considerably larger. However, these counts for Booylgoo Range are markedly lower than for similar surveys in the more southern greenstone ranges, such as the Bremer Range (267 taxa) (Gibson & Lyons 1998a) and Forrestiana greenstone belt (342 taxa) (Gibson 2004b). This regional decrease in species richness with increasing distance inland appears to be associated with a gradient of increasing aridity (Beard 1976, 1990; Hopper *et al.* 1997).

Significant numbers of rare and endemic taxa have been recorded for greenstone outcrops in the Yilgarn Craton (Gibson *et al.* 2007). Six priority taxa were recorded for Booylgoo Range during this survey, of which five were new records for the landform. This is the current total number of priority taxa known for the range (Western Australian Herbarium 1998–). In addition to rare and poorly known taxa, several unusual variants of described taxa were found, notably a flat phyllode variant of *Acacia xanthocarpa* and *Acacia* aff. *siberica*. However, no taxa were found which could be considered endemic to the Booylgoo Range. This lack of endemic taxa has been reported for other greenstone ranges, such as Mt Manning Range (Gibson 2004a), Weld Range (Markey & Dillon 2008a) and the Highclere Hills (Gibson & Lyons 2001b), and only one endemic taxon was located at the Herbert Lukin Ridge (Markey, & Dillon in press). Species diversity and endemism of Western Australian granite outcrops decline with increasing aridity (Hopper *et al.* 1997), and the same trend is becoming evident for BIF ranges on the Yilgarn Craton (Gibson *et al.* 2007).

The representation of genera and families for the Booylgoo Range is typical for the general flora of the Murchison – eastern Goldfields regions (Beard 1976, 1990; Pringle 1994b), and for other ironstone surveys in the eastern Goldfields (e.g. Gibson & Lyons 1998a, 1998b; Gibson 2004a, 2004b). The dominant genera (*Acacia*, *Ptilotus*, *Eremophila*, *Senna* and *Sida*) are characteristically Eremaean (Beard 1976, 1990; Pringle 1994b, 1998b), and many other taxa reported for Booylgoo Range occur in the Gascoyne, Ashburton, Pilbara and Central Desert regions. Genera reported for ranges in the Coolgardie and Yalgoo interzone bioregions are absent or poorly represented on the Booylgoo Range, including *Melaleuca*, *Eucalyptus*, *Banksia*, *Persoonia*, *Hibbertia* and *Mirbelia* (Gibson & Lyons 1998a, 2001a,

2001b; Gibson 2004a, 2004b; Markey & Dillon, 2008b). Of the range extensions of over 100km reported by this survey, all were southern or western range extensions for otherwise more northern or eastern taxa, which further suggest a significant floristic affinity of the Booylgoo Range to other arid regions.

Floristic Communities:

The broad-scale surveys of Beard (1976a), Payne *et al.* (1998) and Pringle and van Vreeswyk (1994) do not readily distinguish floristic differences among different ironstone and greenstone ranges in the Murchison and north-eastern Goldfields. This survey is the first of which has specifically addressed the floristic communities on the Booylgoo Range at a fine scale, and reports seven floristic Community types and subtypes. The primary split in the classification distinguishes those community types on BIF substrates (types 1, 2, 3 and 4) from communities associated with mafic substrates (types 5 and 6). Community type 5 was the most characteristic community of the metabasalt and mafic lithologies which dominate the central portion of the range. In contrast, Pringle (1994a, 1998a) reported that greenstone and ironstone hills shared the same stony ironstone mulga shrublands as a dominant community. However, these units were broadly circumscribed, and the greenstone hill acacia shrublands unit described by Pringle (1994a, 1998a) does not bear a close resemblance to Community type 5. Marked differences between mafic and BIF communities have been found within some other ranges of mixed mafic and BIF geologies on the Yilgarn Craton (Gibson 2004a; Markey & Dillon 2008a; Meissner *et al.* 2009 a, b).

It is interesting to note that the basalt community is composed of taxa that are commonly but not exclusively found on mafic substrates in the wider region. The dominant or significant indicator species (*Acacia xanthocarpa*, *Dodonaea rigida*, *Senna manicula*, *Eremophila granitica*, *Cheilanthes lasiophylla*, *Eremophila exilifolia*, *Eremophila forrestii* and *Grevillea inconspicua*) are most often recorded from mafic hills and rises, but can also be found on other lithologies; usually granite and (to a lesser extent) BIF, other metasediments and sandstone (Western Australian Herbarium 1998–). Within BIF-associated communities, dominant or indicator species (e.g. *Thyptomene decussata*, *Philotheca brucei* subsp. *brucei* and *Prostanthera campbellii*) are not entirely restricted to massive BIF outcrops, but have also been recorded on laterites and occasionally on sandstone, sandplains and hard pans. However, these taxa characteristic of the BIF communities are not often recorded from mafic lithologies. This suggests that the BIF and mafic communities on the Booylgoo Range are being defined by taxa with substrate preferences. The intensive biogeochemical survey in the eastern Goldfields by Cole (1973) demonstrated clear associations of species with mafic/ultramafic substrates, and indicated some physiological responses to metalliferous soils.

Within BIF landforms on the Booylgoo Range, the greatest floristic differences among communities were

between the upland and lowland communities, despite the maximum elevation of only 100 m. This mirrors the general trends found in semi-arid and arid ranges in Australia (Butler & Fensham 2008; van Etten & Fox 2004) and the Yilgarn and eastern Goldfields (Gibson & Lyons 1998a, 2001a, 2001b; Gibson 2004a, 2004b; Markey & Dillon, 2008a, 2008b; Meissner & Caruso 2008a, 2008b, 2008c), where the upper slopes and crest communities are markedly different to the vegetation matrix on the surrounding plains. Three communities (types and subtypes) were resolved for the hill crests and hill slopes (uplands), but one of these was a heterogeneous community (Community type 1b) which occurred from lower slopes to low ridge crests / hillocks (c. 20 m), which may be further subdivided with more sampling. Heterogeneity within this community subtype and overlap in floristic composition among subtypes of Community type 1 may be indicative of broad transitional zones (cf. van Etten & Fox 2004).

Environmental correlates

There was a strong association between site soil chemical and physical parameters with floristic community type, the greatest difference being associated with parent rock type. Soils on mafic substrates are comparatively rich in trace metals, these soils being ultimately derived from a parent bedrock that has high levels of Mg, Mn, Cr, Cu, Co, Ni and Zn (Cole 1973; Cornelius *et al.* 2007; de Castro Vincent & Meguro 2008; Gray & Murphy 2002). These soils were also found to have a comparatively higher cEC (presumably from the higher Mg concentrations) and be less acidic, presumably because of the buffering capacity of exchangeable cations (Gray & Murphy 2002). The presence of calcrete deposits may also account for the neutral – basic pH reported for soils derived from weathered mafics (Anand *et al.* 1997; Gibson & Lyons 1998a, 2001b). Although there is a clear association between the mafic community and substrate, the degree to which soil heavy metals are biologically available (see Cole 1973; Robinson *et al.* 1996) and how they influence species distributions and community composition is largely unknown for greenstones in Western Australia. It is speculated that an ability to resist metal uptake or a relatively higher level of tolerance to elevated levels of soil metals would be expected among some species in the mafic community, as these strategies have been found among mafic/ultramafic species in the eastern Goldfields (Cole 1973).

Within the more intensively sampled BIF landforms of the Booylgoo Range, a catena of community types was found to be associated with a topo-edaphic gradient. Similar enviro-floristic gradients have been studied in detail in other semi-arid and arid ranges in Australia, including in the Hamersley Ranges of the Pilbara (van Etten & Fox 2004) and among greenstone ranges in the goldfields (Chalwell 2003; Gibson & Lyons 1998b, 2001a; Gibson 2004a) and in the Yalgoo and Murchison regions (Markey & Dillon 2008a, 2008b; Meissner & Caruso 2008a, 2008b, 2008c). These sites exhibit the same general

topographical sequence over the landform, and similar general trends in soil development.

The association of floristic community types with topography and soil depth on outcrops has been inferred to be a response (at least in part) to a soil moisture gradient (Gibson & Lyons 1998b, 2001a; Gibson 2004a), where skeletal soils on crests and steep terrain will retain little water in comparison to deeper soils, and where a mantle of surface gravels will impede water runoff and reduce water loss (Specht *et al.* 2006; van Vreeswyk 1994). Deeper soils on the lower slopes and outwashes would be expected to not only receive runoff and retain soil moisture, but also overlie groundwater sources (Chalwell 2003; Conn & Snyder-Conn 1981; Specht *et al.* 2006; van Vreeswyk 1994). The amount of runoff from the Booylgoo Range is sufficient to form permanent springs which support a *Typha-Cyperus* wetland community. Even within upland sites, presumably the entrapment of water in rock crevices and as temporary pools on impermeable surfaces supports other species such as *Cheilanthes brownii* and *Cymbopogon ambiguus*.

Soil depth is also a limiting factor for root development, and communities on rocky uplands were characterised by taxa which could tolerate skeletal, rocky soils by a number of strategies, including being shallow-rooted (e.g. *Sida* sp. *Excedentifolia* (J.L. Egan 1925); *Cymbopogon ambiguus*; *Ptilotus schwartzii*), rooting into rock fissures (e.g. *Prostanthera campbellii*, *Micromyrtus sulphurea*) and / or growing through loose scree (e.g. *Dodonaea petiolaris*). Some of the large shrubs and trees, such as *Callitris columellaris*, would be expected to be very deep-rooted, and it is this strategy that can allow for larger shrubs and trees on rock outcrops to access deeper water sources within the rocks (Chalwell 2003; da Silva & Dillenberg 2007).

Within BIF landforms, soil fertility was found to be strongly associated with topography, such so that the highest values of trace element concentrations, cCEC and soil pH were found in soils on lower slopes, flats and outwashes. It is presumed that upland soils are heavily leached, particularly of the more readily mobilised elements such as Mg, Na and Ca (Britt *et al.* 2001; Cornelius *et al.* 2007). Conversely, soils in depositional areas tend to be enriched by leachates as well as washdown of soil and colluvium, which leads to a higher cCEC and levels of mobile ions such as Ca and Mg (as carbonates) (Cole 1973; Gray & Murphy 2002; Hennig 1998; van Vreeswyk 1994). These weakly acidic to basic soils may be buffered by the higher cCEC and mobile ions (Gray & Murphy 2002). These general trends in soil composition over a topographic gradient have been reported for other ironstone and greenstone ranges in the Murchison and Eastern Goldfields (Cole 1973; Hennig 1998; Gibson & Lyons 2001a, 2001b; Gibson 2004a, 2004b). Saline soils have also been reported from lowland sites under weathered mafics (Gibson & Lyons 1998), exposed pallid zones under laterites (Gibson & Lyons 2001a), and alluvial outwash / colluvial plains (Markey & Dillon *in press*), but saline soils and their associated communities were not evident on the Booylgoo Range.

The opposite trend was observed for soil pH, N, P, organic C and Fe, where concentrations were greatest and soil most acidic at the highest topographic positions in landscape; these being on rocky outcrops of massive BIF. In these rocky, upland sites, soil development is presumably from *in situ* weathering of parent bedrock (Litchfield 1963; Gray & Murphy 2002), which may account for higher acidity and relatively higher levels of iron and phosphorus. It is presumed that the high levels of organic carbon and nitrogen in these soils were derived from the leaf litter collecting in rock fissures, crevices and among cobbles and boulders. Coincidentally, these areas were where the only substantial deposits of soil were to be found. Relatively higher soil N concentrations in upland BIF communities have been reported for some Yilgarn BIF ranges (Gibson 2004a; Markey & Dillon 2008a, 2008b). Other ironstone surveys have found the opposite trend, where relatively higher N concentrations are found in soils from lowland sites supporting *Eucalyptus* woodlands. This was associated with a greater cover of leaf litter in the Hunt Range and adjacent hills in the eastern Goldfields (Gibson & Lyons 2001a) and in a saline lake edge community in the Bremer Range (Gibson & Lyons 1998a).

It would appear that microhabitats among the rocky, fissured terrain of the Booylgoo Range can intercept rainwater and trap organic material. Steep escarpments of massive BIF also support tall stands of *Callitris collumellaris*, which is a well known, fire sensitive species often recorded on steep valley slopes and escarpments of arid zone ranges (Bowman & Latz 1993). It is a common feature of rock outcrops and ranges to possess a heterogeneous array of habitats, including sheltered sites for fire sensitive species and communities, and microhabitats which support less xeric species, and provide sites for effective seed burial and germination (Butler & Fensham 2008; Conn & Snyder-Conn 1981; Jacobi *et al.* 2007; Hopper *et al.* 1997).

Regional Significance

The nearest ironstone and greenstone ranges to the Booylgoo Range which have been adequately surveyed to date are the Herbert Lukin Ridge (on the Joyners Find greenstone belt), Cashmere Downs and Mt Richardson - Mt Forrest. There are notable differences in the flora even among these relatively close ranges. Only 45% of 273 native taxa (species and subspecies) are common to both the Herbert Lukin Ridge and the Booylgoo Range (from Markey & Dillon, 2009 a b). These values are even less for the southern ranges, with 31% and 45% of taxa in common between Booylgoo Range and Cashmere Downs and Mt Richardson - Mt Forrest, respectively (data from Meissner *et al.* *in press*^{a, b}). Dominant taxa on the Herbert Lukin Ridge are absent from Booylgoo Range, including *Acacia pruinocarpa*, *Triodia melvillei*, *Tribulus suberosus* and *Stenathemum petraeum* (Markey & Dillon, 2009). Conversely, species dominant or common on Booylgoo Range (e.g. *Acacia ramulosa* var. *ramulosa*, *Grevillea inconspicua*, *Thryptomene decussata*, *Philotheca brucei*,

Cymbopogon ambiguus and *Acacia xanthocarpa*) are notably absent from the Herbert Lukin Ridge. Similarly, while *Eucalyptus kingsmillii* subsp. *kingsmillii*, *Eucalyptus lucasii*, *Acacia cockertoniana*, *Aluta aspera* subsp. *hesperia* and *Eremophila conglomerata* are rarely encountered on Booylgoo Range, these species are common taxa on Cashmere Downs and Mt Richardson - Mt Forrest (Meissner *et al* 2009 a, b).

In addition to differences in dominant or characteristic taxa, the communities described for the Booylgoo Range bare little similarity with those found on the Herbert Lukin Ridge, Cashmere Downs or Mt Richardson - Mt Forrest. Both the upland *Acacia-Triodia melvillei* shrublands, and saline flat *Acacia aneura*, *A. pruinocarpa* – chenopod communities of the Herbert Lukin Ridge are absent from the Booylgoo Range (Markey & Dillon, 2009). Similarly, fundamentally different communities have been described for ironstone communities on Mt Richardson, Mt Forrest and Cashmere Downs, many of which are dominated by *Eucalyptus* spp, *Acacia cockertoniana* and *Callitris columellaris* (Meissner *et al.* 2009 a b).

The Sandstone and Gum Creek belts are the closest greenstone belts to the Booylgoo Range, the latter of which forms the Black and Montague ranges at least 40km west and 60km north-west, respectively (Tingey 1985; Wyche *et al.* 2004). These ranges have only been recently surveyed, and preliminary results suggest that they are floristically more similar to the Booylgoo Range than the previously discussed ranges, although surveys were conducted during a dry season and species counts for these ranges are low (111 and 91 taxa respectively) (W. Thompson¹, unpublished data). All three ranges share common, widespread species such as *Eremophila latrobei*, *Eremophila jucunda*, *Grevillea inconspicua*, *Grevillea berryana*, *Ptilotus schwartzii* and *Acacia xanthocarpa*, and there are some general similarities among some of the communities. However, when perennial taxa are compared in a combined dataset, the Black and Montague Range have approximately 50% and 40% taxa, respectively, in common with the Booylgoo Range. This suggests that even these close ranges may have floristically dissimilar communities, although this can only be verified by an analysis of combined datasets.

On a regional scale, the flora and floristic communities have been found to vary significantly among adjacent ranges in the Yilgarn Craton (Gibson *et al.* 2007; Department of Environment and Conservation 2007). This has been attributed, to, in part, a gradient of increasing aridity over the wider region, leading to a regional turnover of flora (Beard 1990; Gibson & Lyons 2001b, Gibson 2004a; Gibson *et al.* 2007). Other factors which may also account for such a regional pattern are range-specific differences in edaphic features, geology and topography. It is speculated that floristic composition may also reflect the unique evolutionary history of each range, including their role as refugia during the oscillating climate of the Pleistocene. (Byrne 2008; Gibson & Lyons

1998a,b; 2001a, 2001b, Gibson 2004a; Gibson *et al.* 2007; Hopper and Gioia 2004). The BIF ranges of the northern Yilgarn also lie at the margins of the semi-arid to arid climatic zones, where significant regional shifts in species distributions are postulated to have occurred during climatic oscillations in the Pleistocene (Byrne 2008; Hopper and Gioia 2004). Both this and also be other historical factors may have influenced community assembly among isolated ranges in the arid zone.

Conservation

Within the wider Sandstone region, only a small proportion of the land surface area consists of outcropping greenstone landforms. The Booylgoo Range is significant in this respect. It is an isolated series of extensive, tall ridges and hills, where vegetation communities are tightly linked to topography and substrate. There is even some evidence for two floristic communities being geographically restricted to parts of the Booylgoo Range. The steep ridges and the heterogeneous topography provide a diversity of microhabitats and acts as a refuge for fire-sensitive species. It harbours taxa of conservation significance, has floristic dissimilarities to adjacent ranges and possibly some range-specific communities. These attributes of the Booylgoo Range contribute to conservation values of this arid zone landform.

The vegetation of the Booylgoo Range was found to be in reasonable condition and relatively free of naturalised weeds. There was clear evidence of goat browsing, but this was not considered to be too significant at the time of survey. It was most severe in the southern extent of the range where free water was readily available from operating wells and natural springs. Goats are serious problem in the Sandstone – Yalgoo region (Dowd 1998), and their control or eradication requires a concerted regional effort by a number of pastoral leaseholders and government agencies.

Mining and mineral exploration are a potential threat to the flora and communities of the Booylgoo Range. Greenstone belts of the Yilgarn Craton are highly prospective for mineral resources, and many have been exploited in the Murchison Mineral Field (Department of Industry and Resources 2007; Tingey 1985; Wyche *et al.* 2004). Apart from old exploration tracks and small clearings, there are relatively few signs of past mineral exploration and mining activities on Booylgoo Range. This lack of significant historical activity was due to little evidence for gold mineralisation (Wyche *et al.* 2004). However, iron-ore deposits with economic potential have now been identified for the range (Flint *et al.* 2000). To date, the entire area is covered by tenements and no communities described for the Booylgoo Range are reserved within the secure Conservation Estate. These communities are vulnerable to disturbance, and future activities on the range must follow best practices to protect both geographically restricted communities, and rare and poorly known taxa.

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ACKNOWLEDGEMENTS

Ashley Jacobs of Booylgoo Spring and Charles Cavallard from Depot Spring Stations are both thanked for their support in accessing pastoral leases. Soil analyses were conducted at the Chemistry Centre of Western Australia, and David Allen and Katrina Walton are both thanked for their assistance with these. Volunteers, visitors and staff at the Western Australian Herbarium are gratefully acknowledged for their help with species identifications; A. Brown, M. Hislop, G. Keighery, B. Maslin, D. Mickle, E. Obbens, B. Rye, M. Trudgen, S. van Leeuwen, A. Williams and P. Wilson. Neil Gibson provided assistance with statistical analyses, as well as guidance and comments on early manuscript drafts. Two anonymous reviewers are acknowledged for their comments on final drafts. Permits for flora collection were issued by the Western Australian Department of Environment and Conservation. This project is part of the Biodiversity Conservation Initiative (BCI) of the Saving Our Species (SOS) Program, and has been funded by the Department of Environment and Conservation, Western Australia.

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APPENDIX 1

Flora List for Booylgoo Range. Nomenclature follows Packowska and Chapman (2000), except where recent changes have been incorporated from the Census of Western Australian Plants database (Western Australian Herbarium 1998–). Introduced taxa are indicated by an asterisk, informal (phrase) names have a type collection number in parenthesis and new (unnamed) taxa have accession number in parenthesis.

- Acanthaceae**
Hamieria kempeana subsp. *muelleri*
- Adiantaceae**
Cheilanthes brownii
Cheilanthes lasiophylla
Cheilanthes sieberi subsp. *sieberi*
- Amaranthaceae**
Ptilotus aevroides
Ptilotus chamaecladus
Ptilotus exaltatus
Ptilotus helipteroides
Ptilotus obovatus
Ptilotus polystachyus var. *polystachyus*
Ptilotus roei
Ptilotus schwartzii
- Anthericaceae**
Thysanotus manglesianus
- Asclepiadaceae**
Marsdenia australis
Rhyncharrhena linearis
- Asteraceae**
Brachyscome ciliocarpa
Calocephalus multiflorus
Calotis hispidula
Chrysocephalum puteale
Erymophyllum ramosum subsp. *ramosum*
Gnephosis eriocephala
Gnephosis tenuissima
Helipterum craspedioides
Isoetopsis graminifolia
Lemooria burkittii
Myriocephalus guerinae
Olearia humilis
Pluchea dentex
Podolepis capillaris
Rhodanthe battii
Rhodanthe maryonii
Schoenia ayersii
Taplinia saxatilis
Waitzia acuminata var. *acuminata*
- Boraginaceae**
Heliotropium inexplicitum
Trichodesma zeylanicum
- Brassicaceae**
Lepidium oxytrichum
Lepidium platypetalum
Stenopetalum anfractum
- Caesalpiniaceae**
Senna aff. *glutinosa* (PERTH 07557132)
Senna artemisioides subsp. *x artemisioides*
x subsp. *x sturtii*
Senna artemisioides subsp. *x sturtii*
Senna artemisioides subsp. *helmsii* x *glaucifolia*
- Senna artemisioides* subsp. *helmsii* x *glaucifolia*
x *oligophylla*
Senna artemisioides subsp. aff. *helmsii*
(PERTH 07723113)
Senna artemisioides subsp. *filifolia*
Senna artemisioides subsp. *helmsii*
Senna artemisioides subsp. *x artemisioides*
Senna glaucifolia
Senna glaucifolia x sp. *Meekatharra* (E. Bailey 1-26)
Senna glutinosa subsp. *chatelainiana* x *charlesiana*
Senna manicula
Senna sp. *Meekatharra* (E. Bailey 1-26)
- Casuarinaceae**
Casuarina pauper
- Chenopodiaceae**
Atriplex codonocarpa
Chenopodium melanocarpum forma *melanocarpum*
Chenopodium saxatile
Dysphania kalpari
Dysphania rhadinostachya subsp. *rhadinostachya*
Enchylaena tomentosa var. *tomentosa*
Maireana camosa
Maireana convexa
Maireana georgei
Maireana planifolia x *villosa*
Maireana triptera
Rhagodia drummondii
Rhagodia eremaea
Sclerolaena densiflora
Sclerolaena eriacantha
Sclerolaena gardneri
- Convolvulaceae**
Duperreya commixta
- Crassulaceae**
Crassula colorata var. *acuminata*
- Cucurbitaceae**
*Citrullus lanatus**
- Cupressaceae**
Callitris columellaris
- Cuscutaceae**
*Cuscuta epithymum**
- Cyperaceae**
Bulbostylis barbata
Cyperus vaginatus
- Euphorbiaceae**
Euphorbia australis
Euphorbia boophthona
Euphorbia drummondii subsp. *drummondii*
Phyllanthus erwinii
- Geraniaceae**
Erodium cygnorum

Goodeniaceae

Brunonia australis
Goodenia havilandii
Goodenia macroplectra
Goodenia mimuloides
Scaevola spinescens
Velleia glabrata
Velleia hispida
Velleia rosea

Haloragaceae

Haloragis odontocarpa forma *octoforma*
Haloragis odontocarpa forma *pterocarpa*
Haloragis odontocarpa forma aff. *octoforma*
Haloragis odontocarpa forma *rugosa*
Haloragis trigonocarpa

Lamiaceae

Prostanthera albiflora
Prostanthera althoferi subsp. *althoferi*
Prostanthera althoferi subsp. *althoferi* x *campbellii*
Prostanthera campbellii
Spartothamnella teucriflora

Lobeliaceae

Isotoma petraea

Loranthaceae

Lysiana murrayi

Malvaceae

Abutilon cryptopetalum
Abutilon oxycarpum subsp. *prostratum*
Hibiscus gardneri
Hibiscus solanifolius
Hibiscus sturtii var. *truncatus*
Sida aff. *intricata* (PERTH 07557396)
Sida *ectogama*
Sida sp. dark green fruits (S. van Leeuwen 2260)
Sida sp. Golden calyces glabrous fruit
 (H.N. Foote 32)
Sida sp. *Excedentifolia* (J.L. Egan 1925)
Sida sp. spiciform panicles (E. Leyland s.n. 14/8/90)

Mimosaceae

Acacia aff. *siberica* (PERTH 07556969)
Acacia aneura var. cf. *aneura*
Acacia aneura var. cf. *microcarpa*
Acacia aneura var. cf. *tenuis*
Acacia aneura var. cf. *argentea*
Acacia aneura x *craspedocarpa*
Acacia balsamea
Acacia burkittii
Acacia craspedocarpa
Acacia minyura
Acacia quadrimarginea
Acacia ramulosa var. *ramulosa*
Acacia rhodophloia
Acacia sibirica
Acacia thoma
Acacia tetragonophylla
Acacia xanthocarpa

Myoporaceae

Eremophila exilifolia
Eremophila foliosissima
Eremophila forrestii subsp. *forrestii*
Eremophila forrestii subsp. *hastieana*
Eremophila galeata

Eremophila georgei
Eremophila granitica
Eremophila jucunda subsp. *jucunda*
Eremophila latrobei subsp. *latrobei*
Eremophila longifolia
Eremophila oldfieldii subsp. *angustifolia*
Eremophila oppositifolia subsp. *angustifolia*
Eremophila platycalyx subsp. *platycalyx*
Eremophila serrulata
Eremophila spectabilis subsp. *brevis*

Myrtaceae

Baekkea sp. Melita Station (H. Pringle 2738)
Calytrix desolata
Calytrix erosipetala
Calytrix uncinata
Eucalyptus kingsmillii subsp. *kingsmillii*
Homalocalyx echinulatus
Micromyrtus sulphurea
Thryptomene decussata

Nyctaginaceae

Boerhavia coccinea

Papilionaceae

Indigofera monophylla
Swainsona incei
Swainsona kingii

Phormiaceae

Dianella revoluta

Pittosporaceae

Pittosporum angustifolium

Poaceae

Aristida contorta
Austrostipa elegantissima
Austrostipa scabra subsp. *scabra*
Austrostipa trichophylla
Cymbopogon ambiguus
Cymbopogon obtectus
Digitaria brownii
Enneapogon caeruleus
Eragrostis dielsii
Eragrostis eriopoda
Eragrostis lacunaria
Eragrostis pergracilis
Eriachne helmsii
Eriachne mucronata
Eriachne pulchella subsp. *dominii*
Monachather paradoxus
Neurachne minor
Paspalidium basicladum
Thyridolepis mitchelliana
Thyridolepis multiculmis
Tripogon loliiformis

Polygalaceae

Polygala isingii

Portulacaceae

Calandrinia creethae
Calandrinia eremaea
Calandrinia monosperma
*Portulaca oleracea**

Primulaceae

Anagallis arvensis var. *caerulea**

Proteaceae

Grevillea berryana
Grevillea inconspicua
Hakea lorea subsp. *lorea*
Hakea preissii

Rubiaceae

Psychrax latifolia
Psychrax rigidula
Psychrax suaveolens
Synaptantha tillaeacea var. *tillaeacea*

Rutaceae

Philothea brucei subsp. *brucei*

Santalaceae

Santalum lanceolatum
Santalum spicatum

Sapindaceae

Dodonaea lobulata
Dodonaea microzyga var. *acrolobata*
Dodonaea petiolaris
Dodonaea rigida

Solanaceae

Nicotiana cavicola
Nicotiana occidentalis subsp. *occidentalis*
Nicotiana rosulata subsp. *rosulata*
Solanum ashbyae
Solanum ellipticum
Solanum lasiophyllum
Solanum nummularium

Stackhousiaceae

Stackhousia muricata

Sterculiaceae

Brachychiton gregorii

Stylidiaceae

Stylidium induratum

Typhaceae

Typha domingensis

Zygophyllaceae

Tribulus adelacanthus
Tribulus astrocarpus
Zygophyllum eichleri

APPENDIX 2

Sorted two-way table of sites and perennial species occurrences for the Booylgoo Range, showing species occurrence by community type. Sites appear as columns and species as rows, and are sorted according to groupings determined by classification analyses.

	Community type						
	1a	1b	2	3	4	5	6
Species Group A							
<i>Cheilanthes lasiophylla</i>							
<i>Lysiana murrayi</i>							
<i>Acacia burkittii</i>							
<i>Eremophila exilifolia</i>							
<i>Abutilon cryptopetalum</i>							
<i>Calytrix desolata</i>							
<i>Spartothamnella laevisiflora</i>							
<i>Austrostipa trichophylla</i>							
<i>Eremophila oldfieldii</i> subsp. <i>angustifolia</i>							
<i>Grevillea inconspicua</i>							
<i>Ptilotus exaltatus</i>							
<i>Senna manicula</i>							
<i>Eremophila granitica</i>							
<i>Acacia xanthocarpa</i>							
<i>Scaevola spinescens</i>							
<i>Abutilon oxycarpum</i>							
Species Group B							
<i>Eremophila platycalyx</i> subsp. <i>platycalyx</i>							
<i>Maireana planifolia</i> x <i>villosa</i>							
<i>Sida</i> aff. <i>intricata</i>							
<i>Thyridolepis mitchelliana</i>							
<i>Solanum ellipticum</i>							
<i>Euphorbia drummondii</i> subsp. <i>drummondii</i>							
Species Group C							
<i>Hibiscus gardneri</i>							
<i>Rhynchosarrhena linearis</i>							
<i>Thysanotus mangianthus</i>							
<i>Senna glutinosa</i> subsp. <i>chatelainiana</i> x <i>charlestoniana</i>							
<i>Rhagodia eremaea</i>							
Species Group D							
<i>Enchylaena tomentosa</i>							
<i>Maireana triptera</i>							
<i>Acacia aneura</i> var. cf. <i>argentina</i>							
<i>Sida ectogama</i>							
Species Group E							
<i>Homalocalyx echinulatus</i>							
<i>Neurachne minor</i>							
<i>Acacia</i> sp. Peak Hill							
<i>Acacia thoma</i>							
Species Group F							
<i>Eremophila spectabilis</i> subsp. <i>brevis</i>							
<i>Harniera kempeana</i> subsp. <i>muelleri</i>							
<i>Sida</i> sp. Excedentifolia							
<i>Grevillea berryana</i>							
<i>Phyllanthus erwinii</i>							
Species Group G							
<i>Acacia balsamea</i>							
<i>Dodonaea microzyga</i> var. <i>acrolobata</i>							
<i>Callitris columellaris</i>							
<i>Digitaria brownii</i>							
<i>Feydrax latifolia</i>							
<i>Frostanthera althoferi</i> subsp. <i>althoferi</i> x <i>campbellii</i>							
<i>Frostanthera campbellii</i>							
<i>Baobea</i> sp. Melita Station							
<i>Olearia humilis</i>							
<i>Ptilotheca brucei</i> subsp. <i>brucei</i>							
<i>Thryptomene decussata</i>							
<i>Cheilanthes brownii</i>							
Species Group H							
<i>Brachyckiton gregori</i>							
<i>Acacia craspedocarpa</i>							
<i>Ptilotus rosei</i>							
<i>Senna artemisioides</i> subsp. x <i>helmsii</i> x <i>glaucofolia</i>							
<i>Eremophila galeata</i>							
<i>Senna glaucifolia</i>							
<i>Santalum lanceolatum</i>							
<i>Hibiscus solanifolius</i>							
<i>Dodonaea rigida</i>							
<i>Senna artemisioides</i> subsp. <i>helmsii</i>							
<i>Eremophila forrestii</i>							
<i>Acacia tetragonophylla</i>							
<i>Eneapogon caeruleus</i>							
<i>Acacia ramulosa</i> var. <i>ramulosa</i>							
<i>Sida</i> sp. dark green fruits							
<i>Ptilotus obovatus</i>							
<i>Marsdenia australis</i>							
<i>Frostanthera althoferi</i> subsp. <i>althoferi</i>							
<i>Eragrostis eriopoda</i>							
<i>Acacia quadrimarginea</i>							
<i>Solanum lasiophyllum</i>							
<i>Senna</i> sp. Meekatharra							
<i>Acacia aneura</i> var. cf. <i>aneura</i>							
<i>Eremophila jucunda</i> subsp. <i>jucunda</i>							
Species Group I							
<i>Eragrostis helmsii</i>							
<i>Feydrax suaveolens</i>							
<i>Feydrax rigidula</i>							
<i>Cymbopogon ambiguus</i>							
<i>Acacia aneura</i> var. cf. <i>tenuis</i>							
<i>Dodonaea petiolaris</i>							
<i>Thyridolepis multicaulis</i>							
<i>Eremophila georgei</i>							
<i>Cheilanthes sieberi</i> subsp. <i>sieberi</i>							
<i>Ptilotus schwartzii</i>							
<i>Monachather paradoxus</i>							
<i>Eremophila latrobei</i> subsp. <i>latrobei</i>							
<i>Acacia aneura</i> var. cf. <i>microcarpa</i>							
<i>Sida</i> sp. Golden calyces glabrous fruit							
<i>Solanum ashbyae</i>							

Table 1

Taxa of conservation significance collected within the Booylgoo Range. Priority status is listed under DEC conservation codes for Western Australia (Atkins 2008). Endemic taxa are defined as those restricted to hills within 100km radius. IBRA Regions are denoted as: Yal = Yalgoo, Mur = Murchison, GD = Gibson Desert, LSD = Little Sandy Desert, Pil = Pilbara, Gas = Gascoyne, GS = Geraldton Sandplains (Thackway & Cresswell 1995; Environment Australia 2000).

Family	Taxon	Record for Booylgoo	Priority Code	IBRA Bioregion Distribution
Mimosaceae	<i>Acacia balsamea</i>	new record	4	Mur, Gas, GD, LSD, Pil
Myrtaceae	<i>Baeckea</i> sp. Melita Station	new record	4	Yal, Mur
Myrtaceae	<i>Calytrix erosipetala</i>	new record	3	Yal, Mur
Myrtaceae	<i>Calytrix uncinata</i>	new record	3	Yal, Mur
Proteaceae	<i>Grevillea inconspicua</i>	–	4	Mur
Myrtaceae	<i>Homalocalyx echinulatus</i>	new record	3	Mur, Gas, GS

Table 2

Significant indicator taxa of the eight group classification of BIF landforms within the Booylgoo Range. Indicator values (%) are shown only for taxa which were significant at $p \leq 0.05$ (from Monte Carlo permutation test, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$). The highest indicator values per taxon are indicated by shading.

Community type	1a	1b	2	3	4	5	6
<i>Eremophila latrobei</i> subsp. <i>latrobei</i> ***	21	21	21	13	5	1	2
<i>Acacia aneura</i> var. <i>cf. microcarpa</i> **	22	19	9	22	1	0	10
<i>Sida</i> sp. Golden calyces glabrous fruit **	29	24	20	4	0	0	0
<i>Eriachne helmsii</i> *	35	1	2	5	0	0	0
<i>Solanum ashbyae</i> *	21	21	12	0	21	5	2
<i>Eremophila georgei</i> ***	3	29	23	9	0	0	13
<i>Thyridolepis multiculmis</i> *	0	27	0	0	0	0	0
<i>Philotheca brucei</i> subsp. <i>brucei</i> ***	1	0	91	0	0	0	0
<i>Thryptomene decussata</i> **	1	10	57	0	0	0	0
<i>Olearia humilis</i> **	1	0	59	1	0	0	0
<i>Prostanthera campbellii</i> **	5	0	47	0	0	0	0
<i>Solanum lasiophyllum</i> **	0	0	1	47	0	5	21
<i>Eremophila jucunda</i> subsp. <i>jucunda</i> **	2	2	1	42	13	0	0
<i>Acacia aneura</i> var. <i>cf. tenuis</i> *	3	5	9	29	0	0	0
<i>Brachychiton gregorii</i> ***	0	0	0	0	75	0	0
<i>Senna glaucifolia</i> **	2	5	1	23	38	1	0
<i>Acacia craspedocarpa</i> **	0	0	0	1	47	0	9
<i>Eremophila galeata</i> **	0	0	0	20	44	1	5
<i>Senna artemisioides</i> subsp. <i>helmsii</i> x <i>glaucifolia</i> *	5	0	0	11	31	6	0
<i>Acacia xanthocarpa</i> ***	0	0	0	1	5	73	0
<i>Dodonaea rigida</i> ***	2	33	0	0	0	50	0
<i>Senna manicula</i> **	0	0	0	0	0	60	10
<i>Eremophila granitica</i> **	0	0	0	0	0	46	30
<i>Cheilanthes lasiophylla</i> *	0	0	0	0	0	33	0
<i>Eremophila exilifolia</i> *	0	0	0	0	21	38	0
<i>Eremophila forrestii</i> *	8	0	0	2	12	34	0
<i>Grevillea inconspicua</i> *	0	0	0	0	0	30	13
<i>Senna</i> sp. <i>Meekatharra</i> *	0	1	0	13	3	5	43
<i>Austrostipa trichophylla</i> *	0	0	0	0	0	11	44
<i>Eremophila oldfieldii</i> subsp. <i>angustifolia</i> *	0	0	0	0	0	11	44
<i>Dodonaea petiolaris</i> *	1	7	19	2	0	4	34
<i>Ptilotus exaltatus</i> *	0	1	0	0	5	2	38
Number of quadrats	10	11	8	9	4	6	3

Table 3

Summary statistics (average \pm s.e.) of environmental variables for floristic community types of the Booylgoo Range. Differences among groups were determined using Kruskal – Wallis nonparametric analysis of variance, and groups tested are in bold text. (*= $p < 0.05$, **= $p < 0.01$, ***= $p < 0.001$), with significant Dunn's posthoc test (LSD $p < 0.05$) results indicated by letters in superscript. Parameter codes are explained in the methods section. Units for parameters; EC = mS/m, eCEC = cmol(+)/kg, minerals = mg/kg, organic C and N = %. Abbreviations: Rock Frag = surface rock fragment cover, Rock Max Size = maximum surface rock size category. Aspect is expressed as sine (east-west) or cosine (north-south) of value in radians.

Variable	type 1a	type 1b	type 2	Community Type type 3	type 4	type 5	type 6
Soil parameters							
EC NS	2.4 \pm 0.3	3.6 \pm 0.4	3.0 \pm 0.5	5.7 \pm 2.0	2.5 \pm 0.5	4.5 \pm 1.1	5.3 \pm 1.3
pH***	4.22 \pm 0.06 a	4.46 \pm 0.09 ab	4.25 \pm 0.08 a	4.42 \pm 0.06 ab	5.1 \pm 0.24	5.97 \pm 0.2 b	5.23 \pm 0.32
OrgC***	0.89 \pm 0.11 b	1.00 \pm 0.20 b	1.44 \pm 0.32 b	0.43 \pm 0.03 a	0.31 \pm 0.05	0.58 \pm 0.06 ab	1.14 \pm 0.13
N***	0.07 \pm 0.01 b	0.07 \pm 0.01 b	0.10 \pm 0.02 b	0.04 \pm 0.00 a	0.03 \pm 0.00	0.05 \pm 0.00 ab	0.09 \pm 0.01
Al NS	442.0 \pm 21.7	401.8 \pm 31.6	436.3 \pm 26.3	357.8 \pm 19.7	407.5 \pm 42.7	448.3 \pm 41.2	313.3 \pm 17.6
Ca***	123.2 \pm 15.8 a	215.5 \pm 19 ab	212.3 \pm 50.6 a	184.4 \pm 19.9 a	282.5 \pm 74.9	935.0 \pm 152.5 b	773.3 \pm 413.5
Co***	0.16 \pm 0.08 ab	0.30 \pm 0.08 abc	0.05 \pm 0.01 a	0.64 \pm 0.23 bc	2.39 \pm 0.37	3.09 \pm 0.443 c	2.01 \pm 1.20
Cu*	0.75 \pm 0.05 ab	0.79 \pm 0.07 ab	0.65 \pm 0.05 a	0.73 \pm 0.11 a	1.83 \pm 0.5	2.07 \pm 0.42 b	0.73 \pm 0.2
Fe**	50.5 \pm 8.6 ab	84.5 \pm 25.1 b	109.3 \pm 36.3 b	31.0 \pm 1.4 a	38.3 \pm 2.1	42.8 \pm 3.4 ab	56.3 \pm 3.8
K*	147.6 \pm 12.3	205.8 \pm 18.5	142 \pm 18.5	189.4 \pm 15.9	167.5 \pm 17.5	171.7 \pm 15.4	193.3 \pm 3.3
Mg***	29.3 \pm 3.8 a	51.6 \pm 3.8 abc	42.3 \pm 6.3 ab	60.7 \pm 8.8 cb	135 \pm 13.2	256.7 \pm 63.5 c	270.7 \pm 146.0
Mn**	24.4 \pm 3.3 a	39.8 \pm 9.0 ab	21.4 \pm 3.7 a	38 \pm 9.4 ab	115.5 \pm 21.8	112.3 \pm 18.1 b	64.0 \pm 18.1
Ni***	0.14 \pm 0.02 a	0.35 \pm 0.07 ab	0.16 \pm 0.03 a	0.4 \pm 0.1 ab	1.03 \pm 0.3	1.25 \pm 0.42 b	2.53 \pm 2.08
P**	13.9 \pm 2.7 ab	27.8 \pm 10.8 ab	44.4 \pm 17.9 b	6.3 \pm 0.7 a	5.5 \pm 0.6	6.8 \pm 0.6 a	10.7 \pm 3.2
S**	10.1 \pm 1.0 b	12.1 \pm 1.4 b	10.3 \pm 0.4 b	11.4 \pm 1.9 b	5.3 \pm 1.1	4.8 \pm 0.4 a	9.7 \pm 4.2
Zn NS	3.75 \pm 1.56	4.19 \pm 0.95	2.15 \pm 0.25	5.12 \pm 2.23	2.85 \pm 0.5	3.65 \pm 0.73	3.73 \pm 1.39
ECEC***	1.24 \pm 0.13 a	2.04 \pm 0.156 ab	1.79 \pm 0.34 a	1.97 \pm 0.20 ab	2.97 \pm 0.45	7.23 \pm 1.23 b	6.62 \pm 3.24
Ca:Mg	4.3 \pm 0.2	4.2 \pm 0.2	4.7 \pm 0.5	3.3 \pm 0.3	2.0 \pm 0.3	4.0 \pm 0.6	3.0 \pm 0.4
Physical Site Parameters							
CosAspect NS NS	0.22 \pm 0.20	0.10 \pm 0.23	0.11 \pm 0.16	0.34 \pm 0.26	0.04 \pm 0.51	-0.07 \pm 0.34	-0.10 \pm 0.34
SinAspect EW NS	-0.18 \pm 0.25	-0.44 \pm 0.16	0.24 \pm 0.33	-0.07 \pm 0.21	0.44 \pm 0.07	-0.26 \pm 0.26	0.22 \pm 0.59
Topography***	3.2 \pm 0.4b	3.5 \pm 0.3 b	4.3 \pm 0.3 b	1.4 \pm 0.2 a	1.4 \pm 0.1	3.5 \pm 0.4 b	3.2 \pm 0.2
Slope**	8.6 \pm 1.3 ab	14.4 \pm 2.4 b	17.6 \pm 4.2 b	3.3 \pm 1.0 a	3.0 \pm 0.9	8.7 \pm 1.1 ab	14.7 \pm 4.3
Rock Frag*	5.1 \pm 0.1	5.2 \pm 0.2	4.4 \pm 0.3	4.3 \pm 0.5	5.0 \pm 0	5.3 \pm 0.2	5.0 \pm 0
MxR**	4.5 \pm 0.2 ab	5.0 \pm 0.3 ab	5.6 \pm 0.2 b	3.7 \pm 0.4 a	4.0 \pm 0	5.0 \pm 0.3 ab	5.7 \pm 0.3
Outcrop**	1.8 \pm 0.7 ab	2.4 \pm 0.6 ab	4.3 \pm 0.3 b	0.1 \pm 0.1 a	0.5 \pm 0.3	1.2 \pm 0.2 ab	2.0 \pm 1.0
Runoff NS	2.4 \pm 0.2	2.9 \pm 0.1	2.8 \pm 0.3	2.1 \pm 0.3	2.5 \pm 0.3	2.7 \pm 0.2	3.0 \pm 0.0
Soil depth**	1.9 \pm 0.3 ab	1.4 \pm 0.2 a	1.3 \pm 0.1 a	2.9 \pm 0.1 b	2.9 \pm 0.1	2.2 \pm 0.3 ab	2.0 \pm 0.6
%Leaf	13.3 \pm 2.7	13.6 \pm 2.5	14.4 \pm 4.3	14.1 \pm 2.9	8.0 \pm 2.9	12.7 \pm 3.5	18.3 \pm 7.3
%Bare	87.5 \pm 2.4	85 \pm 2.1	86.3 \pm 2.5	89 \pm 2.6	88.8 \pm 3.1	84.2 \pm 3	83.3 \pm 6
Altitude*	518.9 \pm 8	540.2 \pm 9.3	548.3 \pm 13.4	519.2 \pm 7.1	522.3 \pm 10	547.9 \pm 5.7	542.3 \pm 6.4
Latitude*	-27.88 \pm 0.026ab	-27.844 \pm 0.027 ab	-27.916 \pm 0.032 a	-27.797 \pm 0.024 b	-27.844 \pm 0.033	-27.814 \pm 0.034 ab	-27.803 \pm 0.072
Longitude**	119.947 \pm 0.009	119.926 \pm 0.009	119.955 \pm 0.009	119.91 \pm 0.01	119.918 \pm 0.014	119.91 \pm 0.01	119.913 \pm 0.023
Number of species / quadrat							
All taxa 1	23.2 \pm 1.9	28.1 \pm 1.7	27.1 \pm 1.4	31.1 \pm 2.5	31.5 \pm 3.9	32.0 \pm 1.9	33.3 \pm 3.5
Annuals only	7.4 \pm 1.0	9.3 \pm 0.8	9.6 \pm 1.5	8.9 \pm 1.5	10 \pm 3.6	9.7 \pm 1.3	7 \pm 2
Number of quadrats	10	11	8	9	4	6	3

¹ including singleton taxa

Table 4: Matrix of Spearman rank correlation coefficients for environmental variables collated from 51 quadrats established on the Booylgoo Range. Only correlations significant at $p < 0.01$ are shown. Full details of environmental parameter codes are given in the methods section.

	EC	pH	OrgC	N	Al	Ca	Co	Cu	Fe	K	Mg	Mn	Ni	P	S	Zn	eCEC	NS	EW	To	Slope	RockFrag	MwR	Outcrop	Runoff	I Depth D	%Leaf	%Bare	Altitude	Latitude											
Soil chemical parameters																																									
EC	.																																								
pH	.	.																																							
OrgC	.	.	.																																						
N	.	.	0.99	.																																					
Al	-0.42	.	.	.	.																																
Ca	.	0.86	.	.	.	.																															
Co	.	0.82	.	.	.	0.74	.																																		
Cu	.	0.57	.	.	.	0.36	0.78	.																																	
Fe	.	.	0.84	0.83																																
K																															
Mg	.	0.81	.	.	.	0.93	0.75																														
Mn	.	0.71	.	.	.	0.47	0.88	0.88	.	.	0.48	.																													
Ni	.	0.62	.	.	.	0.81	0.65	.	.	.	0.87	.																													
P	.	.	0.81	0.79																													
S	0.52	-0.51	.	.	.	-0.42	-0.55	-0.48	.	.	-0.41	.																													
Zn	0.38	.	.	.	.	.	.	0.48	0.64	.																											
eCEC	.	0.85	.	.	.	0.99	0.76	.	.	.	0.97	0.48	0.64	.																											
Physical parameters																																									
Aspect NS
Aspect EW
Topography	.	.	0.55	0.56	0.46	.	.	.	0.44	0.43	
Slope	.	.	0.70	0.71	.	.	.	0.83	0.80	0.49	
RockFrag	
MwR	.	.	0.59	0.84	.	.	.	.	0.51	.	.	.	.	0.48	.	.	.	.	.	.	0.70	0.64	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Outcrop	.	.	0.68	0.65	0.37	.	.	.	0.58	.	.	.	.	0.57	.	.	.	.	.	.	0.79	0.68	.	0.66	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Runoff	.	.	0.42	0.44	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0.46	0.58	.	0.69	0.44	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Soil	.	.	-0.56	-0.55	-0.38	.	.	.	-0.47	.	.	.	.	.	.	.	.	.	.	.	-0.72	-0.69	.	-0.68	-0.76	-0.51	.	.	.	.	.	.	.	.	.	.	.	.
%Leaf	
%Bare	-0.57		
Altitude	.	.	0.45	0.45	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	0.55	0.37	.	0.52	0.50	0.36	-0.45	.	.	.	.	.	.	.	.	.	.	.
Latitude	
Longitude	-0.36	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	-0.84		

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

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ABSTRACT

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

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

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

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

INTRODUCTION

The Yilgarn Craton of Western Australia is a sizeable area of Archaean bedrock that harbours a series of metamorphosed volcanic and sedimentary mineral belts embedded in granitoids. Known locally as greenstones, these mineralisation belts consist of metasedimentary rocks, notably banded iron formation (BIF), and mafic and ultramafic metavolcanic rocks. These greenstone belts outcrop as isolated ranges and hills above surrounding plains of weathered Cainozoic sediments. They are highly prospective for base and precious metals, and have been exploited for mineral resources for over a century. It is expected that the recent resurgence in the iron ore industry in the Midwest of Western Australia will see an

unprecedented level of exploration and mining activity target these BIF landforms of the Yilgarn Craton (Department of Industry and Resources 2007). Given current deficiencies in the knowledge on the biota of these ranges, there is a need to survey the biodiversity of such prospective areas for conservation planning and management purposes (Department of Environment and Conservation 2007).

A series of quadrat-based botanical surveys is in progress, and is producing a regional overview of the flora and floristic communities on banded iron formations of the northern Yilgarn Craton (Department of Environment and Conservation 2007; Gibson 2004a, 2004b; Gibson & Lyons 1998a, 1998b, 2001a, 2001b; Gibson *et al.* 2007; Markey & Dillon 2008a, 2008b; Meissner & Caruso 2008a, 2008b, 2008c). These detailed surveys extensively sample individual ranges and can resolve fine-scale patterns in floristic communities (as defined by their

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

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

Study Site

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

The predominant industries in the Yalgoo region are pastoralism and mining, and the entire survey area and much of the wider region is covered by pastoral leases. As with all rangelands, the native vegetation is left for grazing and the study area has escaped the extensive clearing of vegetation that has occurred in the adjacent northern wheatbelt, the eastern margin of which is 12km south-west of the Gullewa survey area. The pastoral leases in the Gullewa region are

among the first established in the Midwest region, having been established during the 1870's and 1880's (Hennig 1998a). Mellenbye and Bannawarra are active sheep stations, while Barnong was recently purchased by the Department of Conservation and Environment for future inclusion in the conservation estate.

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

Climate

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

Geology

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

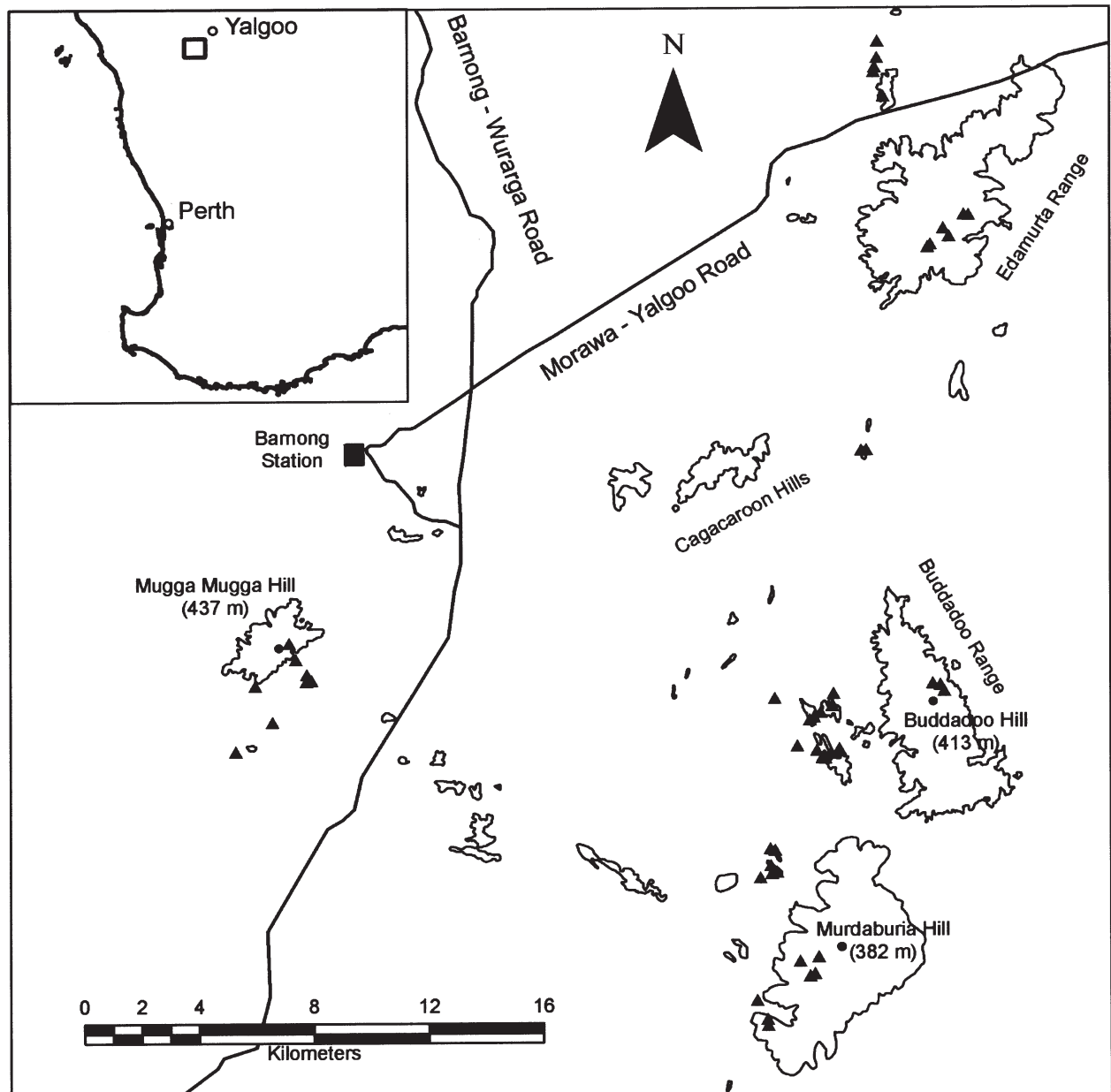


Figure 1. Location of the Gullewa survey area within the Midwest region of Western Australia (inset). The ranges and hills of the Gullewa survey area have been outlined at the 300-350m contour and significant landmarks are labelled. The distribution of the 50 floristic quadrats across the survey area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

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

As with the greater Yalgoo region, the underlying bedrock consists of greenstone belts of deformed, metamorphosed igneous and sedimentary rocks embedded within the gneissic granitoids of the northern Yilgarn craton (Muhling & Low 1977; Payne & Pringle 1998). These belts consist of complexes of mafic, ultramafic and felsic intrusive and volcanic rocks, and BIF and associated metasedimentary rocks. They form prominent ranges and, in the case of BIF, generally north-south trending, narrow strike ridges (Cornelius *et al.* 2007; Johnson 1998; Muhling & Low 1977). Magnetite and haematite deposits will be associated with these greenstone belts (Cornelius

et al. 2007.) Extensive deposits of colluvium from eroded bedrock accumulate around the slopes, pediments and plains around these landforms, from scree on steeper slopes to stony mantles on lower gradients. Likewise, alluvial deposits will accrue in drainage lines and outwashes around the ranges (Johnson 1998; Payne & Pringle 1998). Soils of the rocky uplands of these landforms are typically skeletal or shallow (< 50cm), stony and acidic (pH \leq 5.1) silty clay loams and sandy loam rudosols, which progress into shallow, stony red earths, ferruginous gravels and red clayey sands on the depositional slopes and outwashes (Hennig 1998b).

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

Vegetation

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

The most recent vegetation survey which has covered the Gullewa survey area is that of Pringle (1998), where Gullewa is inclusive of a larger rangeland inventory for the Paynes Find – Yalgoo – Sandstone region, which was mapped on scales of 1:250 000 and 1:500 000. Pringle (1998) adapted floristic classifications from previous rangeland surveys to describe a large number of regional

vegetation communities (termed 'habitats'). Within each Land System are several vegetation communities, each of which occupies a distinct part of the landform toposequence in a manner akin to the 'catenary sequence' of the Vegetation Systems of Beard (1976a, 1976b, 1990). There are four land systems (primarily the Gabanintha and Tallering, but also the Watson and Wiluna land systems) mapped for the hills and ranges in the Gullewa survey area, which contain a total of 16 communities (Mabbutt *et al.* 1963; Payne *et al.* 1998). However, these communities are broadly described and are not specific to any particular range or to any single land system in the wider Midwest region. A detailed, quadrat-based survey of BIF ranges immediately south-east of the Gullewa survey area identified eight floristic community types, of which some were restricted to parts of range-specific communities (Markey & Dillon 2008a).

METHODS

Fifty 20 x 20m² permanent vegetation quadrats were established over the survey area during a two week period that commenced in late September 2006 (Fig. 1). These were established on the slopes and pediments of Mugga Mugga Hill (mafics, felsics, weathered metasedimentaries and laterites), the undulating pediments and breakaways around Murdaburia Hill (laterites, weathered metasedimentaries and BIF), on the Buddadoo Range (BIF, magnetite and haematite, Buddadoo Gabbro), on the eastern edge of Cagacaroon Hills (metamorphosed basalt) and on the Edamurta Range (metamorphosed medium grained dolerite, muscovite schist and seams of haematite) (Muhling & Low 1977). Quadrats were placed strategically on landforms to cover the extent of the toposequence of vegetation communities on ranges and hills; from hillcrests and slopes, to pediments and plains of colluvium and alluvial outwash. This methodology has been used to survey other ranges in Western Australia (Gibson 2004a, 2004b) and is consistent with the previous survey on adjacent central Tallering Land System (Markey & Dillon 2008a). Quadrats were established only in what could be estimated to be the least disturbed vegetation in the area, thereby avoiding recently burnt, heavily grazed, cleared and mined areas. However grazing was an unavoidable factor in much of the study area, and all sites were impacted to an appreciable degree.

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

mm) and soil chemical composition was assayed at the Chemistry Centre of Western Australia (Table 1).

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

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

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

Three dimensional semi-strong hybrid (nonmetric) multidimensional scaling (SSH MDS) was used to ordinate sites using presence / absence data of floristic composition (Belbin 1991), using 1000 random starts and 50 iterations. Principal Component Correlation (PCC) (also known as rotational correlation analysis) was run in PATN as a form of simultaneous multiple linear regression of the extrinsic environmental parameters with the site ordination. A MCAO test, using 10000 iterations, evaluated the significance of these correlation coefficients (Belbin 1991). Significant vectors ($p < 0.05$), oriented

on axis of best fit, were superimposed on to the site ordination. The Spearman rank correlation coefficient was used to examine relationships among site environmental attributes, and the Kruskal-Wallis nonparametric analysis of variance tested for differences in these environmental parameters among floristic community types, followed by Dunns' posthoc multiple comparisons (Zar 1984). Parameter values were not transformed except for aspect, where values were converted from degrees to radians and then transformed by a sine and cosine function. This produced linear values between -1 and 1, for the respective east-west and north-south orientations.

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

RESULTS

Flora

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

Priority taxa

Five taxa listed as being of conservation significance (Atkins 2008) were collected during the course of this

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

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

Range extensions / New records

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

The largest range extension found by this survey was that of *Alectryon oleifolius*, which has two subspecies which are allopatric with a disjunction over the mid west region. *A. oleifolius* subsp. *oleifolius* is centred in the north-west of the state while *A. oleifolius* subsp. *canescens* is largely restricted to the south-east. The nearest collection for *A. oleifolius* subsp. *oleifolius* is 300km north-west of Gullewa, which is a range extension for the subspecies. Two collections, which have not been resolved to

subspecific level, have been recorded at two other locations within the Murchison-Yalgoo region, the nearest collection being c. 110km east of Gullewa. Although tending to subsp. *oleifolius*, these collections have characters intermediate of both subspecies.

Floristic Communities

Classification Analysis

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

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

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

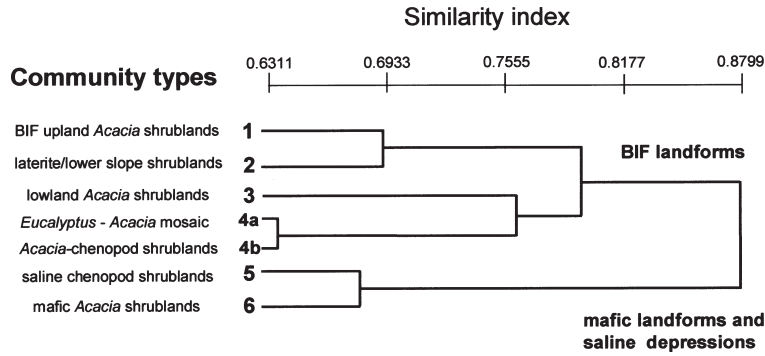


Figure 2. Summary dendrogram of floristic community types classified for the Gullewa survey area. Resolved from classification analysis and UPGMA clustering of a presence absence data matrix (Bray-Curtis measure of dissimilarity) of 104 perennial taxa from 48 quadrats. The dendrogram is resolved to the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

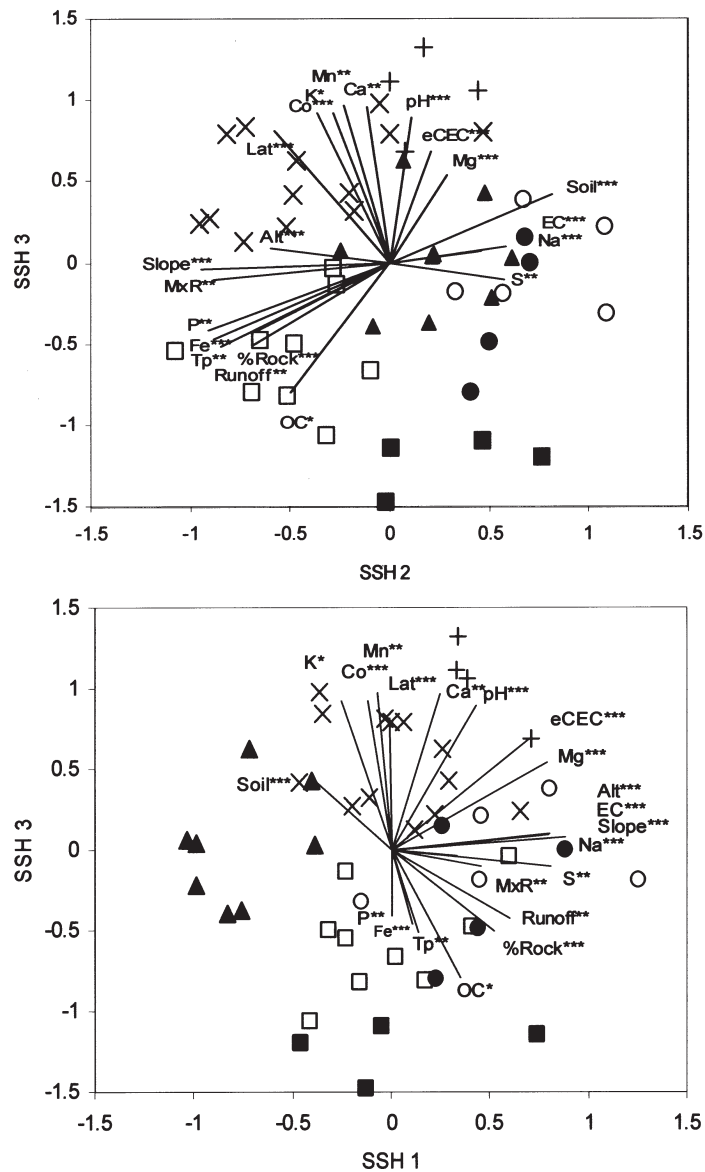


Figure 3. 3D SSH MDS ordination of sites for the Gullewa survey area, based on dissimilarities in floristic composition from a presence/absence data matrix of 104 perennial taxa from 48 quadrats (stress = 0.18). Sites are coded by their respective floristic community types (1 □, 2 ■, 3 ▲, 4a ●, 4b ○,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

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

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

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

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

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

Compared to Community type 1, Community type 2 has very little or no representation in Species groups A and D–G, and reduced representation across species in Species group C, H and I (Appendix 2). On the whole, while this community is affiliated floristically to

Community type 1, it is species-depauperate and has the lowest species diversity among the six community types (27 ± 3.2 (s.e.) taxa per quadrat) (Table 3, Appendix 2).

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

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

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

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

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

Relative to other BIF communities, Community type 4 lacks taxa from Species group H, and has reduced numbers of taxa from Species group C (Appendix 2). Community types 4a and 4b are closely allied, and both have moderate species diversity among the various community types (averaging 35 and 37 taxa per quadrat

respectively, Table 4). The main floristic differences are the presence of Species group D and more consistent representation in Species group F in Community type 4a (Appendix 2). Both Community subtypes share *P. obovatus* and *A. burkittii* as significant indicator species (Table 2).

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

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

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

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

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

Community type 5 was sampled at four sites on the Edamurta and Buddadoo Ranges, and was a community associated with chenopod-rich low depressions in valley flats among BIF ridges, weathered haematite and lateritic breakaways. This was a distinctive community, which typically consisted of a sparse shrubland of *A. eremaea*, *Eremophila oldfieldii* subsp. *oldfieldii* and *Hakea preissii*

over mid-lower strata shrub layers dominated by a rich variety of chenopods. Common and typical shrub species for this community include *Rhagodia eremaea*, *Rhagodia drummondii*, *S. spinescens*, *Solanum lasiophyllum*, *Maireana triptera*, *Atriplex codonocarpa*, *Maireana pyramidata*, *Maireana tomentosa* subsp. *tomentosa*, *Sclerolaena ericantha*, *S. densiflora* and *Maireana georgei* (Table 2). *M. nodiflorum* was common to sites of this community, and was estimated to form a mid-dense (30–70%) cover at some sites. Many of these characteristic taxa for this community are grouped in Species groups E, F and I, which are the main Species groups associated with this Community type (Appendix 2). There is very little representation from the other Species groups. At an average of 33 ± 4.1 (s.e.) taxa per quadrat, sites are moderately species-rich (Table 3)

Community type 6: Mafic *Acacia umbraculiformis* shrublands

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

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

Excluded sites

A pair of floristically similar quadrats were excluded from the analyses owing to their high floristic dissimilarity to the other 48 sites. Both sites consisted of sparse *Acacia effusifolia* and *A. ramulosa* var. *ramulosa* tall shrublands

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

SSH MDS Analysis

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

Environmental Correlates

Topsoils from the Gullewa survey were generally shallow (2.18 ± 0.1 soil depth class, which equates to 5-20cm), leaf litter cover was scarce (average = $16.0\% \pm 1.5$ (s.e.)), and the bare ground covered $85.8\% \pm 1.1$ (s.e.) of the quadrat area. Soils were stony, with a surface mantle of rock fragments covering $> 50\%$ on average (cover class = 4.7 ± 0.1 (s.e.)), ranging from 10% to $> 90\%$. Soil colour and texture was generally red to red-brown clay loam- sandy clay loams and clay sands, with a uniform profile and with a surface crust over loose soil. Soils were moderately acidic on average ($\text{pH} = 5.4 \pm 0.1$ (s.e.)), and ranged from strongly acidic ($\text{pH} 4.2$) to the more neutral-slightly alkaline ($\text{pH} 7.3$) (for values measured in CaCl_2 , cf. Slattery *et al.* 1999).

Two elements (B, Mo) were removed from the dataset as these elements were undetected in over half of the samples (Table 4). Most soil elements were highly inter-correlated (Ca, Cd, Co, Cu, K, Mn, Mg, Na, Ni and Zn), and positively correlated with soil pH and eCEC. Another inter-correlated group consists of P, S, N and organic C, and was positively correlated with eCEC but independent of pH (Table 4). Among site physical variables, runoff,

outcrop, maximum rock size, topographic position and slope were all inter-correlated, and this group was positively correlated with Fe and negatively correlated with soil depth. Both N and organic C were positively correlated with topographic position and rock outcrop cover (Table 3). Otherwise, there were few strong correlations between the suite of minerals, eCEC and pH and the suite of topographical variables (Table 4).

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

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

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

material from surrounding lateritic breakways, BIF ridges and mafic hills.

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

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

The second major gradient consists of the inter-

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

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

DISCUSSION

Flora

This survey reports a total 235 taxa and three hybrids for the Gullewa survey area, which is a rich flora of similar magnitude to ranges in the northern Eastern Goldfields, where counts from similar, quadrat-based surveys on BIF ranges vary from 238 to 345 taxa Gibson 2004b; Gibson & Lyons 2001a, 2001b; Gibson *et al.* 1997). It is also similar to counts from other surveys in the Yalgoo IBRA region, where 238 taxa were reported for the Koolanooka and Perenjori Hills (c. 55–70km south) (Meissner & Caruso 2008c) and 243 taxa for the Mount Gibson Hills (Meissner & Caruso 2006b). However, a more intensive survey recorded 414 taxa on the central Talling Land System (c. 80km southeast), and 335 taxa were found around Mt Karara to Windaning Hill alone (c. 55km southeast, Markey & Dillon, 2008a). The flora list for Gullewa would be expected to increase if additional hills

within the survey area are subject to detailed survey. These species counts are roughly comparable, as they do not take into account variations in season, survey area size and landform geology. When mafic landforms are excluded, 205 species were recorded from within the Gullewa survey area, which is at the lower end of the range of species estimates.

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

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

No regionally endemic taxa were identified within the study area and none are known from herbarium records, although *A. subsessilis* has been considered to be a 'near endemic'. This is far less than the nine regional endemics and near endemics which were identified by the central Talling land system survey (Markey & Dillon 2008a). Relatively fewer taxa of conservation significance and no putative new taxa were recorded in the Gullewa survey area. In comparison, 12 taxa of conservation significance and several new taxa were also identified in the central Talling land system, most of which were found in the southern portion of the survey area (Markey & Dillon 2008a). Similarly, eight priority taxa and five new taxa

were located at the Koolanooka and Perenjori Hills (Meissner & Caruso 2008c) and eight taxa of conservation significance and one new species were recorded from the Mount Gibson Range. Using the criterion of counts of rare and poorly known taxa, these adjacent ranges have relatively higher conservation values than the Gullewa landforms.

Floristic comparisons

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

This high β diversity among adjacent ranges becomes most apparent when comparing the proportion of

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

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

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

Vegetation Communities:

This current study described seven community types and subtypes for the Gullewa survey area. There is some general correspondence of these communities to some of the communities ('habitats') described for the Gabanintha, Talling, Wiluna and Watson land systems by Pringle (1998). Community type 6 would be broadly equivalent to the greenstone hill acacia shrubland on hill slopes of the Gabanintha Land System. On the Talling, Watson and Wiluna Land Systems, Community type 1

corresponds to stony ironstone mulga shrubland, and Community types 3, 4 and 5 could be equated to stony *Acacia/Eremophila* shrubland, lateritic hardpan plain mulga shrubland and stony plain bluebush mixed shrubland respectively. However, these 'habitats' of Pringle (1998) are defined by a relatively few dominant species, and do not take into account the progressive turnover of species over the wider Yalgoo and Murchison regions (Beard 1976a; Gibson *et al.* 2007; Markey & Dillon 2008a, 2008b; Meissner & Caruso 2008b, 2008c). Therefore, it is unlikely that some or all of the floristic communities described for Gullewa area will be widespread over the mapped extent of the land systems of Payne *et al.* (1998).

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

Environmental correlates

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

The association of distinct floristic communities with mafic and BIF substrates has been documented in the wider Goldfields and Midwest regions (Mabbutt *et al.* 1961; Payne *et al.* 1998) and within individual greenstone ranges of varied geology (Cole 1973; Gibson 2004a; Markey & Dillon, 2008b). Floristic communities within the Gullewa region were grouped primarily on geology, where mafic and saline communities were segregated from

BIF and laterite communities. In particular, a distinctive mafic community (Community type 6) was found on rocky hill slopes of metamorphosed basalt, dolerite and gabbro, where surface soils were found to be weakly acidic and relatively rich in metals. Soil chemical composition will reflect parent bedrock composition, particularly when it has developed in situ, and mafic rocks typically produce soils rich in Ni, Cr, Co, Mn, Fe and Mg, but low in N, Ca and P (Cole 1973; Cornelius *et al.* 2007; Britt *et al.* 2001; Gray & Murphy 2002). Clays produced from mafic rock also generally have a higher cCEC and reduced acidity as a consequence of the buffering capacity of exchangeable cations (Gray & Murphy 2002).

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

Within the BIF and lateritic communities of Gullewa, there was a clear catenary sequence of floristic communities that corresponded to an edapho-topographic gradient, and the greatest floristic differences were at the gradient extremes of upland versus lowland sites. Soil development is influenced by topographic position (Cole 1973; Hennig 1998b; Gray & Murphy 2002), and soils of the Gullewa upland communities (Community types 1 and 2) were skeletal, strongly acidic (c. pH 4.5), with low concentrations of exchangeable cations and reduced trace mineral concentrations, all of which are likely to be a consequence of both prolonged weathering and leaching of soils and bedrock (Ben-Shahar 1990; Cole 1973; Cornelius *et al.* 2007; Tiller 1962). Both underlying composition and prolonged weathering may also account for elevated levels of iron, the insoluble oxides of which remain in weathered rocks and laterites (Anand 2001; Brand & Butt 2001; Britt *et al.* 2001; Cornelius *et al.* 2007; Foulds 1993; Tiller 1962). Relatively high levels of phosphate have been recorded from other soils from BIF outcrops in the Yilgarn (Gibson & Lyons 2001b; Foulds 1993), which are notably higher than for other

soils in southwest Australia (Foulds 1993). Both deficiencies in basic cations and relatively elevated levels of sulfur may lead to more acidic soils given the reduced capacity for soil buffering and the production of sulfates (Gray & Murphy 2002; Slattery *et al.* 1999). What little volumes of surface soils were available were found to be high in nitrogen and carbon, presumably because they were being enriched with a high proportion of organic material, particular from nitrogen-fixing *Acacia* species (Eldridge & Wong 2005; Foulds 1993),

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

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

Conservation

Within the Gullewa survey area, exotic plants and animals, pastoralism and mining are some of the obvious threatening processes to the communities on outcropping mafic volcanics and BIF. All survey sites were found to be relatively weed-free in terms of cover and diversity, and all 15 introduced species were annuals. The most commonly encountered naturalised species was the grass, *Pentstemonis airoides* (30 of 50 plots), followed by the parasitic vine, *Cuscuta epithymum*, and the succulent herbs, *Cleretum*

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

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

There are no areas within the Gullewa survey region which currently occur within conservation reserves, the closest being the Barnong Nature Reserve which covers woodlands and shrublands on sandy flats west of Gullewa. Barnong station has been recently acquired by Western Australian Department of Conservation for eventual incorporation in the conservation estate, but its current tenure status is unallocated crown land. There are very few reserves within the Yalgoo IBRA bioregion, and no ironstone or greenstone ranges in this wider area are protected. South-east of the Gullewa survey area, the Warriedar, Lochada and Karara pastoral leases have been

purchased with the intention for future inclusion in the conservation estate. However, mining and exploration activities are already underway or proposed for the BIF ranges within this currently unallocated crown land (Department of Industry and Resources 2007; Markey & Dillon 2008a). Given the resurgence in mining and exploration activity within the Gullewa survey area, it is recommend that proposals are both carefully assessed and that industry adopts best practise measures to minimise impacts on the conservation-listed taxa, geographically restricted communities and on the general landscape.

ACKNOWLEDGEMENTS

The assistance of various station managers in accessing their respective pastoral leases is gratefully acknowledged: Robert and Kathryn Mitchell (Barnong Station), George and Pat Bennett (Mellenbye Station) and Max Martin (Bunnawarra Station). Soil analyses were conducted by David Allen and Katrina Walton at the Chemistry Centre of Western Australia. The following visitors, volunteers and staff at the Western Australian Herbarium are thanked for their assistance with species identifications; L. Cobb, N. Gibson, M. Hislop, M. Langley, G. Keighery, B. Maslin, F. Obbens, B. Rye, M. Trudgen, S. van Leeuwen, A. Williams and P. Wilson. Neil Gibson provided comments on early drafts of the manuscript and guidance on survey methodology and statistical analyses, and two anonymous reviewers provided further critique and improvements on this manuscript. Flora collection permits were issued by the Western Australian Department of Environment and Conservation. This project was funded by the Department of Environment and Conservation, under the auspices of the Biodiversity Conservation Initiative (BIC) of the Saving Our Species (SOS) Program.

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APPENDIX 1

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

Adiantaceae

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

Aizoaceae

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

Amaranthaceae

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

Anthericaceae

Thysanotus manglesianus
Thysanotus pyramidalis

Apiaceae

Daucus glochidiatus
Trachymene ornata

Asclepiadaceae

Cynanchum floribundum
Marsdenia australis
Marsdenia graniticola
Rhyncharrhena linearis

Asteraceae

Brachyscome cheilocarpa
Brachyscome ciliocarpa
Calocephalus multiflorus
Calotis hispidula
Calotis multicaulis
Cephalopterum drummondii
Chthonocephalus pseudevax
Dielitzia tysonii
Gnephosis arachnoidea
Helipterum craspedioides
*Hypochaeris glabra**
Isoetopsis graminifolia
Lemooria burkittii
Millotia myosotidifolia
Olearia humilis
Olearia pimeleoides
Olearia stuartii
Podolepis canescens
Podolepis capillaris
Podolepis kendallii
Podolepis lessonii
Podotrochea gnaphalioides

Rhodanthe battii
Rhodanthe chlorocephala subsp. *splendida*
Rhodanthe maryonii
Schoenia cassiniana
Schoenia filifolia
*Sonchus oleraceus**
*Urospermum picroides**
Vittadinia humerata
Waitzia acuminata var. *acuminata*

Boraginaceae

Halgania cyanea
Trichodesma zeylanicum

Boryaceae

Borya sphaerocephala

Brassicaceae

*Sisymbrium erysimoides**

Caesalpiniaceae

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

Caryophyllaceae

*Petrorhagia dubia**
*Spergula pentandra**

Casuarinaceae

Allocasuarina acutivalvis subsp. *prinsepiana*

Chenopodiaceae

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

Sclerolaena fusiformis
Sclerolaena gardneri
Sclerolaena microcarpa

Crassulaceae

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

Cupressaceae

Callitris collumellaris

Cuscutaceae

*Cuscuta epithymum**

Dasyogonaceae

Chamaexeros macranthera

Droseraceae

Drosera macrantha

Euphorbiaceae

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

Geraniaceae

Erodium cygnorum

Goodeniaceae

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

Haloragaceae

Haloragis trigonocarpa

Lamiaceae

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

Lobeliaceae

Lobelia heterophylla

Malvaceae

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

Mimosaceae

Acacia andrewsii
Acacia aneura var. cf. *aneura*
Acacia aneura var. cf. *microcarpa*
Acacia aneura var. cf. *tenuis*
Acacia aneura var. cf. *argentina*
Acacia aneura var. nov. (PERTH 07557671)
Acacia aneura var. nov. (PERTH 07557698)
Acacia aneura x *craspedocarpa*

Acacia anthochaera
Acacia aulacophylla
Acacia burkittii
Acacia effusifolia
Acacia colletioides
Acacia eremaea
Acacia erinacea
Acacia exocarpoides
Acacia grasbyi
Acacia incognita
Acacia microcalyx
Acacia ramulosa var. *ramulosa*
Acacia sclerosperma subsp. *sclerosperma*
Acacia umbraculiformis
Acacia speckii
Acacia subsessilis
Acacia tetragonophylla

Myoporaceae

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

Myrtaceae

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

Papilionaceae

Glycine canescens
Mirbelia bursarioides
Swainsona oliveri

Phormiaceae

Dianella revoluta

Pittosporaceae

Bursaria occidentalis
Cheiranthra filifolia var. *simplicifolia*
Pittosporum angustifolium

Plantaginaceae

Plantago aff. *hispida*

Poaceae

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

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

Polygalaceae

Comesperma integerrimum

Polygonaceae

*Acetosa vesicaria**

Portulacaceae

Calandrinia eremaea
Calandrinia granulifera
Calandrinia ptychosperma
*Portulaca oleracea**

Proteaceae

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

Rhamnaceae

Cryptandra imbricata

Rutaceae

Philotheca brucei subsp. *brucei*
Philotheca sericea

Santalaceae

Exocarpos aphyllus
Santalum spicatum

Sapindaceae

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

Solanaceae

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

Stackhousiaceae

Stackhousia muricata

Stylidiaceae

Stylidium longibracteatum

Thymelaeaceae

Pimelea forrestiana
Pimelea microcephala subsp. *microcephala*

Zygophyllaceae

Zygophyllum eremaeum
Zygophyllum lobulatum
Zygophyllum simile

APPENDIX 2

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

	Community type						
	type 1	type 2	type 3	type 4a	type 4b	type 5	type 6
Species Group A							
<i>Chilomena brownii</i>							
<i>Maireana australis</i>							
<i>Maireana planifolia</i> x <i>villosa</i>							
<i>Conosperma integerrimum</i>							
<i>Phyllanthus erwinii</i>							
<i>Acacia aneura</i> var. cf. <i>aneura</i>							
<i>Scleroloma microcarpa</i>							
Species Group B							
<i>Prostanthera patens</i>							
<i>Thysanotus mangletianus</i>							
<i>Eremophila clarkii</i>							
<i>Austrostrombosia scabra</i>							
<i>Allocasuarina acutivalvis</i> subsp. <i>princepsiana</i>							
<i>Crevinella obliquistigma</i> subsp. <i>obliquistigma</i>							
<i>Acacia excarpoides</i>							
<i>Acacia aneura</i> x <i>craspedocarpa</i>							
<i>Dianella revoluta</i>							
<i>Acacia aneura</i> var. cf. <i>tenuis</i>							
Species Group C							
<i>Mitrasacme subsp. hemperia</i>							
<i>Stylidium longibracteatum</i>							
<i>Phallophora sericea</i>							
<i>Sida chrysocalyx</i>							
<i>Prostanthera althoferi</i> subsp. <i>althoferi</i>							
<i>Thryptomena decasata</i>							
<i>Phallophora brucei</i> subsp. <i>brucei</i>							
<i>Thryptomena costata</i>							
<i>Acacia midacophylla</i>							
<i>Mirbelia busarioides</i>							
<i>Eremophila latrobei</i> subsp. <i>latrobei</i>							
<i>Hakea recurva</i> subsp. <i>recurva</i>							
<i>Somnolobum spicatum</i>							
<i>Chelidonium adiantoides</i>							
<i>Micromyrtus subpaurea</i>							
<i>Perzoonia hexagona</i>							
<i>Acacia aneura</i> var. cf. <i>microcarpa</i>							
<i>Dodonaea petiolaris</i>							
Species Group D							
<i>Eremophila pauciflora</i>							
<i>Acacia andrewsii</i>							
<i>Eremophila oppositifolia</i> subsp. <i>angustifolia</i>							
<i>Dodonaea inaequalifolia</i>							
<i>Excocarpus apiculatus</i>							
Species Group E							
<i>Senna</i> sp. <i>Mesochloa</i> (E. Bailey 1-26)							
<i>Eremophila grantii</i>							
<i>Atriplex burburyana</i>							
<i>Psilotes exaltatus</i>							
<i>Hakea pretensis</i>							
<i>Psilotes divaricatus</i> var. <i>divaricatus</i>							
<i>Acacia eremaea</i>							
<i>Scleroloma ericacantha</i>							
<i>Rhagodia drummondii</i>							
<i>Maireana pyramidata</i>							
Species Group F							
<i>Senna</i> sp. <i>Austin</i> (A. Stiel 20210)							
<i>Eremophila oldfieldii</i> subsp. <i>oldfieldii</i>							
<i>Scaevola spinosescens</i>							
<i>Solanum mammosarum</i>							
<i>Acacia burkittii</i>							
<i>Euphorbia drummondii</i>							
<i>Austrodracopis caespitosa</i>							
<i>Atriplex condonocarpa</i>							
<i>Atriplex semilunaris</i>							
<i>Maireana georgei</i>							
<i>Maireana tomentosa</i> subsp. <i>tomentosa</i>							
<i>Scleroloma diacantha</i>							
<i>Senna charlesiana</i>							
<i>Maireana cornuta</i>							
Species Group G							
<i>Hemigenia</i> cf. sp. <i>Yuma</i>							
<i>Scaevola tomentosa</i>							
<i>Eremophila platycalyx</i> subsp. <i>platycalyx</i>							
<i>Salsola tragus</i>							
<i>Austrostrombosia nodosa</i>							
<i>Senna glutinosa</i> subsp. <i>chatelainiana</i>							
<i>Dodonaea amplesima</i>							
<i>Acacia subaestiva</i>							
<i>Sida calyphymenia</i>							
<i>Pimelea forrestiana</i>							
<i>Maireana trichoptera</i>							
Species Group H							
<i>Spartothamnella tenuisiflora</i>							
<i>Rhynchospora linearis</i>							
<i>Hakea recurva</i> subsp. <i>arida</i>							
<i>Chelidonium steberti</i> subsp. <i>steberti</i>							
<i>Sida ectogama</i>							
<i>Psilotes drummondii</i> var. <i>drummondii</i>							
<i>Maireana planifolia</i>							
<i>Maireana convexa</i>							
<i>Acacia grasbyi</i>							
<i>Maireana thymoides</i>							
Species Group I							
<i>Rhagodia eremaea</i>							
<i>Abutilon cyclocarpum</i>							
<i>Enneapogon carndesensis</i>							
<i>Maireana triptera</i>							
<i>Austrostrombosia nitida</i>							
<i>Echylpama lanata</i>							
<i>Psilotes obovatus</i>							
<i>Scleroloma densiflora</i>							
<i>Solanum lasiophyllum</i>							
<i>Solanum ellipticum</i>							
<i>Cymbopogon ambiguus</i>							
<i>Acacia umbrelliformis</i>							
<i>Monochather paradoxus</i>							
<i>Acacia ramulosa</i> var. <i>ramulosa</i>							
<i>Eremophila forrestii</i>							
<i>Sida atrovienea</i>							
<i>Acacia latragonaphylla</i>							
<i>Abutilon cryptopetalum</i>							
<i>Austrostrombosia elegantissima</i>							

Table 1

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

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

Table 2

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

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

Table 3

Summary statistics (average \pm s.e.) of environmental variables for Community types of the Gullewa survey area. Differences between Community types for parameter averages (in bold) were determined using Kruskal – Wallis nonparametric analysis of variance (^{NS} indicates not significant, * indicates $p < 0.05$, ** indicates $p < 0.01$, *** indicates $p < 0.001$), with Dunn's posthoc test results indicated by letters (LSD $p < 0.05$). Parameter codes are explained in Table 1. Units for parameters; eCEC = cmol(\pm)/kg, minerals = mg/kg. Abbreviations: Rock Frag = surface rock fragment cover, Rock Max Size = maximum surface rock size category. Aspect values (radians) have been transformed into sine (EW) and cosine (NS) functions. Soil pH values are direct measures from CaCl₂ solution (i.e. soil pH_{Ca} values).

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

¹ including singleton taxa

Flora and vegetation of banded iron formations of the Yilgarn Craton: Barloweerie and Twin Peaks Greenstone Belts

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ABSTRACT

The Twin Peaks and Barloweerie Greenstone Belts are located within the Youanmi Terrane and are represented by two ranges, separated by 24km. This paper describes the flora and vegetation of these ranges and their relationship with environmental attributes. One hundred and ninety nine taxa, including 90 ephemerals and four introduced taxa, were recorded from the hills. Seven priority taxa, including one endemic, *Baeckea* sp. Mount Barloweerie (J.Z. Weber 5079), were recorded from the ranges. Hierarchical classification identified three floristic communities on the ranges. Geomorphology differentiated the communities into upland and lowland communities. Significant differences were found between soil depth, rock outcrops and surface fragments as well as some difference in trace elements. No representative areas of the Twin Peaks and Barloweerie Greenstone Belts are within Western Australian conservation estate.

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

INTRODUCTION

Banded iron formations (BIF) are ancient sedimentary rocks formed in the Archaean period approximately 3.8 to 2.5 billion years ago. Within the Yilgarn Craton, BIFs occur as relatively thin deposits associated with Archaean greenstone belts (Page 2001) and as they are more resistant to erosion, BIF form distinct ranges and hills within the region.

The Twin Peaks and Barloweerie Greenstone Belts are located in the Murchison Interim Biogeographic Regionalisation for Australia (IBRA) (Department of the Environment and Water Resources 2004), which is characterised by *Acacia aneura* low woodlands and abundant ephemerals. Within the Murchison region, the primary land use is pastoralism and the greenstone belts occur across Wooleen, Billabalong and Boolardy Stations. Wooleen and Billabalong Stations were part of the first blocks settled by 1874 and 1880, respectively, in the region along the Murchison River (Curry *et al.* 1994). The Barloweerie Greenstone Belt occurs largely within the Pia Wadjarri aboriginal reserve.

Previous vegetation surveys of ironstone ranges on the Yilgarn Craton have shown that each range supports plant communities distinct from other ironstone ranges and

often have unique and rare flora (Markey & Dillon 2008a,b; Meissner & Caruso 2008 a,b,c). The objective of this study is to describe the flora and plant communities of the banded ironstone ranges on the Twin Peaks and Barloweerie Greenstone Belts and their relationships with environmental variables, and to provide baseline information for future management.

Geology

The ironstone ranges surveyed are part of two greenstone belts, Twin Peaks and Barloweerie and occur within the Youanmi Terrane of the Yilgarn Craton (Watkins 1990). The BIF occur within the Windaning Formation, which is defined as a succession of jaspilite BIF and grey-white chert units interlayered with felsic volcanic, volcanoclastic, and volcanogenic rocks, and minor amounts of basalt (Watkins & Hickman 1990). The Windaning formation occurs throughout the Youanmi Terrane and is a distinct stratigraphic marker (Watkins & Hickman 1990).

The main exposure of BIF in the Twin Peak Greenstone Belt is represented by a range approximately 8km along a relatively low strike ridge along a northeast bearing (Fig. 1). South of this range, the exposure near Mount Hope is poor and very weathered (Baxter 1974). Within the Barloweerie Greenstone Belt, 24km to the east of the Twin Peaks belt, the ironstone is exposed in a narrow fold that forms the dominant ridge of Mount Barloweerie, the highest peak in the area (Fig. 1).

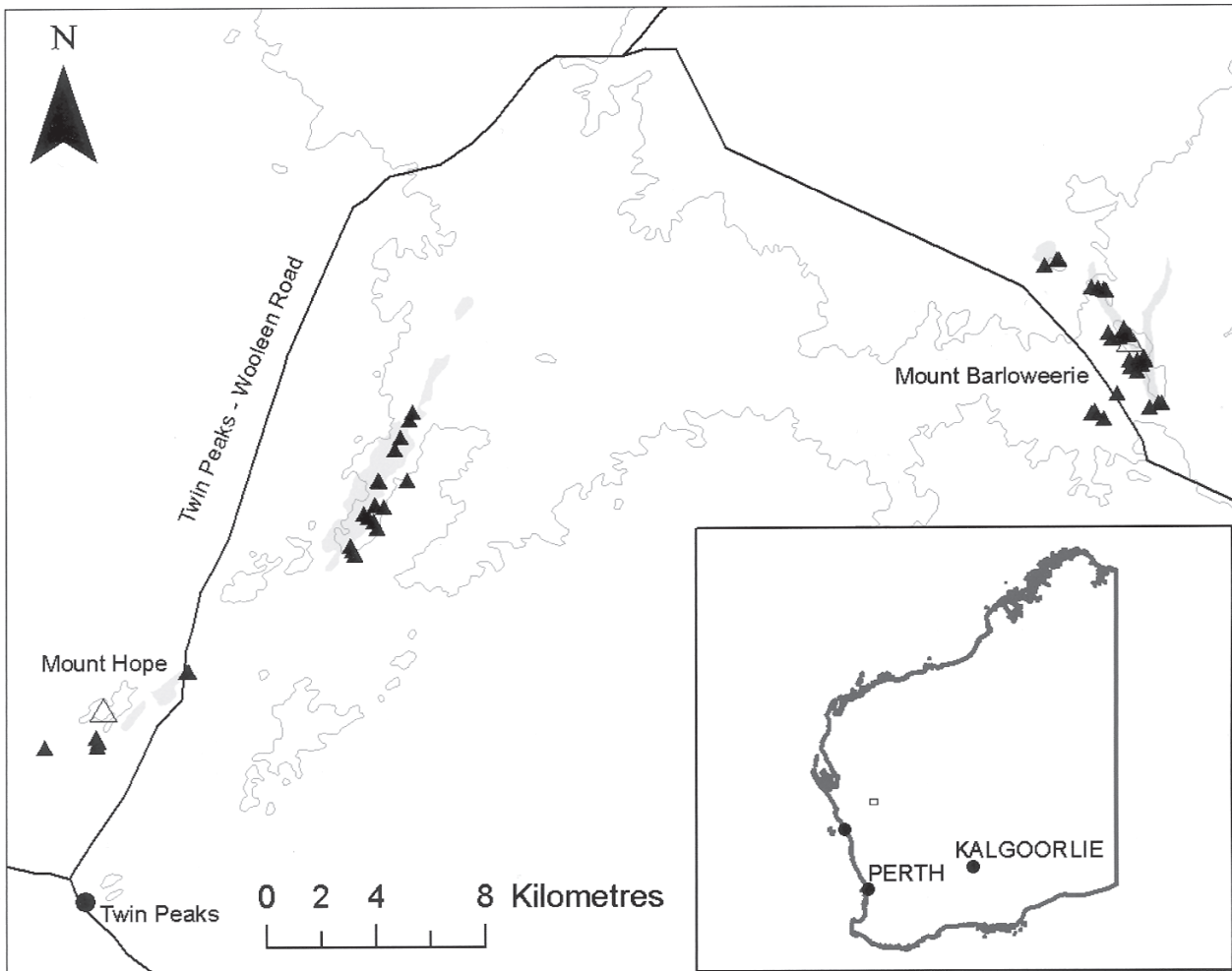


Figure 1. Location of the 51 plots (▲) established on the Twin Peaks and Mount Barloweerie Greenstone Belts. The 300 m contour is shown with the highest peaks of Mount Hope (330m) and Mount Barloweerie (428m). Shaded grey represent banded iron formation of the Windaning formation.

Climate

The climate of the region is classified as arid and characterised by hot, dry summers and mild winters. Rainfall is bimodal, with significant rainfall events occurring in winter and summer (Beard 1976). The two highest mean monthly rainfalls at Murchison Settlement (ca. 50km north of Mount Hope) occur in January and June (31.2mm and 30.5mm respectively), with highest recorded daily rainfall of 143.8mm in January 1963. Mean annual rainfall at Murchison Settlement is 245.1mm, with large variation (139.2mm 1st decile; 402.5mm 9th decile; recorded 1989 to 2009).

Summer rainfall is influenced by cyclonic activity off the north west coast of Western Australia with convectational activity bringing either isolated thunderstorms in localised areas, or widespread rainfall (Curry *et al.* 1994). In contrast, winter rainfall is associated with low pressure systems originating in the Southern Ocean. The cold fronts arising from the south west systems often weaken as they move inland and result in isolated showers and strong winds (Curry *et al.* 1994).

The highest maximum temperatures occur during summer, with the January as hottest month (mean maximum temperature 39.2 °C and mean 14.4 days above 40 °C). Winters are mild with lowest mean maximum temperature of 20.9 °C recorded for July. Temperatures rarely fall below 2 °C in winter and there is a mean minimum of 6.1 °C in July.

Vegetation

Beard (1976) mapped the ranges of the Twin Peaks and Barloweerie Greenstone Belts as several vegetation associations. The lower and colluvial slopes were mapped as *A. aneura* shrublands over *Eremophila spathulata* and *Eremophila sp. aff. compacta* shrublands. The BIF vegetation on the Twin Peaks Greenstone Belt was mapped as *A. aneura* and *Acacia quadrimarginea* open shrublands, while the vegetation on Mount Barloweerie was mapped as *A. aneura* and *Acacia* spp. (*A. ramulosa* var. *linophylla*, *A. effusifolia*) shrublands over *Thyryptomene johnsonii*, *Eremophila forrestii*, *Solanum lasiophyllum*, *Maireana*

convexa, *Eremophila* sp. over *Myriocephalus gueriniae* and *Brachyscome* sp.

In a more recent rangeland condition survey, the BIF of the Twin Peaks and Mount Barloweerie Greenstone Belt are characterised by the Gabanintha land system (Curry *et al.* 1994). Land systems are used to assess rangeland resources and describe recurring patterns of geomorphology, vegetation and soils (Curry *et al.* 1994). The Gabanintha land system is characterised as ridges, hills and footslopes of various greenstones, supporting sparse *Acacia* and other mainly non-halophytic shrublands.

Typically, the crests and upper slopes of the ranges were characterised by either Rocky Hill Mixed Shrublands or Stony Mulga Mixed Shrublands vegetation types, with the latter characterising the lower slopes and stony plains (Curry *et al.* 1994). The Rocky Hill Mixed Shrublands are dominated by *A. aneura*, *Eremophila macmillaniana* and *Ptilotus obovatus* and several species found only within this vegetation type, *Acacia grasbyi*, *Eremophila glutinosa*, *Solanum ashbyae*, *Tribulus platypterus*, *Cheilanthes austrotenuifolia* and *Spyridium* sp. (Curry *et al.* 1994). The Stony Mulga Mixed Shrubland on the stony slopes, footslopes and plains was dominated by *A. aneura*, *A. pruinocarpa*, *A. grasbyi*, *Eremophila macmillaniana*, *E. spathulata*, *E. fraseri*, *E. freelingii*, *E. spathulata*, *Solanum lasiophyllum*, *Ptilotus rotundifolius*, *Senna helmsii*, *P. obovatus* and *Ptilotus schwartzii*.

METHODS

The methodology employed in this survey follows the standard procedure used in previous vegetation surveys of other ironstone and greenstone ranges in Western Australia (Markey and Dillon 2008a,b; Meissner and Caruso 2008a,b,c). Fifty one 20 x 20 m quadrats were established on the crests, slopes and foot slopes of the Twin Peaks and Mount Barloweerie Greenstone Belts in August 2008 (Fig. 1). The quadrats were established using an environmentally stratified approach to cover the major geographical, geomorphologic and floristic variation but biased (non random) as there were restrictions in access to the range. Each quadrat was permanently marked with four steel fence droppers and its position was determined using a Global Positioning System (GPS) unit. Presence/absence of 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 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 vertical stratum of vegetation (tallest, mid- and lower) to describe the structure of plant communities following McDonald *et al.* (1990).

Twenty soil samples were collected from the upper 10 cm of the soil profile within each quadrat. The samples were bulked and the 2mm fraction extracted using the

Mehlich No. 3 procedure (Mehlich 1984). The extracted samples were analysed for B, Ca, Cd, Co, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S and Zn using an Inductively Coupled Plasma - Atomic Emission Spectrometer (ICP-AES). This procedure is an effective and cost-efficient alternative to traditional methods for evaluating soil fertility and has been calibrated for Western Australian soils (Walton & Allen 2004). The soil pH was measured in 0.01M CaCl₂ at soil to solution ratio of 1:5. Effective cation exchange capacity (eCEC) was calculated from the sum of exchangeable Ca, Mg, Na and K (Rengasamy & Churchman 1999). Exchangeable Ca, Mg, Na and K were obtained by multiplying the values of Ca, Mg, Na and K obtained from ICP-AES by a standard constant. Organic carbon was measured on soil that was ground to less than 0.15mm using Metson's colorimetric modification of the Walkley and Black method 6A1 (Metson 1956; Walkley 1947). It involved wet oxidation by a dichromate-sulfuric acid mixture, which produced enough heat to induce oxidation of the organic carbon (Rayment & Higginson 1992). Total Nitrogen was measured using the Kjeldahl method 7A2 (Rayment & Higginson 1992). The nitrogen was measured by automated colorimetry by the nitroprusside/dichloro-S-triazine modification (Blakemore *et al.* 1987) of the Berthelot indophenol reaction reviewed by Searle (1984). Electrical conductivity (EC) was based on a 1:5 soil/deionised water extract and measured by a conductivity meter at 25° C (Rayment & Higginson 1992).

Quadrats were classified on the basis of similarity in species composition using perennial species only and excluding singletons. This was to maintain consistency with previous ironstone surveys (Meissner and Caruso 2008 a,b,c). Preliminary analysis showed high correlations between the similarity matrix derived from the full data set and that with the annual species and singletons were removed ($r = 0.793$).

The quadrat and species classifications were undertaken using the Bray and Curtis coefficient followed by Flexible Unweighted pair-group mean average (UPGMA; Clarke & Gorley 2006) clustering. The Bray and Curtis coefficient is commonly used in ecological studies especially in presence/absence datasets (Belbin 1989; Clarke *et al.* 2006) while Flexible UPGMA is an effective method of recovering true group structure (Belbin & McDonald 1993). Quadrat classification was followed by similarity profile (SIMPROF) testing to determine the significance of internal group structures using permutation testing (Clarke & Gorley 2006). Indicator species and species assemblages characterising each community were determined following Dufréne and Legendre (1997) using INDVAL routine in PC-ORD (McCune and Mefford 1999). Quadrats were ordinated using semi-strong hybrid (SSH) multidimensional scaling, a non parametric approach which is not based upon the assumptions of linearity, or assuming any underlying model of species response gradients. Correlations of environmental variables were determined using Principal Component Correlation (PCC) routine and significance determined by Monte Carlo Attributes in Ordination (MCAO) routine in PATN

(Belbin 1989). PCC uses multiple linear regressions of variables in the three dimensional ordination space (Belbin 1989). Statistical relationships between quadrat groups were tested using Kruskal-Wallis non-parametric analysis of variance (Siegel 1956), followed by Dunn's multiple comparison test (Zar 1999).

Taxonomic nomenclature generally follows Paczkowska and Chapman (2000).

RESULTS

Flora

A total of 199 taxa, including 91 genera from 36 families, were recorded from the Twin Peaks and Mount Barloweerie Greenstone Belt. These were dominated by Asteraceae (27 taxa), Mimosaceae (25), Chenopodiaceae (20), Poaceae (17), Myoporaceae (11) and Caesalpiniaceae (10). The dominant genera were *Acacia* (24), *Eremophila* (nine), *Senna* (10), *Ptilotus* (eight) and *Maireana* (eight). Ninety ephemerals and four introduced taxa were recorded.

Rare and Priority Flora

Priority taxa are considered to be poorly known, potentially rare or threatened taxa (Atkins 2008). Seven priority flora, as defined by Atkins (2008), were recorded in this survey, with two new records for the study area.

- *Hemigenia tysonii* (Priority 3) is a low spinescent and divaricate shrub found on rocky slopes and flats. The taxon is distinguishable from its closest relatives by dendritic indumentum and larger bracteoles (Guerin 2008). It is only known from 13 specimens within the State Herbarium but was locally abundant on footslopes and plains in the survey area.
- *Eremophila simulans* subsp. *megacalyx* (Priority 3) is a shrub to 2m with distinct serrated leaves. It is restricted to the area around Boolardy and Wooleen stations, where this survey was undertaken. It was found growing on lateritic slopes and crests adjacent to Mount Barloweerie. It is distinguished from *E. simulans* subsp. *simulans* by larger petals and sepals with a mixture of glandular and eglandular hairs (Chinnock 2007).
- *Acacia* sp. Muggon Station (S. Patrick & D. Edinger SP 3235) (Priority 2) is a low, flat topped shrub to 1m, characterised by three nerved, erect phyllodes. It is currently known from only three specimens, growing on rocky ridges and slopes. The taxon was found at two separate locations on the Twin Peaks range on rocky outcrops.
- *Prostanthera petrophila* (Priority 1) is shrub to 1.5m with small white flowers with violet striations on the lobes. The type was collected from Mount Barloweerie with other populations found on the Twin Peaks range. Since the original description (Conn 1988), it has been found on the Weld range

(Markey & Dillon 2008b). It grows on rocky slopes and crests as well as laterite.

- *Micromyrtus placoides* (Priority 3) is a myrtaceous shrub to 2m with white flowers and a distinctive laterally swollen hypanthium (Rye 2006). It was recorded growing on the slopes and crests of Mount Barloweerie and is a new record for the area. It has been collected from other nearby ironstone ranges, namely Weld Range and Tallering Peak.
- *Baeckea* sp. Mount Barloweerie (J.Z. Weber 5079) (Priority 1) is a myrtaceous shrub to 2m. Prior to this survey, it was known from only two collections from Mount Barloweerie. This survey found new populations on the Twin Peaks Greenstone Belt growing on the mid and lower slopes of the range. This species appears to be highly restricted and endemic to the two ranges.
- *Gunniopsis divisa* (Priority 1) is a prostrate annual herb with pale white flowers. This species is distinctive with wiry branchlets and flowers with many stamens (Venning 1984). It has been collected previously from the area occurring in areas of drainage and the footslopes of ranges, and appears to be an ephemeral.

Flora of taxonomic interest

Three taxa were collected during the survey that could not be identified beyond genus, even with sufficient floral and fruiting material. Further taxonomic work and additional collections need to be made to determine their significance and status.

- *Solanum* aff. *sturtianum* (Meissner & Wright 2083) is a shrub to 2m with a distinct dense tomentum of short & long multiseriate hairs on the leaves. The specimen was collected from a single site on the crest of Mount Barloweerie. It differs from *Solanum sturtianum* in the indumentum, which has sessile porrect-stellate hairs (Symon 1981). *Solanum* aff. *sturtianum* matches another collection from the area, and identified as *S. sturtianum* (PERTH 03699218) but was noted on the specimen, at the time of the *Solanum* revision (Symon 1981), to be an atypical example. Further collections with fruit and flowers are needed to clarify the status of this taxon.
- *Hemigenia* aff. *ciliata* (Meissner & Wright 2080) is a shrub to 60 cm, with conduplicate leaves and large purple flowers. It was growing on an outcrop of banded ironstone on the midslope of the Twin Peaks range with *Mirbelia rhagodioides* and *Baeckea* sp. Mount. Barloweerie (J.Z. Weber 5079). It differs from *Hemigenia ciliata* mainly in the size of the flowers, with the calyx lobes shorter than the tube of the corolla and the corolla from *Hemigenia* aff. *ciliata* nearly three times as large. This population occurs approximately 130km north west of the nearest population of *Hemigenia ciliata*, but without further collections it is difficult to determine whether the

population is atypical and may be at an extreme end of variation.

- *Hibiscus* aff. *solanifolius* is a shrub to 60 cm found growing on the slopes of both greenstone belts. The collections are similar to those made from Robinson Ranges (Meissner *et al.* 2009) and differed from *H. solanifolius* with fewer epicalyx lobes, the calyx lobes did not exceed the capsule and the capsule had appressed silky hairs rather than tomentose. *Hibiscus solanifolius sensu stricta* is found mainly on the Central Ranges of Western Australia, near the South Australian border.

Plant communities

Prior to analysis, several varieties within *A. aneura* were combined into morphological groups, as the current taxonomy of this group is still under study. Taxa that could not be determined to subspecies level were also combined (e.g. *E. forrestii*). The final analysis included 75 perennial taxa.

Three plant communities were described for the Twin Peaks and Barloweerie Ranges. Four sites were species poor and could not be classified into a community type. The species poor sites, on the left of the dendrogram, were the first sites to be separated in the classification (Table 1). Communities 1 and 2 were the most similar to each other, with Community 1 occurring mainly on the crests, upper and mid slopes of both greenstone belts, and Community 2 found mainly on the lower slopes and footslopes, predominately on the Twin Peaks Greenstone Belt. Community 3 occurred on lateritic breakaways derived from meta-basalt, located on the Barloweerie Greenstone Belt. Table 1 shows the patterns of species occurrence across the communities and unclassified plots.

Community one – This community was found on the crest and upper slopes of both ranges and has an as isolated to sparse shrublands of *A. aneura* and *A. ramulosa* over open to sparse shrublands of *Thryptomene decussata*, *Eremophila latrobei*, *Eremophila glutinosa* and *Acacia scleroclada* over open to sparse shrublands and grasslands of *Sida* sp. Golden calyces glabrous (H.N. Foote 32), *P. obovatus*, *P. schwartzii*, *Eriachne pulchella* and *Aristida contorta*. Mean species richness was 13.4 taxa (± 0.8) per site. The indicator species were *Cheilanthes sieberi* subsp. *sieberi*, *E. latrobei* subsp. *latrobei* and *T. decussata*.

Community two – This community occurred mainly on the lower slopes and footslopes of the Twin Peaks Greenstone Belt. It is characterised by open to sparse shrublands of *A. aneura* and *A. ramulosa* over open to sparse shrublands of *Acacia tetragonophylla*, *Senna artemisioides* subsp. *helmsii*, *Senna* sp. Meekathara (*E. Bailey* 1–26), *Eremophila* spp. (*E. macmillaniana*, *E. simulans* and *E. glutinosa*) over mid-dense to open forbland and grassland of *P. obovatus*, *Aristida contorta* and *Eriachne pulchella*. Mean species richness was 14.3 taxa (± 0.8) per site. The indicator species were *S. artemisioides* subsp. *helmsii*, *Sida ectogama*, *Acacia aneura* subsp. *alata*, *E. galeata* and *Maireana triptera*.

Community three – This community occurred on laterite breakaways surrounding Mount Barloweerie and is described as open to sparse shrublands of *A. aneura* and *A. aulacophylla* over open to sparse shrublands of *Philotheca sericea* over sparse shrublands and forblands of *P. schwartzii* and *Stylidium longibracteatum*. The mean species richness was 12.2 taxa (± 1.5) per site and indicator species were *A. aulacophylla*, *Stylidium longibracteatum*, *Philotheca sericea* and *Acacia* aff. *sibirica*.

Environmental variables

Non-parametric analysis found four of the eighteen soil attributes (Table 2) and seven of the twelve site attributes (Table 3) were significantly different between vegetation communities. Community 1, the upland sites found on both greenstone belts, occurred on less acidic soils than Community 3 and sites with higher organic carbon and iron content than Community 2. This community occurred on stony sites with greater cover of exposed bedrock, and as consequence, the soils were shallower.

The lowland community (Community 2) occurred mainly on the Twin Peaks Greenstone Belt, and frequently on the footslopes and lower slopes. This community had less acidic and deeper soils than Communities 1 and 3. The soil of Community 2 was lower in organic carbon and iron than Community 1 and higher in a several trace elements, boron, cobalt and manganese, than Community 3. The community occurred on gentle slopes with lower surficial rock, smaller coarse fragments.

Community 3, found on lateritic breakaways, had the greatest cover of surficial rock and shallowest soil. These soils were the most acidic and had the highest concentration of iron of all communities but lowest concentration of boron. The sites assigned to Community 3 occurred on gentle slopes with the highest cover of bare soil.

Three dimensional SSH ordination (stress = 0.2228; Fig. 2) show similar patterns to univariate analysis. Communities 1 and 2 are clearly separated on the ordination (Fig. 2a & 2c), with Community 3 intermediate between the two. From the PCC, rock outcrop abundance, coarse fragment size, steeper slopes, higher iron, organic carbon and nitrogen concentrations were higher in Community 1 and lower in Community 2 (Fig. 2b & 2d) confirming the results of the univariate analysis.

DISCUSSION

Flora

Species richness of the Twin Peaks and Barloweerie Greenstone Belt was similar to other ironstone ranges, Jack Hills (208 taxa; Meissner & Caruso 2008a) and the Weld Range (239 taxa; Markey & Dillon 2008b). Both surveys occurred following an above average rainfall that resulted in a high abundance of ephemeral taxa. Prior to the current survey approximately 60mm of rain was recorded at Murchison Settlement and abundant

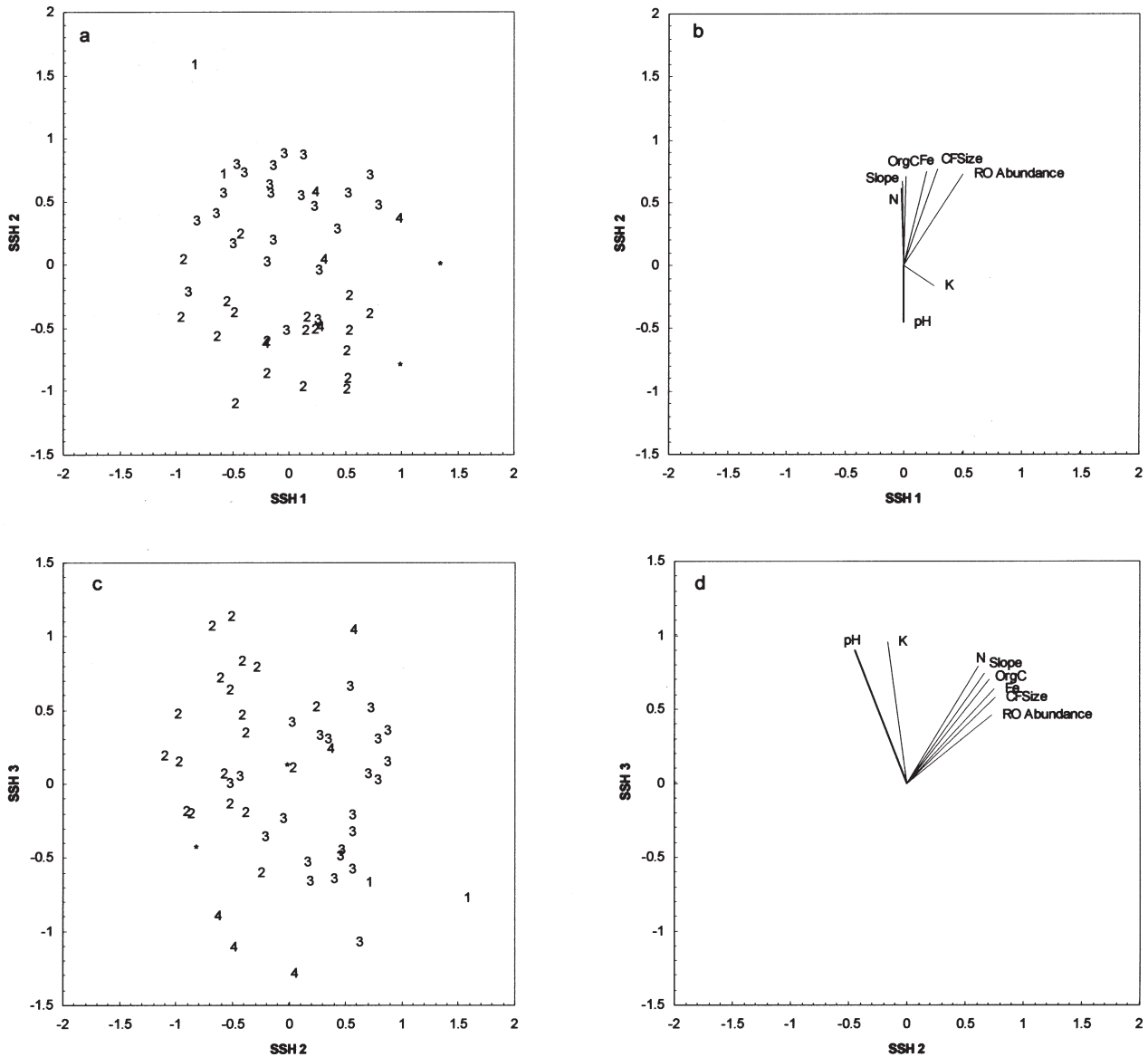


Figure 2. Three dimensional SSH ordination of the 51 quadrats established on Twin Peaks and Barloweerie Greenstone Belts. The three communities are shown and lines represent the strength and direction of the best fit linear correlated variables ($P < 0.05$).

ephemerals were recorded. Ephemerals comprised approximately 44% of the taxa recorded in this survey with the majority belonging to Asteraceae, a pattern typical of winter rainfall in the Murchison (Mott 1972).

Endemism and high occurrence of priority taxa are characteristic of ironstone ranges within the Yilgarn Craton (Gibson *et al.* 2007). In this survey, high numbers of priority taxa were recorded from the ranges, with the highest number from Mount Barloweerie. As well as being a priority taxon, *Baeckea* sp. Mount Barloweerie (J.Z. Weber 5079) is also endemic to the ranges. Originally this species was only found on Mount Barloweerie but several other collections were made from the Twin Peaks Range. Two ironstone and regional endemics were also recorded, namely *Mircomyrtus placoides* and *Prostanthera*

petrophila. Endemism associated with the arid ranges has been hypothesised to act as evidence of refugia during periods of climatic change (Byrne 2008).

Vegetation

These three communities in this survey were determined by geomorphology which in turn influenced soil properties. The two main communities occurred in different positions in the landscape, upland (Community 1) and lowland (Community 2), with Community 3 found only on laterite. The upland communities had skeletal soil and higher cover of exposed bedrock, while the lowland communities had deeper soils and little to no surficial rock. A soil moisture gradient, which was not measured in this

survey, may contribute to the distribution of the communities, where the more skeletal soil found on the upland community will retain little water in comparison to deeper soils in the lowland community.

In addition to a possible soil moisture gradient, there were some differences in the concentration of several trace and mobile elements between the upland and lowland communities. With weathering, the mobile elements in the soil are leached from the crests and enrich the lower slopes (Ben-Shahar 1990). This is consistent with the soil chemistry at each community; boron, cobalt and manganese were highest in Community 2 (lowland) and lowest in Community 3 (upland). Differences between upland and lowland communities have been observed on other ironstone ranges (Meissner & Owen, in review a) and in the catenas of Eastern Transvaal in South Africa and was attributed to soil nutrients (Ben-Shahar 1990). The laterite community (Community 3) was also lower in some mobile elements and higher in iron, a characteristic of the laterite communities, which are the product of extensive weathering in the Tertiary (Cornelius *et al.* 2007; Britt *et al.* 2001).

The main communities found on the ranges roughly correspond to the Rocky Hill Mixed Shrublands and Stony Mixed Mulga Shrublands vegetation types (Curry *et al.* 1994). The descriptions are generalised however it is difficult to make a precise comparison. These vegetation descriptions have been applied to other ironstone ranges on the Yilgarn, such as the nearest ranges, Wolla Wolla and Wadgingarra Hills, 50km south of Twin Peaks (Markey & Dillon in review). The main community from Markey & Dillon (in review) occurred on the crests and upper slopes of the hills and was typified by the presence of *Sida ectogama*, *Acacia umbraculiformis*, *Sida* sp. Golden calyces glabrous, *Hakea recurva* subsp. *arida*, *Arthropodium dyeri* and *Thryptomene decussata*. Some similarities exist between the Markey & Dillon (in review) community and the upland community in this survey, but several of its indicator species are absent *ie. A. umbraculiformis*, *Hakea recurva* subsp. *arida*, *Arthropodium dyeri*. The species turnover, even over a distance of 50km, is characteristic of the ranges within the Yilgarn (Meissner & Owen, in review b).

Conservation

The high number of endemic and priority taxa present on these ranges, especially on Mount Barloweerie, makes the ranges an important area for conservation. The majority of the Twin Peaks range occurs on a single pastoral lease while the bulk of Mount Barloweerie occurs within the Pia Wadjari Aboriginal Reserve. Currently none of the ranges occur within conservation estate,

ACKNOWLEDGEMENTS

We would like to thank: David Pollock of Wooleen Station, Peter Jeffries of Billabalong station and the Pia Wadjari Aboriginal Community for allowing access to the

properties; Katrina Walton, WA Chemcentre for Soil Analysis; the staff at the Western Australian Herbarium, especially Karina Knight; Bruce Maslin, Rob Davies and Paul Wilson for their taxonomic expertise. Stephen van Leeuwen and Neil Gibson are also thanked for their advice and support. Permits for flora collection were issued by the Western Australian Department of Environment and Conservation. This project is part of the Biodiversity Conservation Initiative (BCI) of the Saving Our Species (SOS) Program, and has been funded by the Department of Environment and Conservation, Western Australia.

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APPENDIX

Floristic list for Twin Peaks and Barloweerie Greenstone Belts, including all taxa from the sampling quadrats and adjacent areas. Nomenclature follows Paczkowska and Chapman (2000). P1, P2 and P3 represent conservation status as per Atkins (2008) * introduced taxa

Adiantaceae

Cheilanthes brownii
Cheilanthes sieberi subsp. *sieberi*

Aizoaceae

Cleretum papulosum
Gunniopsis divisa P1
Tetragonia cristata
Tetragonia diptera

Amaranthaceae

Ptilotus aevroides
Ptilotus gaudichaudii var. *gaudichaudii*
Ptilotus gaudichaudii var. *parviflorus*
Ptilotus helipteroides
Ptilotus macrocephalus
Ptilotus obovatus
Ptilotus polystachyus var. *polystachyus*
Ptilotus schwartzii

Anthericaceae

Thysanotus manglesianus
Thysanotus speckii

Apiaceae

Trachymene cyanopetala
Trachymene ornata
Trachymene pilbarensis

Asclepiadaceae

Marsdenia australis
Rhyncharrhena linearis

Asteraceae

Brachyscome cheilocarpa
Brachyscome cillocarpa
Calocephalus multiflorus
Calotis hispidula
Calotis multicaulis
Cephalopterum drummondii
Ceratogyne obionoides
Chthonocephalus pseudevax
Dielitzia tysonii
Erymophyllum ramosum subsp. *ramosum*
Gilruthia osbornei
Gnephosis arachnoidea
Helipterum craspedioides
Lawrencella rosea
Lemooria burkittii
Myriocephalus guerinae
Olearia stuartii
Podolepis canescens
Podolepis gardneri
Pogonolepis stricta
Rhodanthe battii
Rhodanthe charsleyae
Rhodanthe citrina
Rhodanthe floribunda
Rhodanthe maryonii
Schoenia cassiniana
Waitzia acuminata var. *acuminata*

Boraginaceae

Trichodesma zeylanicum var. *grandiflorum*

Brassicaceae

Lepidium oxytrichum
Stenopetalum anfractum

Caesalpinaceae

Senna artemisioides subsp. *filifolia*
Senna artemisioides subsp. *helmsii*
Senna artemisioides subsp. x *sturtii*
Senna charlesiana
Senna glaucifolia
Senna glutinosa subsp. x *luerssenii*
Senna sp. Austin (A. Strid 20210)
Senna sp.
Senna sp. Meekatharra (E. Bailey 1-26)
Senna stricta x *artemisioides* ssp. *petiolaris*
(E.N.S. Jackson 2888)

Chenopodiaceae

Atriplex codonocarpa
Dysphania glomulifera subsp. *eremaea*
Dysphania melanocarpa forma *melanocarpa*
Dysphania rhadinostachya subsp. *inflata*
Dysphania rhadinostachya subsp. *rhadinostachya*
Enchylaena sp.
Enchylaena tomentosa var. *tomentosa*
Maireana camosa
Maireana convexa
Maireana georgei
Maireana planifolia
Maireana sp.
Maireana thesioides
Maireana triptera
Maireana villosa
Rhagodia eremaea
Salsola australis
Sclerolaena densiflora
Sclerolaena eriacantha
Sclerolaena gardneri

Colchicaceae

Wurmbea inframediana

Crassulaceae

Crassula colorata var. *acuminata*

Cuscutaceae

**Cuscuta epithymum*
**Cuscuta planiflora*

Euphorbiaceae

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

Frankeniaceae

Frankenia laxiflora

Geraniaceae

- Erodium cygnorum*
Erodium sp. (Meissner & Wright 2273)

Goodeniaceae

- Brunonia australis*
Goodenia berardiana
Goodenia kingiana
Goodenia macroplectra
Goodenia occidentalis
Goodenia pinnatifida
Scaevola spinescens
Velleia hispida

Haloragaceae

- Haloragis odontocarpa*
Haloragis odontocarpa forma *octoforma*
Haloragis odontocarpa forma *pterocarpa*
Haloragis odontocarpa forma *rugosa*
Haloragis trigonocarpa

Lamiaceae

- Hemigenia* aff. *ciliata* (Meissner & Wright 2080)
Hemigenia tysonii P3
Prostanthera petrophila P1
Spartothamnella teucriflora

Malvaceae

- Abutilon cryptopetalum*
Abutilon oxycarpum
Hibiscus aff. *solanifolius* (Meissner & Wright 2307)
Hibiscus gardneri
Hibiscus sp.
Sida ectogama
Sida sp. dark green fruits (S. van Leeuwen 2260)
Sida sp. Golden calyces glabrous (H.N. Foote 32)

Mimosaceae

- Acacia* aff. *sibirica* (Meissner & Wright 2320)
Acacia aneura var. cf. *alata* (narrow phyllode variant) (BRM9058)
Acacia aneura var. cf. *argentea* (short phyllode variant) (BRM9300)
Acacia aneura var. *alata* (Fairman 238)
Acacia aneura var. *alata* (narrow phyllode variant) (BRM 9058)
Acacia aneura var. *alata/microcarpa* (BRM 9083)
Acacia aneura var. *argentea* (narrow phyllode variant) (BRM 9745)
Acacia aneura var. *fuliginosa*
Acacia aneura var. *microcarpa* (BRM 9794)
Acacia aneura var. *microcarpa* (broad, incurved phyllode variant) (BRM 9929)
Acacia aulacophylla
Acacia citrinoviridis
Acacia craspedocarpa
Acacia cuthbertsonii subsp. *cuthbertsonii*
Acacia ermaea
Acacia grasbyi
Acacia pruinocarpa
Acacia ramulosa var. *linophylla*
Acacia ramulosa var. *ramulosa*
Acacia rhodophloia
Acacia scleroclada
Acacia sp.
Acacia sp. Muggon Station (S. Patrick & D. Edinger SP 3235) P2
Acacia tetragonophylla

Myoporaceae

- Eremophila clarkei*
Eremophila forrestii subsp. *forrestii*
Eremophila forrestii subsp. *hastieana*
Eremophila galeata
Eremophila georgei
Eremophila glutinosa
Eremophila latrobei subsp. *latrobei*
Eremophila macmillaniana
Eremophila simulans subsp. *megacalyx* P3

Myrtaceae

- Aluta aspera* subsp. *hesperia*
Baeckea sp. Mount Barloweerie (J.Z. Weber 5079)
P1
Calytrix sp. Paynes Find (F. & J. Hort 1188)
Micromyrtus placoides P1
Micromyrtus sulphurea
Thryptomene decussata

Papilionaceae

- Mirbelia rhagodioides*

Poaceae

- Aristida contorta*
Austrostipa nitida
Austrostipa scabra
Austrostipa trichophylla
Cymbopogon ambiguus
Enneapogon caeruleus
Eragrostis dielsii
Eragrostis lanipes
Eragrostis pergracilis
Eriachne aristidea
Eriachne pulchella
Monachather paradoxus
Paspalidium basicladum
**Pentaschistis airoides* subsp. *airoides*
**Rostraria pumila*
Thyridolepis multiculmis

Portulacaceae

- Calandrinia* cf. *eremaea*
Calandrinia cf. *polyandra*
Calandrinia cf. *translucens*
Calandrinia creethae
Calandrinia ermaea complex
Calandrinia sp. Bullardoo (F. Obbens & F. Hort FO 57/04)
Calandrinia sp. The Pink Hills (F. Obbens FO 19/06)
Portulaca oleracea

Proteaceae

- Grevillea berryana*
Hakea recurva subsp. *arida*

Rubiaceae

- Psydrax suaveolens*
Philothea brucei subsp. *brucei*
Philothea sericea

Santalaceae

- Santalum spicatum*

Sapindaceae

- Dodonaea pachyneura*
Dodonaea petiolaris

Solanaceae

- Nicotiana rosulata* subsp. *rosulata*
- Nicotiana simulans*
- Solanum* aff. *sturtianum* (Meissner & Wright 2083)
- Solanum lasiophyllum*
- Solanum nummularium*

Stackhousiaceae

- Stackhousia muricata*

Stylidiaceae

- Stylidium longibracteatum*

Zygophyllaceae

- Tribulus astrocarpus*
- Tribulus forrestii*
- Tribulus suberosus*
- Zygophyllum eichleri*

Table 1

Sorted two-way table of quadrats established on the Twin Peaks and Barloweerie Greenstone Belt showing species by community type. Taxa shaded grey within a community are indicator species determined by Dufréne and Legendre (1997) ($p < 0.05$).

Species	One	Two	Three	*	*	*
<i>Abutilon cryptopetalum</i>						
<i>Austrostipa scabra</i>						
<i>Calytrix</i> sp. Paynes Find (F. & J. Hort 1188)						
<i>Cymbopogon ambiguus</i>						
<i>Acacia scleroclada</i>						
<i>Hibiscus</i> aff. <i>solanifolius</i>						
<i>Abutilon oxycarpum</i>						
<i>Rhagodia eremaea</i>						
<i>Senna artemisioides</i> subsp. <i>helmsii</i>						
<i>Acacia citrinoviridis</i>						
<i>Acacia pruinocarpa</i>						
<i>Austrostipa trichophylla</i>						
<i>Euphorbia tannensis</i> subsp. <i>eremophila</i>						
<i>Acacia aneura</i> var. <i>microcarpa</i>						
<i>Eremophila glutinosa</i>						
<i>Acacia ramulosa</i>						
<i>Monachather paradoxus</i>						
<i>Ptilotus obovatus</i>						
<i>Solanum lasiophyllum</i>						
<i>Ptilotus schwartzii</i>						
<i>Acacia tetragonophylla</i>						
<i>Sida</i> sp. dark green fruits (S. van Leeuwen 2260)						
<i>Maireana planifolia</i>						
<i>Sclerolaena densiflora</i>						
<i>Sida</i> <i>ectogama</i>						
<i>Cheilanthes sieberi</i> subsp. <i>sieberi</i>						
<i>Eremophila latrobei</i> subsp. <i>latrobei</i>						
<i>Thryptomene decussata</i>						
<i>Prostanthera petrophila</i>						
<i>Acacia aulacophylla</i>						
<i>Stylidium longibracteatum</i>						
<i>Philotheca sericea</i>						
<i>Dodonaea pachyneura</i>						
<i>Baeckea</i> sp. Mount Barloweerie (J.Z. Weber 5079)						
<i>Sclerolaena ericantha</i>						
<i>Maireana villosa</i>						
<i>Philotheca brucei</i> subsp. <i>brucei</i>						
<i>Acacia</i> aff. <i>sibirica</i>						
<i>Aluta aspera</i> subsp. <i>hesperia</i>						
<i>Thysanotus manglesianus</i>						
<i>Eremophila simulans</i>						
<i>Sida</i> sp. Golden calyces glabrous (H.N. Foote 32)						
<i>Eragrostis lanipes</i>						
<i>Senna glaucifolia</i>						
<i>Maireana convexa</i>						
<i>Maireana georgei</i>						
<i>Thyridolepis multiculmis</i>						
<i>Eremophila clarkei</i>						
<i>Grevillea berryana</i>						
<i>Acacia aneura</i> var. <i>alata</i>						
<i>Eremophila galeata</i>						
<i>Acacia cuthbertsonii</i> subsp. <i>cuthbertsonii</i>						
<i>Maireana thesioides</i>						
<i>Scaevola spinescens</i>						
<i>Senna artemisioides</i> subsp. <i>x sturtii</i>						
<i>Micromyrtus sulphurea</i>						
<i>Senna</i> sp. Austin (A. Strid 20210)						
<i>Austrostipa nitida</i>						
<i>Maireana triptera</i>						
<i>Senna</i> sp. Meekatharra (E. Bailey 1-26)						
<i>Spartothamnella teucriflora</i>						
<i>Maireana carmosa</i>						
<i>Sclerolaena gardneri</i>						
<i>Acacia grasbyi</i>						
<i>Hakea recurva</i> subsp. <i>arida</i>						
<i>Eremophila macmillaniana</i>						
<i>Micromyrtus placoides</i>						
<i>Acacia aneura</i> var. <i>argentea</i>						
<i>Acacia</i> sp. Muggon Station (S. Patrick & D. Edinger SP 3235)						
<i>Eremophila georgei</i>						
<i>Acacia rhodophloia</i>						
<i>Cheilanthes brownii</i>						
<i>Dodonaea petiolaris</i>						
<i>Eremophila forrestii</i>						
<i>Marsdenia australis</i>						

Table 2

Mean values for soil attributes (measured in mg/kg except pH and ECEC) by plant community type. Differences between ranked values tested using Kruskal –Wallis non–parametric analysis of variance and differences between communities determined using Dunn's post–hoc comparison. Standard error in parentheses. a and b represent significant differences between community types at $p < 0.05$ (n = number of quadrats, p = probability).

	n=	Community One 23	Community Two 19	Community Three 5	P value
pH(CaCl ₂)		4.4 (0.055) ^a	4.6 (0.071) ^a	4.18 (0.18) ^b	0.0124
ECEC		1.2 (0.12)	1.4 (0.13)	1.3(0.4)	0.3145
P		38 (13)	14 (1.4)	35 (21)	0.2369
K		99 (6)	113 (6.2)	86 (26)	0.055
Mg		37 (3.1)	47 (6.3)	45 (9.8)	0.3014
Total N		0.056 (0.0037)	0.045 (0.0027)	0.054 (0.012)	0.0865
OrgC		0.62 (0.055) ^a	0.41 (0.032) ^b	0.59 (0.15) ^{ab}	0.0157
B		0.07 (0.052) ^{ab}	0.1 (0.013) ^b	0.05 (0) ^a	0.018
Ca		122 (17)	135 (16)	126 (53)	0.5022
Co		0.1 (0.02) ^b	0.29 (0.049) ^a	0.074 (0.016) ^b	0.0003
Cu		0.61 (0.023)	0.67 (0.032)	0.62 (0.049)	0.3012
Fe		67 (12) ^a	32 (1.5) ^b	71 (21) ^a	0.0006
Mn		17 (2.9) ^{ab}	21 (3.1) ^b	9.4 (5.7) ^a	0.0283
Na		12 (2)	14 (2.5)	16 (2.2)	0.3006
Ni		0.1 (0.011)	0.12 (0.013)	0.08 (0.012)	0.2201
S		8 (0.56)	7.3 (0.5)	8.8 (1.1)	0.214
Zn		1.2 (0.25)	0.91 (0.061)	1.3 (0.95)	0.113
Pb		0.49 (0.041)	0.55 (0.049)	0.42 (0.08)	0.354

Table 3

P Mean values for site attributes by plant community type; Aspect (degrees); Slope (degrees); Morphology type (1 – crest, 2 – upper slope, 3 – mid slope, 4 – lower slope, 5 – simple slope); Land type (1 – summit, 2 – hill crest, 3 – hill slope, 4 – breakaway); Disturbance (0 – no effective disturbance, 1 – no effective disturbance except grazing by hoofed animals); Maximum size of coarse fragments (CF Size) (1 – fine gravelly 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 non–parametric analysis of variance. Standard error in parentheses. a, b and c represent significant differences between community types at $P < 0.05$ (n = number of quadrats, p = probability).

	n=	Community One 23	Community Two 19	Community Three 5	P value
Aspect		186 (19) ^a	185 (17) ^a	288 (18) ^b	0.0335
Slope		4.8 (0.61) ^a	2.6 (0.66) ^b	2.4 (1.4) ^{ab}	0.0184
Morph Type		1.9 (0.23) ^a	3.4 (0.42) ^b	1.4 (0.24) ^a	0.0019
Land Type*		2.4 (0.14)	2.8 (0.10)	4.2 (1.02)	0.049
Disturbance		0.35 (0.1)	0.53 (0.12)	0.8 (0.2)	0.1552
CF_Abundance		4.3 (0.13)	3.9 (0.14)	4.6 (0.24)	0.0655
CF_Size		4.8 (0.21) ^a	3.6 (0.22) ^b	4.2 (0.58) ^{ab}	0.0043
RO_Abundance		1.9 (0.29) ^a	0.53 (0.21) ^b	2.2 (0.58) ^a	0.0012
Runoff		1.9 (0.19)	1.5 (0.23)	2 (0)	0.2894
Soil Depth		1.7 (0.13) ^b	2.3 (0.17) ^a	1 (0) ^b	0.0012
%Leaf_Litter		1.1 (0.06)	1.1 (0.072)	1 (0)	0.7583
%Bare_Ground		3.9 (0.072) ^a	3.6 (0.12) ^a	4 (0) ^b	0.0393

* post-hoc analysis not significant

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

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ABSTRACT

The Brooking Hills and the South Cook Well Greenstone Belt are banded ironstone ranges located within the Southern Cross Granite-Greenstone Terrane in the eastern Murchison Interim Biogeographic Regionalisation for Australia (IBRA) sub-region. Recent increases in the value of iron ore has made the mining of banded iron formations economically prospective. A flora and vegetation survey of on these ranges recorded 104 taxa. These included a single range extension and no flora of conservation significance. Hierarchical classification identified four communities with the main floristic difference between upper slope and crest communities (upland) and lower and colluvial slopes communities (lowland). Soil nutrients, elevation and landform were correlated with the three dimensional ordination. The ranges within the survey were floristically different to previously surveyed ranges to the north indicating a species turnover from north to south, due to decreasing aridity. Ranges are currently under mining exploration and no part of the range is within conservation estate.

INTRODUCTION

Banded iron formations (BIF) are iron rich deposits composed of alternating layers of iron and silica rich layers, formed 3.8 to 2.5 billion years ago by deposition in quiet, deep water (Page 2001). Within the Yilgarn Craton, BIFs are associated with greenstone belts, forming prominent strike ridges due to a greater resistance to erosion than the surrounding landscape. Pastoralism and mining are the main land uses within the Yilgarn Craton, with the latter focussed on gold and nickel. Recent increases in the value of iron ore have made the mining of BIF economically viable.

Previous floristic and vegetation surveys on the Yilgarn craton have been undertaken on the ironstone ranges on Cashmere Downs and the Mount Forrest-Mt Richardson area to the north of this current survey. Both surveys found unique floristic communities associated with different substrates and positions in the landscape (Meissner *et al.* 2009a, 2009b). The aim of this paper is to describe the flora and vegetation of Brooking Hills and the adjacent range on the South Cook Well Greenstone Belt and their relationships with environmental variables to provide baseline information for future management.

Geology

The Brooking Hills and the adjacent range to the west are located within the Southern Cross Granite-Greenstone domain of the Youanmi Terrane. The ranges occur on two

separate greenstone belts; the Illaara and South Cook Well Greenstone Belt (Chen 2004; Cassidy *et al.* 2006).

Brooking Hills represents the central part of the Illaara Greenstone Belt, which continues further north as the Mt Forrest-Mt Richardson area and was surveyed in 2006 (Meissner *et al.*, 2009b). The Illaara Greenstone Belt is dominated by BIF and metamorphosed mafic and ultramafic volcanic rocks (Chen 2004). Brooking Hills has two prominent parallel strike ridges of BIF and minor banded chert running north-south. Associated at the flanks of the ridges are metamorphosed mafic rock, metabasalt and quartzite, quartz metasiltsone formations (Chen 2004).

The main strike ridges of banded ironstone on the South Cook Well Greenstone Belt run in a north-south direction and occur approximately 12km to the west of Brooking Hills. Metagabbro, a coarse grained mafic rock, is commonly exposed on the flanks of the ironstone ridges or intercalated with the banded ironstone formations (Chen 2004).

Climate

The climate of the region is Semi-desert Mediterranean with a mild wet winter and hot dry summers (Beard 1990). Mean annual rainfall at Cashmere Downs Station (ca 40km west of Brooking Hills) is 252.9mm, with moderate seasonal variation over the 83 years of record (1919–2002: decile 1, 128.5mm; decile 9, 426.9mm). Mean rainfall is spread throughout the year, with little winter-summer bias. The highest maximum temperatures occur during summer (January mean maximum temperature 36°C and mean 6.2 days above 40°C). Winters are mild with lowest mean

maximum temperatures recorded for July of 17.5 °C. Temperatures occasionally fall below 0°C in winter (a mean 0.9 days below 0°C), with a mean minimum of 5.9°C in July.

Vegetation

Past surveys of the Eastern Murchison IBRA sub-region have described the dominant species in the vegetation (Beard 1976; Milewski & Dell 1992; Keighery *et al.* 1995). The vegetation associations by Beard (1976) described the Brooking Hills and South Cook Well Greenstone Belt as shrubland of *Acacia aneura* (mulga) and *Acacia quadrimarginea* scrub. Pringle *et al.* (1994) mapped land systems of the eastern goldfields, incorporating information on soils, geology and vegetation. The Brooking Hills and South Cook Well ranges were mapped as part of the Brooking Land system, which is described as prominent ridges of banded ironstone formation supporting *A. aneura* shrublands with occasional minor halophytic communities in the south east. This land system was characterised by Stony Ironstone Mulga Shrublands (SIMS), a vegetation type characterised by shrublands of *A. aneura*, *Acacia ramulosa* and *Acacia tetragonophylla* and *Eremophila* spp. (*E. fraseri*, *E. forrestii*), *Senna* spp. over shrublands of *Sida calyxhymenia*, *Solanum lasiophyllum* and *Spartothamnella teucriflora* (Pringle *et al.* 1994).

A flora and vegetation survey of the northern Illaara Greenstone Belt (Mount Forrest -Mount Richardson Range), approximately 5 km north of Mount Alfred, described seven vegetation communities (Meissner *et al.* 2009b). The most common community on the Mount Forrest – Mount Richardson range occurred on the crests and upper slopes and was described as *A. aneura*, *A. quadrimarginea*, *A. cockertoniana*, *Callitris columellaris* and *Grevillea berryana* over sparse to open shrubland of *Eremophila glutinosa*, *Drummondita microphylla*, *Thryptomene decussata*, *Baeckea* sp. Melita Station (H. Pringle 2738), *Dodonaea petiolaris*, *Aluta aspera* subsp. *hesperia* over sparse fernland of *Cheilanthes sieberi* subsp. *sieberi*.

METHODS

The Brooking Hills and the South Cook Well Greenstone Belt are located in the Murchison IBRA region on Perrinvale pastoral station, approximately 240km north-west of Kalgoorlie, adjacent to the eastern tip of Lake Barlee (Fig. 1). Fifty 20 x 20 m quadrats were established on the crests, slopes and foot slopes of ranges on Brooking Hills and South Cook Well Greenstone Belt in August 2007 (Fig. 1). The quadrats were established using an environmentally stratified approach to cover the major geographical, geomorphologic and floristic variation but biased (non random) as there were restrictions in access to the range. Each quadrat was permanently marked with four steel fence droppers and its position was determined using a Global Positioning System (GPS) unit. All vascular

plants within the quadrat were recorded and collected for later identification at the Western Australian Herbarium.

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

Twenty soil samples were collected from the upper 10cm of the soil profile within each quadrat. The soil was bulked and the 2mm fraction analysed for B, Ca, Co, Cu, Fe, K, Mg, Mn, Na, Ni, P, S and Zn using the Mehlich No. 3 procedure (Mehlich 1984). The extracted samples were then analysed using Inductively Coupled Plasma - Atomic Emission Spectrometer (ICP-AES). This procedure is an effective and cost efficient alternative to traditional methods for evaluating soil fertility and has been calibrated for Western Australian soils (Walton & Allen 2004). pH was measured in 0.01M CaCl₂ at soil to solution ratio of 1:5. Organic carbon was measured on soil ground to less than 0.15mm using Metson's colorimetric modification of the Walkley and Black method 6A1 (Metson 1956; Walkley 1947). Total Nitrogen was measured using the Kjeldahl method 7A2 (Rayment & Higgenson 1992). Electrical conductivity (EC) was based on a 1:5 soil/deionised water extract and measured by a conductivity meter at 25°C (Rayment & Higgenson 1992).

Quadrats were classified on the basis of similarity in species composition on perennial species only, to be consistent with previous studies of banded ironstone ranges (Gibson 2004 a, b). The quadrat and species classifications were undertaken using flexible Unweighted Pair-Group Mean Average (UPMGA) of Bray and Curtis similarities (? = 0; Belbin 1989). The quadrat classification was followed by similarity profile (SIMPROF) testing to determine the significance of internal group structures using permutation testing (Clarke & Gorley 2006).

Similarity percentages (SIMPER), based upon Bray Curtis similarities, was used to determine typifying species for each community. SIMPER analyses the contribution of individual species to the average similarity within groups and average dissimilarity between groups (Clarke & Warwick 2001).

Quadrats were ordinated using semi-strong hybrid (SSH) multidimensional scaling. Correlations between the environmental variables and SSH axis were determined using Principal Component Correlation (PCC) analysis. The significance of these correlations was determined by Monte-Carlo Attributes in Ordination (MCAO) routine in PATN (Belbin 1989). PCC is a routine that runs multiple linear regressions on the variables and the ordination coordinates, resulting in a vector for each variable within the ordination plot. The MCAO is a Monte-Carlo permutation test that determines the robustness of the PCC results by randomly assigning values of variables to objects and then running the PCC routine (Belbin 1989). The significance differences between quadrat groups for each environmental variable were tested

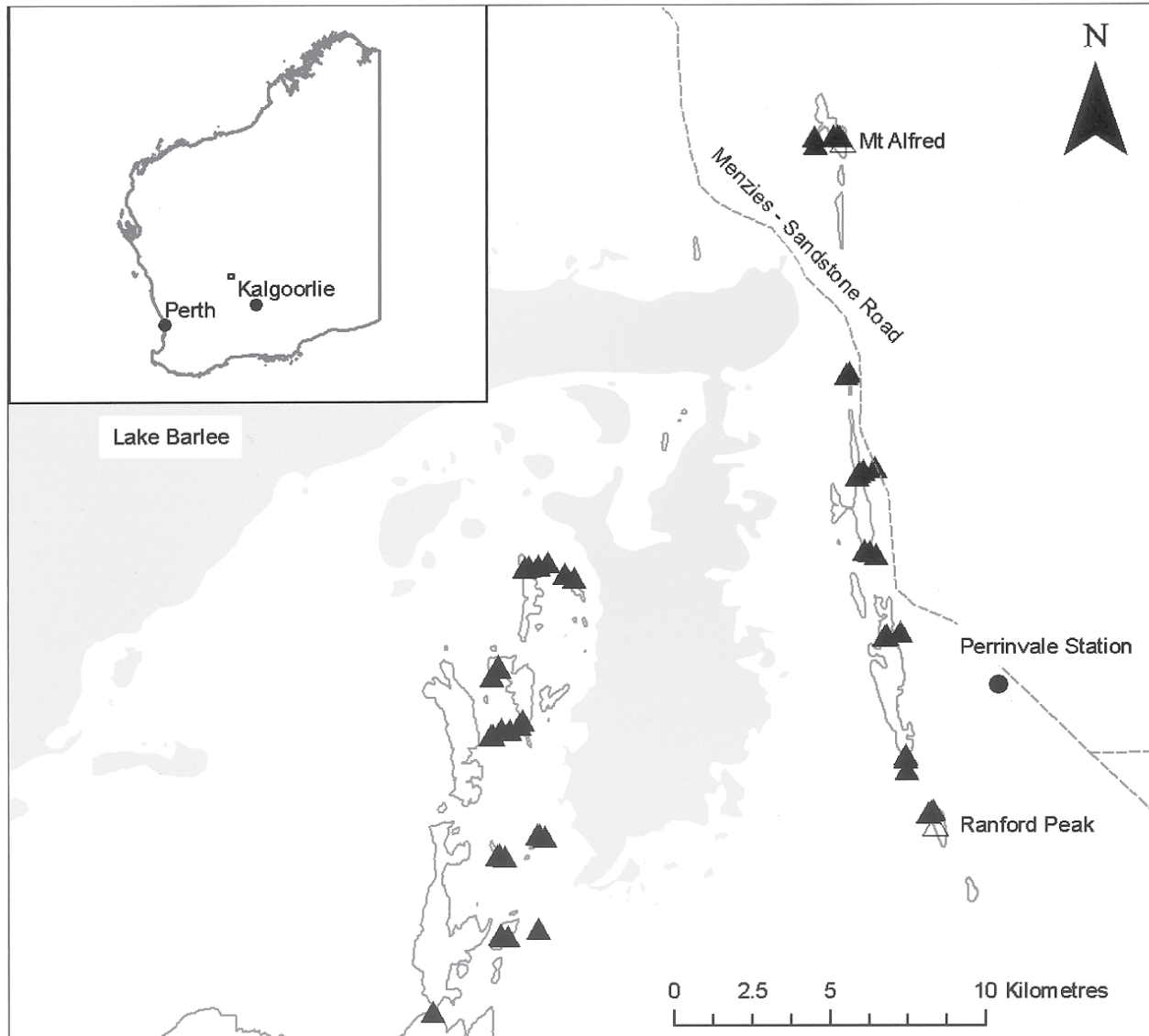


Figure 1. Location of the Brooking Hills (right) and South Cook Well greenstone belt (left) study area, showing the location of 50 sites (▲). The 440m contour is shown with the highest peaks, Mt Alfred (495m) and Ranford Peak (487m).

using Kruskal-Wallis non parametric analysis of variance (Siegel 1956), followed by non-parametric comparison (Zar 1999).

Taxonomic nomenclature generally follows Paczkowska and Chapman (2000).

RESULTS

Flora

A total of 104 taxa were recorded from the Brooking Hills and South Cook Well Greenstone Belt represented by 56 genera within 32 families. The dominant families were Caesalpiniaceae (nine taxa), Chenopodiaceae (eight), Mimosaceae (13), Myoporaceae (eight), and Poaceae (10). No flora of conservation significance and twenty two ephemerals, including one introduced species, were recorded from the ranges.

Range Extensions

A single range extension, defined as any new record more than 200km from the nearest population, was collected during the survey. *Trachymene pilosa* is an annual herb to 30cm with small white flowers and heteromorphic fruit, with one bristly and one tuberculate mericarp (Hart & Henwood 2006). The nearest population is 200km to the south. It was found growing on the midslope of South Cook Well GB in open woodland of *A. aneura* and *Grevillea berryana* over *Eremophila forrestii*.

Plant Communities

Ephemerals and singletons were removed resulting in a total of fifty one taxa used in the final analysis. Similarity profile (SIMPROF) analysis identified four significant groups ($p < 0.05$; Clarke & Warwick 2001). The first division in the dendrogram separated Community 4,

found on the lower slopes of the ranges, from Community 1, 2, and 3, indicating a greater level of floristic dissimilarity between Community 4 and the other groups. The next division occurred between Community 3, found only on Brooking Hills, from Communities 1 and 2, found on midslopes and crests of both ranges.

Community 1 represented sites found on the midslopes to crests of Brooking Hills and South Cook Well range with higher cover of surficial bedrock. It was described as open to sparse shrublands of *A. aneura*, *Acacia quadrimarginea* and *Acacia cockertoniana* over open shrublands to shrublands of *Eremophila latrobei*, *D. petiolaris*, *Dodonaea rigida*, and *Eremophila georgei* over isolated to sparse shrublands of *Eremophila georgei*, *Ptilotus obovatus* and *Sida chrysocalyx*. Typical species were *E. latrobei* subsp. *latrobei*, *A. aneura* var. cf. *microcarpa*, *E. georgei*, *Sida chrysocalyx*, *D. rigida*, *P. obovatus* and *A. quadrimarginea* (Table 1). This community had the lowest mean species richness of 12.3 taxa (± 0.4 SE) per plot.

Community 2 was found on the upper slopes and crests on Brookings Hills, with all sites except one located on Mt Alfred in the northeast of the survey area. It is described as open to sparse shrubland of *A. aneura* over open shrubland of *E. georgei*, *Philotheca brucei* subsp. *brucei* and *P. obovatus*. The typical species of this community were *D. petiolaris*, *E. georgei*, *P. obovatus* and *S. chrysocalyx* (Table 1). The species richness was 12.5 taxa (± 2.4) per plot.

Community 3 was represented by 4 sites found on slopes and a crest of Brooking Hills. It was characterised by open to sparse shrublands of *A. aneura* and *A. quadrimarginea* over sparse shrublands of *P. obovatus* and *E. latrobei* subsp. *latrobei*. The characteristic species of the community were *E. latrobei* subsp. *latrobei*, *P. obovatus*, *Solanum lasiophyllum*, *Abutilon cryptopetalum*, *A. quadrimarginea*, *A. tetragonophylla* and *C. sieberi* subsp. *sieberi* (Table 1). This community had the highest mean species richness of 13.8 (± 1.0) taxa per plot.

Community 4 was a common community encountered found on both ranges, mainly on lower and simple slopes of the ranges. It is described as open to sparse shrubland of *A. aneura*, *A. quadrimarginea*, and *A. ramulosa* var. *ramulosa* over open to sparse shrubland of *E. forrestii* subsp. *forrestii*, *Senna* spp. (*S. glaucifolia*, *S. artemisioides* subsp. *filifolia*), *D. rigida* and *E. georgei*. Typical species are *E. forrestii*, *P. obovatus*, *D. rigida*, *A. tetragonophylla*, *A. ramulosa* var. *ramulosa*, *A. aneura* var. cf. *aneura* and *Solanum lasiophyllum* (Table 1). Mean species richness is 13.6 taxa (± 0.7) per plot.

Environmental variables

Non-parametric analysis found significant differences between 12 of the 17 soil attributes, mainly differentiating Community 1 from Communities 3 and 4 (Table 2). Community 2 shows intermediate soil parameters between these communities. It occurs on intermediate soil acidity, but similar fertility to Community 1 and intermediate trace

elements. However, Community 2 had the highest phosphorus and iron soil concentrations, which were significantly different to Community 4 (Table 2).

Community 1, a common community, occurred on the most acidic sites and fertile soil (Table 3). The community had significantly higher organic carbon and total nitrogen than Community 4 but lower magnesium than Community 3. Community 1 had significantly lower concentrations of the minor trace elements, cobalt, copper, manganese and nickel than Community 3 and 4 and significantly lower concentration of iron and sulphur than Community 4 (Table 2).

All the site attributes, except land type, showed a significant difference between communities (Table 3). Similar to the results of the soil nutrients, the main differences occurred between Community 1, on the midslopes and crests, and Community 4, lower and colluvial slopes of the ranges. Community 1 occurred at higher elevations, had a greater abundance of coarse fragment, greater coarse fragment size, rock outcrop cover, steeper slopes and runoff, and shallower soils than Community 4. Community 1 sites tended to occur on crest and upper slopes while Community 4 on lower and simple slopes.

The three dimensional SSH ordination (stress = 0.1840) substantiates the univariate results (Fig. 2). Community 1 and 2, both typical of sites on upper slopes and crests of the range, occur in the upper half of Fig. 2a, and correlate with high coarse fragment abundance and size, elevation, rock outcrop abundance, iron and organic carbon are higher in the upper right quadrant of axes 1 and 2 (Fig. 2c). In contrast, Community 4, characterised sites from lower slopes, occurs separately from Community 1 and 2 and correlates with deeper soil, higher concentrations of several soil nutrients. Axes 2 and 3 show a clearer separation of the communities and that Community 3 is intermediate between Communities 1 and 4 (Fig. 2b, 2d).

DISCUSSION

Flora

A total of 104 taxa were recorded from Brooking Hills and South Cook Well Greenstone Belt, a number similar to the 116 taxa recorded on Mount Forrest -Mt Richardson range (Meissner *et al.* 2009b). However, the areas shared 42 taxa even though Brooking Hills is only 15km to the south. The low number of common taxa indicates a species turnover progressing south on the greenstone belt. Shifts in species composition have been observed on other ironstone ranges where species composition was very different between two adjacent parts of the same range (Meissner & Caruso 2008c). This north-south change in species is correlated with a gradient of decreasing aridity and increasing influence of flora from the South West Province (Beard 1976; Beard *et al.* 2000).

No endemic or taxa of conservation significance were recorded for these ranges. The paucity of endemic or

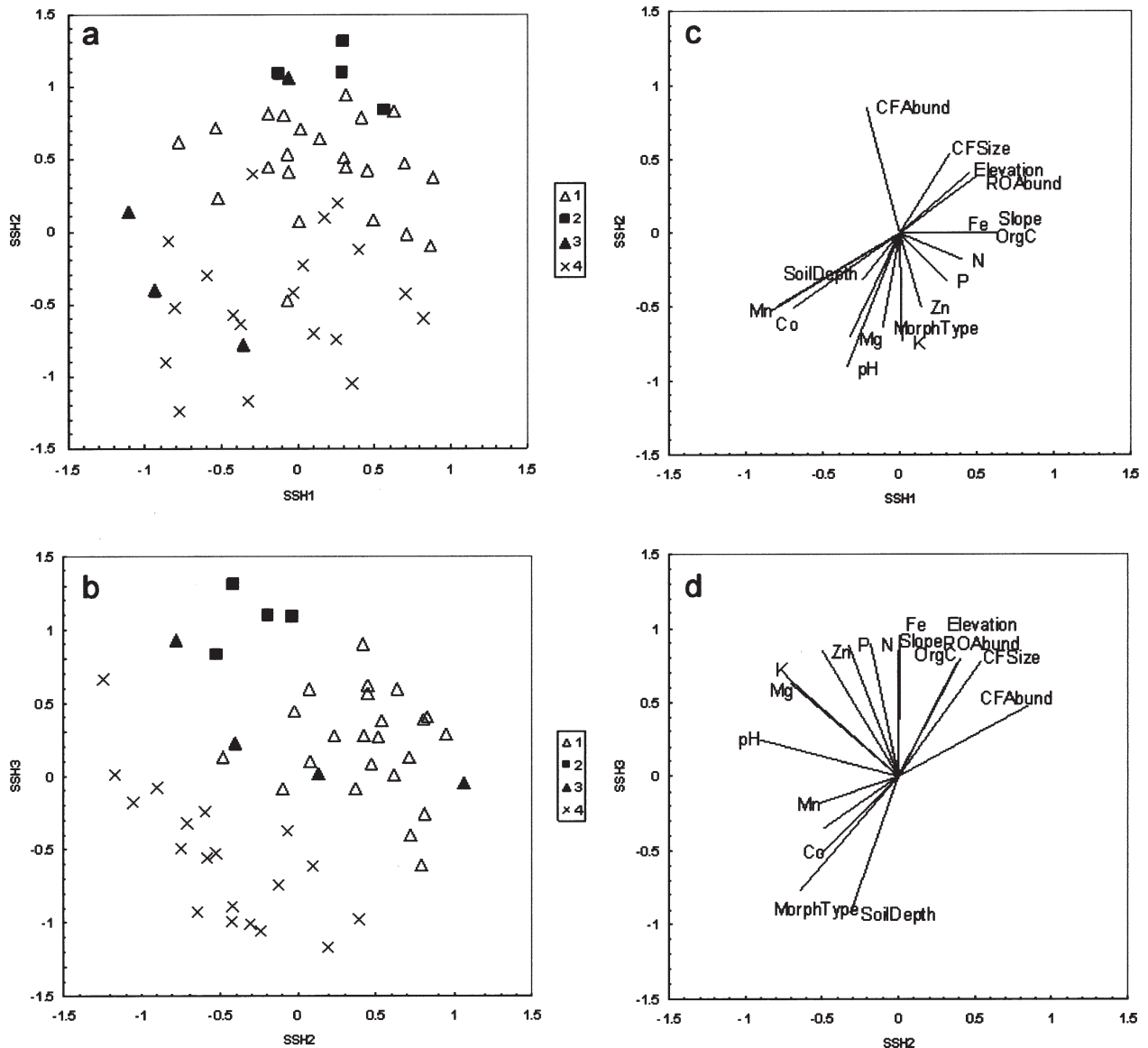


Figure 2. Three dimensional ordination showing Axis 1, 2 and 3 of the 50 quadrats established on Brooking Hills and South Cook Well greenstone belt. The four plant communities and lines showing the strength and direction of the best fit linear correlated variables ($P < 0.05$) are shown.

conservation taxa is not unusual for ironstone ranges, and low numbers have been recorded on other ranges within the Eastern Murchison (Markey & Dillon in press; Meissner *et al.* 2009b). In contrast, ranges within the South Western interzone (Beard *et al.* 2000) and Yalgoo IBRA subregion, show a high level of endemic and rare species (Gibson *et al.* 1997; Markey & Dillon 2008a; Meissner & Caruso 2008b). These latter ranges are found in areas that intergrade between Eremaeum and South West flora (Beard *et al.* 2000).

Plant Communities

This survey described four communities on the Brooking Hills and South Cook Well Greenstone Belt. Unlike the Mount Forrest – Mount Richardson Range to the north (Meissner *et al.* 2009b), there were no restricted

communities. Communities 1 and 4 were widespread, occurring on both ranges, while the remaining communities (2 & 3) were found only on Brooking Hills. These communities appear to be a continuum between the upland (Community 1) and lowland community (Community 4). Community 2, occurring on upper slopes and crests, showed floristic affinities with Community 1, also on midslopes to crests of the ranges. As well as similar soils and site parameters, Community 2 shares three characteristic species, *E. georgei*, *S. chrysocalyx* and *P. obovatus*, with Community 1. This relationship is shown in the ordination and classification, with both communities occurring close in three dimensional space. In contrast, Community 3, occurring on slopes and crest has a closer affinity to Community 4, on the lowlands. Similarly, Community 3 and 4 have similar soil nutrients, being less

acidic and higher concentrations of trace elements, and occurring lower in the landscape with deeper soils and less and smaller coarse fragments. They also shared three characteristic species, *Solanum lasiophyllum*, *A. tetragonophylla* and *Ptilotus obovatus*.

Communities 1 and 4 generally correlate to the vegetation type mapped within the Brooking Land system (Pringle *et al.* 1994). The Brooking Land system encapsulated all four landforms; ridges, hillslopes, stony plains and drainage tracts, and all, except the drainage tracts, were sampled in the survey of the Brooking Hills area. The vegetation types within these landforms were all described under one broad vegetation type: Stony Ironstone Mulga Shrublands is a broad vegetation type which encompasses the upland and lowland community types from this survey.

The main floristic difference found in this survey occurred between upland (Community 1) and lowland (Community 4) communities. This is similar to patterns found on other ironstone ranges (Markey & Dillon 2008 a, b; Meissner & Caruso 2008a, 2008b, 2008c). These floristic differences were reflected in differences in soils and site characters, though these may not necessarily drive the floristic communities. The upland community occurred at higher elevations on steeper slopes with a greater cover of surficial rock and shallower soil. Many of the mobile soil nutrients, Mg, Ca, Cu, Mn, Na, Ni and S, were all lower in upland and higher in the lowland sites, attributed to leaching and weathering in the soil (Britt *et al.* 2001).

A preliminary analysis of the floristic communities between the Mount Forrest- Mount Richardson range (Meissner *et al.* 2009b) and the ranges in this survey, found that the ranges were significantly different (ANOSIM Global R = 0.379, P < 0.01, Clarke & Warwick 2001). This indicates a rapid species turnover from north to south, confirming the differences found in the flora. The two ranges are part of the same greenstone belt but are not continuous and are separated by several breaks in the strike ridges. The Illaara Greenstone Belt continues further south, with the next expression of low strike ridges 15km south of Ranford Peak. If an additional survey was undertaken on the southern part of the Illaara Greenstone Belt further species turnover will be expected.

The difference between the north and south ranges was not found in eastern and western ranges in this survey. The communities in this survey occurred on both greenstone belts (Illara and South Cook Well) which are separated by 15km in an east-west direction. This adds support for the presence of an environmental gradient such as increasing rainfall and decreasing aridity (Beard 1976).

Conservation

The BIFs of the Brooking Hills and South Cook Well Greenstone Belt are currently under prospective mining interest. Unlike the Mount Forrest-Mount Richardson range, the ranges within this survey are not within secure Western Australian Conservation Estate.

ACKNOWLEDGEMENTS

We would like to thank the following people: Dave Allen and Katrina Walton, WA Chemcentre for Soil Analysis; Perrinvale Station for their cooperation and help during the field survey; the staff at the Western Australian Herbarium, especially Karina Knight; Rob Davies, Bruce Maslin, Frank Obbens and Barbara Rye on for their taxonomic expertise. Neil Gibson is also thanked for his advice and support. This project was funded by the Department of Environment and Conservation, Western Australia.

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APPENDIX

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

-
- Adiantaceae**
Cheilanthes brownii
Cheilanthes sieberi subsp. *sieberi*
- Amaranthaceae**
Ptilotus aevroides
Ptilotus obovatus
- Apiaceae**
Trachymene omata
Trachymene pilosa
- Asclepiadaceae**
Marsdenia australis
Rhyncharrhena linearis
- Asteraceae**
Olearia humilis
Olearia stuartii
Rhodanthe battii
Streptoglossa liatroides
- Brassicaceae**
Lepidium oxytrichum
- Caesalpiniaceae**
Senna artemisioides subsp. *filifolia*
Senna artemisioides subsp. *helmsii*
Senna artemisioides subsp. *x sturtii*
Senna cardiosperma
Senna charlesiana
Senna glaucifolia
Senna glutinosa subsp. *chatelainiana*
Senna pleurocarpa var. *pleurocarpa*
- Casuarinaceae**
Casuarina obesa
- Chenopodiaceae**
Chenopodium melanocarpum
Chenopodium saxatile
Enchylaena tomentosa var. *tomentosa*
Maireana convexa
Maireana pyramidata
Maireana suaedifolia
Rhagodia eremaea
Sclerolaena gardneri
- Cucurbitaceae**
 **Cucumis myriocarpus*
- Euphorbiaceae**
Euphorbia tannensis subsp. *eremophila*
- Geraniaceae**
Erodium crinitum
Erodium cygnorum
- Goodeniaceae**
Scaevola spinescens
- Lamiaceae**
Prostanthera althoferi intergrade
- Prostanthera althoferi*
Spartothamnella teucriflora
- Lobeliaceae**
Isotoma petraea
- Loranthaceae**
Amyema fitzgeraldii
Amyema gibberula var. *gibberula*
Amyema preissii
Lysiana murrayi
- Malvaceae**
Abutilon cryptopetalum
Abutilon oxycarpum subsp. *prostratum*
Sida chrysocalyx
Sida sp. unisexual (N.H. Speck 574)
- Mimosaceae**
Acacia cf. *aneura*
Acacia aneura var. cf. *aneura*
Acacia aneura var. cf. *argentea*
Acacia aneura var. cf. *microcarpa*
Acacia burkittii
Acacia cockertoniana
Acacia cf. *cockertoniana*
Acacia craspedocarpa
Acacia minyura
Acacia quadrimarginea
Acacia ramulosa var. *ramulosa*
Acacia tetragonophylla
- Myoporaceae**
Eremophila alternifolia
Eremophila forrestii subsp. *forrestii*
Eremophila georgei
Eremophila latrobei subsp. *latrobei*
Eremophila metallicorum
Eremophila oldfieldii subsp. *angustifolia*
Eremophila platycalyx subsp. *platycalyx*
- Myrtaceae**
Thryptomene decussata
- Nyctaginaceae**
Boerhavia coccinea
- Phormiaceae**
Dianella revoluta var. *divaricata*
- Poaceae**
Aristida contorta
Austrostipa platychaeta
Austrostipa scabra
Enneapogon caerulescens
Eragrostis dielsii
Eragrostis eriopoda
Eriachne helmsii
Eriachne pulchella
Monachather paradoxus
Paspalidium basicladum
- Portulacaceae**
Calandrinia eremaea complex

Proteaceae

Grevillea berryana
Grevillea nematophylla subsp. *supraplana*
Hakea preissii

Rubiaceae

Psychodax latifolia
Psychodax rigidula
Psychodax suaveolens

Rutaceae

Philotheca brucei subsp. *brucei*

Santalaceae

Santalum spicatum

Sapindaceae

Dodonaea lobulata
Dodonaea petiolaris
Dodonaea rigida
Dodonaea viscosa subsp. *angustissima*

Solanaceae

Nicotiana cf. *rotundifolia*
Solanum ashbyae
Solanum ellipticum
Solanum lasiophyllum
Solanum nummularium

Sterculiaceae

Brachychiton gregorii

Urticaceae

Parietaria cardiostegia

Table 1

Sorted two-way table of quadrats established on Brooking Hills and the South Cook Well greenstone belt showing species by plant community. Taxa shaded grey within a community are typifying species identified by SIMPER (Clarke & Warwick 2001) at the 4group level ($P < 0.05$).

Species	One	Two	Three	*	*	*
<i>Abutilon cryptopetalum</i>						
<i>Austrostipa scabra</i>						
<i>Calytrix</i> sp. Paynes Find (F. & J. Hort 1188)						
<i>Cymbopogon ambiguus</i>						
<i>Acacia scleroclada</i>						
<i>Hibiscus</i> aff. <i>solanifolius</i>						
<i>Abutilon oxycarpum</i>						
<i>Rhagodia eremaea</i>						
<i>Senna artemisioides</i> subsp. <i>helmsii</i>						
<i>Acacia citrinoviridis</i>						
<i>Acacia pruinocarpa</i>						
<i>Austrostipa trichophylla</i>						
<i>Euphorbia tannensis</i> subsp. <i>eremophila</i>						
<i>Acacia aneura</i> var. <i>microcarpa</i>						
<i>Eremophila glutinosa</i>						
<i>Acacia ramulosa</i>						
<i>Monachather paradoxus</i>						
<i>Ptilotus obovatus</i>						
<i>Solanum lasiophyllum</i>						
<i>Ptilotus schwartzii</i>						
<i>Acacia tetragonophylla</i>						
<i>Sida</i> sp. dark green fruits (S. van Leeuwen 2260)						
<i>Maireana planifolia</i>						
<i>Sclerolaena densiflora</i>						
<i>Sida ectogama</i>						
<i>Cheilanthes sieberi</i> subsp. <i>sieberi</i>						
<i>Eremophila latrobei</i> subsp. <i>latrobei</i>						
<i>Thryptomene decussata</i>						
<i>Prostanthera petrophila</i>						
<i>Acacia aulacophylla</i>						
<i>Stylidium longibracteatum</i>						
<i>Philoteca sericea</i>						
<i>Dodonaea pachyneura</i>						
<i>Baeckea</i> sp. Mount Barloweerie (J.Z. Weber 5079)						
<i>Sclerolaena eriacantha</i>						
<i>Maireana villosa</i>						
<i>Philoteca brucei</i> subsp. <i>brucei</i>						
<i>Acacia</i> aff. <i>sibirica</i>						
<i>Aluta aspera</i> subsp. <i>hesperia</i>						
<i>Thysanotus manglesianus</i>						
<i>Eremophila simulans</i>						
<i>Sida</i> sp. Golden calyces glabrous (H.N. Foote 32)						
<i>Eragrostis lanipes</i>						
<i>Senna glaucifolia</i>						
<i>Maireana convexa</i>						
<i>Maireana georgei</i>						
<i>Thyridolepis multiculmis</i>						
<i>Eremophila clarkei</i>						
<i>Grevillea berryana</i>						
<i>Acacia aneura</i> var. <i>alata</i>						
<i>Eremophila galeata</i>						
<i>Acacia cuthbertsonii</i> subsp. <i>cuthbertsonii</i>						
<i>Maireana thesioides</i>						
<i>Scaevola spinescens</i>						
<i>Senna artemisioides</i> subsp. <i>x sturtii</i>						
<i>Micromyrtus sulphurea</i>						
<i>Senna</i> sp. Austin (A. Strid 20210)						
<i>Austrostipa nitida</i>						
<i>Maireana triptera</i>						
<i>Senna</i> sp. Meekatharra (E. Bailey 1-26)						
<i>Spartothamnella teucriflora</i>						
<i>Maireana carmosa</i>						
<i>Sclerolaena gardneri</i>						
<i>Acacia grasbyi</i>						
<i>Hakea recurva</i> subsp. <i>arida</i>						
<i>Eremophila macmillaniana</i>						
<i>Micromyrtus placoides</i>						
<i>Acacia aneura</i> var. <i>argentea</i>						
<i>Acacia</i> sp. Muggon Station (S. Patrick & D. Edinger SP 3235)						
<i>Eremophila georgei</i>						
<i>Acacia rhodophloia</i>						
<i>Cheilanthes brownii</i>						
<i>Dodonaea petiolaris</i>						
<i>Eremophila forrestii</i>						
<i>Marsdenia australis</i>						

Table 2

Mean values for soil attributes (measured in mg/kg except EC and pH) by plant community type. Differences between ranked values tested using Kruskal –Wallis non-parametric analysis of variance. Standard error in parentheses. a and b represent significant differences between community types at $P < 0.05$ (n = number of quadrats, P = probability).

	Community Type				P
	1	2	3	4	
EC	4.3 (0.4)	27.0 (20.4)	6.5 (3.8)	6.1 (3.5)	0.0212
pH	4.3 (0.1)a	5.3 (0.6)ab	5.5 (0.4)b	5.0 (0.2)b	<0.0001
P	25.9 (7.4)ab	87.0 (52.0)a	36.0 (31.3)ab	8.8 (1.8)b	0.0167
K	173.4 (16.6)	335.0 (66.5)	282.5 (76.3)	203.6 (21.6)	0.0357
Mg	63.3 (6.1)a	260.8 (153.6)ab	292.5 (136.2)b	128.5 (29.0)ab	0.0008
Org C	1.3 (0.1)a	2.0 (0.8)a	0.7 (0.3)ab	0.7 (0.1)b	0.0005
Total N	0.09 (0.01)a	0.17 (0.08)a	0.08 (0.03)ab	0.06 (0.01)b	0.0033
B	0.28 (0.04)	1.09 (0.84)	0.45 (0.23)	0.31 (0.04)	0.9197
Ca	300.9 (29.0)	777.5 (407.9)	580.0 (208.3)	616.3 (229.6)	0.1490
Co	0.59 (0.17)a	0.48 (0.29)ab	2.62 (0.69)b	1.94 (0.30)b	0.0002
Cu	0.89 (0.03)a	0.95 (0.18)ab	1.58 (0.18)b	1.57 (0.18)b	<0.0001
Fe	98.7 (15.2)a	144.5 (39.8)a	66.5 (24.6)ab	49.1 (4.8)b	0.0008
Mn	40.4 (5.0)a	55.8 (6.2)ab	147.5 (18.8)b	97.3 (13.8)b	0.0002
Na	2.5 (0.4)a	66.3 (61.3)ab	11.3 (2.8)b	3.1 (1.2)a	0.0019
Ni	0.55 (0.14)a	0.35 (0.03)ab	1.48 (0.50)b	1.15 (0.20)b	0.0014
S	12.4 (0.6)a	21.5 (12.4)ab	8.5 (2.6)ab	20.6 (12.8)b	0.0143
Zn	1.7 (0.2)	7.2 (3.8)	3.3 (1.7)	1.7 (0.2)	0.1699
n	23	4	4	19	

Table 3

Mean values for site attributes by plant community type; Elevation (m); Soil depth (1 – skeletal, 2 – shallow, 3 – deep); Coarse fragment (CF) abundance (0 – no coarse fragments to 6 very abundant coarse fragments); Maximum size of coarse fragments (1 – fine gravelly to 7 large boulders); Rock outcrop (RO) abundance (0 – no bedrock exposed to 5 – rockland); Slope (degrees), runoff (0 – no runoff, 1 – very slow, 2 – Slow, 3 – Moderately rapid); Morphology type (1 – crest, 2 – upper slope, 3 – mid slope, 4 – lower slope, 5 – simple slope, 6 – hillock); Land Type (1 – hillcrest, 2 – hill slope, 3 – footslope, 4 – summit, 5 – mount, 6 – breakaway). Differences between ranks tested using Kruskal –Wallis non-parametric analysis of variance. Standard error in parentheses. a, b and c represent significant differences between community types at $P < 0.05$ (n = number of quadrats, P = probability, ns = not significant).

	Community Type				P
	1	2	3	4	
Elevation (m)	450.9 (3.6)a	470.5 (10.5)a	433.0 (4.9)ab	424.2 (3.3)b	<0.0001
Soil Depth	1.5 (0.1)a	1.5 (0.3)ab	1.8 (0.3)ab	2.2 (0.1)b	0.0062
Coarse Fragment Size	5.6 (0.2)a	5.8 (0.3)a	4.5 (0.6)ab	3.6 (0.3)b	<0.0001
Rock outcrop abundance	2.6 (0.4)a	1.5 (0.9)ab	1.0 (1.0)ab	0.5 (0.3)b	0.0020
Slope	9.2 (1.1)a	12.5 (2.7)ab	8.5 (3.4)ab	4.9 (1.1)b	0.011
Runoff	2.5 (0.2)a	2.5 (0.6)ab	2.8 (0.3)ab	1.6 (0.2)b	0.0208
CF Abundance	4.7 (0.1)a	4.3 (0.3)ab	4.5 (0.3)ab	3.6 (0.3)b	0.0038
Land Type	2.1 (0.2)	2.0 (0.6)	2.5 (0.5)	2.8 (0.2)	0.0685
Morph Type	1.9 (0.2)a	1.8 (0.5)ab	2.8 (0.6)ab	3.6 (0.3)b	0.0005
n	23	4	4	19	

Flora and vegetation of banded iron formations of the Yilgarn Craton: Mt Ida Greenstone Belt and Mt Hope

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ABSTRACT

The Mount Ida greenstone belt is located within the Southern Cross Granite-Greenstone terrane (Wyche 2003) and is expressed as low ranges of banded ironstone formation. Recent increases in the value of iron ore have made the mining of banded iron formations more attractive. This paper describes the flora and vegetation on these ranges. A total eighty seven taxa, including one annual, were recorded from the ranges. One priority species (Atkins 2008), *Calytrix erosipetala*, and two range extensions were recorded. Hierarchical classification identified four plant communities on the ranges. The dominant floristic communities occurred on the slopes and crests (Community 2) and on the lower and colluvial slopes (Community 3). Upland communities were less fertile and there was a lower concentration of soil mobile elements than in the lowland communities. Currently, the Mt Ida Greenstone Belt is not within a conservation estate.

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

INTRODUCTION

Banded iron formations (BIF) are ancient sedimentary rocks formed in the Archaean period approximately 3.8 to 2.5 billion years ago. On the Yilgarn Craton, BIFs occur as relatively thin deposits associated with Archaean greenstone belts (Page 2001). As they are more resistant to erosion, BIFs form distinct ranges and hills within the Yilgarn region and include the ranges of the Mount Ida Greenstone Belt (Fig. 1). Mining in the area has occurred to the east of the ranges at Copperfield and Bottle Creek mines, focusing upon gold (Wyche & Duggan 2003) but with the current increase in iron ore values, mining low grade iron ore has become economical once again.

Previous vegetation surveys of ironstone ranges on the Yilgarn Craton have shown that each range supports distinct plant communities and an often unique and rare flora (Markey & Dillon 2008a,b; Meissner & Caruso 2008 a,b,c). The aim of this paper is to describe the flora and vegetation of the Mt Hope and the Mt Ida Greenstone Belt and their relationships with environmental variables to provide baseline information for future management.

Geology

The Mt Ida Greenstone Belt is located on the Southern Cross Granite-Greenstone Terrane (Wyche 2003) approximately 200km northeast of Kalgoorlie (Fig. 1). Mt Hope occurs approximately 50km south of Mt Ida and is part of a small unnamed greenstone belt.

The main range of the Mt Ida Greenstone Belt can be divided into two areas; the Mount Mason range in the north extending 13km, and the Mt Ida Range, south of Mt Mason and extending c. 7km. The Mt Mason range is composed of ridges of metamorphosed BIF intercalated with medium to coarse-grained mafic rock flanked by iron-enriched lateritic duricrust and ferruginous colluvium. Minor outcropping of BIF occurs parallel to the main ridge, to the east and at lower elevations (Wyche & Duggan 2003). The Mt Ida range has undergone greater deformation and consists of major ridges of banded ironstone intercalated with minor mafic rock and flanked by regolith of lateritic duricrust and ferruginous colluvium (Wyche & Duggan 2003).

Climate

The climate of the region is Semi-desert Mediterranean with mild wet winters and hot dry summers (Beard 1990). Mean annual rainfall at Cashmere Downs Station (c. 75km west of the range) is 252.9mm, with moderate seasonal variation over the 83 years of record (1919–2002: decile 1, 128.5mm; decile 9, 426.9mm). Mean rainfall is spread throughout the year, with little winter-summer difference. The highest maximum temperatures occur during summer, with the January as the hottest month (mean maximum 36°C and mean 6.2 days above 40°C). Winters are mild with the lowest mean maximum temperature of 17.5°C recorded for July. Temperatures occasionally fall below 0°C in winter (a mean of 0.9 days below 0°C), with a mean minimum of 5.9°C in July.

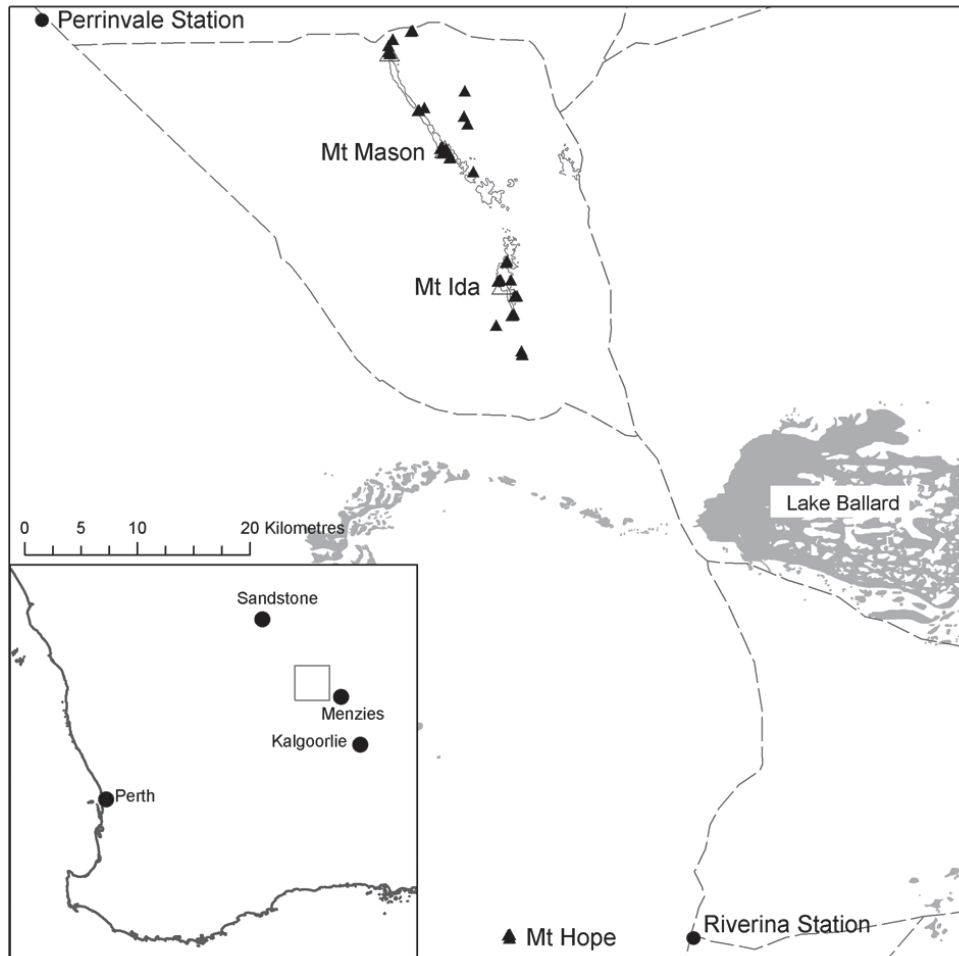


Figure 1. Location of the Ida Greenstone Belt showing the location of the 51 sites (▲). The 520 m contour is shown with the highest peaks of Mt Mason (566m) and Mt Isa (594m).

Vegetation

The ironstone ranges on the Mt Ida Greenstone Belt covers two main land systems: the Bevon and the Brooking (Pringle et al. 1994). A land system describes a catena of landforms, their geological features and vegetation types. The Bevon land system encompasses the lower colluvial slopes of the Mt Ida Greenstone Belt and is defined as irregular low ironstone hills and stony lower slopes supporting *Acacia aneura* shrublands. The Brooking Landsystem, named after the Brooking Hills, 35km to the west, describes the main ironstone ranges of the greenstone belt. The land system is defined as prominent ridges of banded iron formation supporting *A. aneura* shrublands; occasional halophytic communities in the southeast.

METHODS

Fifty 20 x 20m quadrats were established on the crests, slopes and foot slopes of banded ironstone ranges of the Mt Ida Greenstone Belt and Mt Hope in September 2007 (Fig. 1). The quadrats were established using an environmentally stratified approach to cover the major

geographical, geomorphologic and floristic variation but biased (non random) as there were restrictions in access to the range. Each quadrat was permanently marked with four steel fence droppers and its position was determined using a Global Positioning System (GPS) unit. All vascular plants within the quadrat were recorded and collected for later identification at the Western Australian Herbarium.

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

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

fertility and has been calibrated for Western Australian soils (Walton & Allen 2004). The pH was measured in 0.01M CaCl₂ at a soil to solution ratio of 1:5. Effective cation exchange capacity (eCEC) was calculated from the sum of exchangeable Ca, Mg, Na and K (Rengasamy & Churchman 1999). Exchangeable Ca, Mg, Na and K were obtained by multiplying the values of Ca, Mg, Na and K obtained from ICP-AES by a standard constant. Organic carbon was measured on soil that was ground to less than 0.15mm using Metson's colorimetric modification of the Walkley and Black method 6A1 (Metson 1956; Walkley 1947). Total Nitrogen was measured using the Kjeldahl method 7A2 (Rayment & Higginson 1992). Electrical conductivity (EC) was based on a 1:5 soil/deionised water extract and measured by a conductivity meter at 25°C (Rayment & Higginson 1992).

Quadrats were classified on the basis of similarity in species composition on perennial species only, to be consistent with the other analyses of banded ironstone ranges (Gibson 2004 a,b). The quadrat classification was followed by similarity profile (SIMPROF) testing to determine the significance of internal group structures using permutation testing (Clarke & Gorley 2006).

Similarity percentages (SIMPER), based upon Bray and Curtis similarities, was used to determine typifying species for each community. SIMPER analyses the contribution of individual species to the average similarity within groups and average dissimilarity between groups (Clarke & Warwick 2001).

Quadrats were ordinated using Semi-Strong Hybrid (SSH) multidimensional scaling, correlations of environmental variables were determined using Principal Component Correlation (PCC) routine and significance determined by Monte-Carlo Attributes in Ordination (MCAO) routine in PATN (Belbin 1989).

Statistical relationships between quadrat groups were tested using Kruskal-Wallis non parametric analysis of variance (Siegel 1956), followed by non-parametric comparison (Zar 1999).

Nomenclature generally follows Paczkowska and Chapman (2000).

RESULTS

Flora

A total of 87 taxa from 26 families were recorded from the Mt Ida Greenstone Belt and Mt Hope. Dominant families were Mimosaceae (15 species), Myrtaceae (10), Myoporaceae (9) and Poaceae (8). No exotic species and a single annual, *Eriachne pulchella*, were recorded in the survey.

Priority Species

A single priority species was recorded in the survey. Priority taxa are considered to be poorly known, potentially rare or threatened (Atkins 2008). *C. erosipetala* is a Priority 3 (poorly known) shrub that grows to 70 cm with white to

pink flowers. It is closely related to *Calytrix warburtonensis* but is distinguished by its erose to sub-erose petal margin and longer hypanthium (Craven 1987). It was collected on the slopes of laterised ironstone near Mt Mason growing with *A. aneura*, *A. cockertoniana*, *Philotheca brucei* and *Prostanthera althoferi*.

Range Extensions

Range extensions were defined as any new record more than 100km from the nearest population to be consistent with previous surveys (Meissner & Caruso 2008a). This survey recorded range extensions for two species.

Callitris canescens, a tree that grows to 5m, differs from the more common arid species, being distinguished by dorsal surface of the cone being rounded and the dorsal point of cone being inconspicuous. This species is commonly found on breakaways, rock outcrops and slopes around salt lakes. In this study, it was found growing near Mount Hope, in an open woodland of *Casuarina pauper* and *A. aneura* shrubland on a crest of banded ironstone and mafic rock.

Hemigenia sp. Yalgoo (A.M. Ashby 2624) is a spinescent, low shrub to 90 cm with white, blue or purple flowers commonly found on lateritic soil. This is a range extension of approximately 250km north of the nearest population. It was found growing at two sites on a rocky crest and lower slope of banded ironstone.

Plant Communities

Fifty three perennial taxa, occurring in two or more plots (singletons were removed), were used in the final analyses. A preliminary comparison between the full and final dataset showed high correlation between the two matrices (correlation of 0.99), indicating that the removal of singletons would have little effect on the classification and ordination analyses.

Four community groups and an outlier were determined following the hierarchical classification using SIMPROF ($p < 0.05$). The outlier, MTMN14, was located in the northern part of the survey near Mt Bevon, on a small crest of laterised ironstone. Only a few species recorded from the site occurred in the major communities, making it difficult to determine if the site was a species-poor representation of one of the four communities or a different community.

The outlier, MTMN14, was the first division in the dendrogram. Community 1, found on lower slopes and flats of the range, separated first on the dendrogram from the other communities. Community 2, the most prevalent community on the range and found mainly on the crests and midslopes of the ranges, was the next division in the dendrogram, separating from Communities 3 and 4, the communities that were most similar to each other. Community 3 was found on mid to lower slopes while Community 4 was found mainly on colluvial and lower slopes. Both communities had species in common with Community 2 but also had additional species that are found mainly in Communities 3 and 4 (Table 1).

Community 1 occurred on the lower slopes and flats associated with the ironstone ranges of Mt Ida and Mt Mason. It was characterised as open shrublands and mallee shrublands of *A. quadrimarginea*, *A. aneura*, *A. ramulosa* var. *ramulosa*, *Allocasuarina dielsiana* and *Eucalyptus rigidula* over open to sparse shrublands of *Eremophila forrestii* subsp. *forrestii* and *P. althoferi* over shrubland of *Ptilotus obovatus*. The mean species richness was the lowest of all communities, with 8.0 (± 0.9) taxa per plot. The community was typified by *A. aneura* var. cf. *aneura*, *A. quadrimarginea* and *E. forrestii*.

Community 2 was a common community found on the crests and slopes of the ranges. It can be described as open to sparse shrublands dominated by *A. aneura* and other *Acacia* spp. (*A. cockertoniana*, *A. quadrimarginea* and *A. minyura*) over open to sparse shrublands of *Eremophila* spp. (*E. forrestii* subsp. *forrestii*, *E. latrobei* subsp. *latrobei*, *E. georgei*, *E. glutinosa*), *P. althoferi* subsp. *althoferi*, *Olearia humilis*, *P. brucei* subsp. *brucei*, *Allocasuarina acutivalvis* subsp. *acutivalvis* and *Dodonaea lobulata*. The mean species richness was 11.0 (± 0.5) taxa per plot and the typical species were *A. quadrimarginea*, *E. georgei*, *E. latrobei* subsp. *latrobei*, *O. humilis*, *P. brucei* subsp. *brucei* and *P. althoferi* subsp. *althoferi*.

Community 3 was found on the mid- to lower slopes of the banded ironstone ranges. It was characterised by open to sparse shrubland of *A. aneura*, *Casuarina pauper*, *A. quadrimarginea*, *A. ramulosa* var. *ramulosa* and *Allocasuarina dielsiana* over sparse to open shrubland of *Acacia tetragonophylla*, *A. ramulosa* var. *ramulosa*, *Scaevola spinescens*, *E. latrobei* subsp. *latrobei*, *P. brucei* subsp. *brucei*, *Sida* sp. unisexual (N.H. Speck 574), *Dodonaea rigida*, *Dodonaea lobulata*, *Scaevola spinescens* and *E. forrestii* subsp. *forrestii* over shrublands of *Ptilotus obovatus*. The typifying species were *A. aneura* var. cf. *microcarpa*, *A. tetragonophylla*, *E. forrestii*, *E. latrobei* subsp. *latrobei*, *Ptilotus obovatus* and *Scaevola spinescens*. This community had the highest mean species richness of 13.8 (± 0.9) taxa per plot.

Community 4 was found on low terrain, on mid, lower and colluvial slopes and crests of banded ironstone of the ranges. The community was described as open to sparse shrublands of *A. aneura*, *A. quadrimarginea* and *A. cockertoniana* over open shrubland of *E. forrestii* subsp. *forrestii* and *E. georgei* over sparse shrubland of *Ptilotus obovatus*, *Solanum lasiophyllum* and *Sida chrysocalyx*. The mean species richness of the community was 11.0 (± 0.3) taxa per plot with only two typifying species, *E. forrestii* and *Sida chrysocalyx*.

Physical Parameters

Non-parametric analysis of variance found significant differences in 13 of the 17 soil parameters and six of the nine site parameters (Table 2 and 3). Communities 2 and 3 differed the most, representing opposite ends of a continuum between lowland and upland communities, with Communities 1 and 4 possessing intermediate values between the two.

Community 2 was a common plant community,

occurring on sites at higher elevations on the crests and slopes of the range. The sites had greater cover of exposed bedrock, shallower to skeletal soils and a greater surficial coarse fragment size than Community 3 sites (Table 3). In comparison, Community 3 occurred on sites at lower elevations on the mid-slopes and lower slopes of the ranges. The soils were less acidic, higher in potassium and magnesium but lower in organic carbon than Community 2 soils. The remaining trace elements (B, Ca, Co, Cu, Mn and Ni) were all significantly lower in concentration in Community 2 soils, but were significantly higher for iron and sulphur (Table 2).

The soils of Communities 1 and 4 showed intermediate concentrations of nutrients between the two main communities. Community 1 was less fertile, with the lowest concentrations of phosphorus, organic carbon and total nitrogen, but these were not significantly different from the other communities (Table 2). It was significantly lower in cobalt and iron, possibly reflecting the lower coarse fragment size and presence of rock outcrops, both of which represent potential sources of these elements (Gray & Murphy 2002). Community 4 occurred on sites at lower elevations on deeper soils with significantly higher potassium than Community 1 soils (Table 3).

The three dimensional ordination (Fig. 2; stress = 0.1919) using SSH multidimensional scaling showed results similar to that found in the univariate analysis. Communities 2 and 3 are clearly separated from each other with Community 2 occurring in the lower half and Community 3 in the upper half of the ordination. Communities 1 and 4 are intermediate between these two communities.

The principal components correlation (PCC) showed many environmental variables correlated with the ordination. High levels of Cu, pH, Mg, Ni, K, Mn, N and Co were associated with Community 3 in the upper left quadrant while higher values of organic C and S were associated with Community 2 in the lower half of the ordination (Fig. 2). Community 2 was also correlated with positions higher in the landscape (land type) and higher elevations, results also shown by the univariate analysis. Copper, magnesium, pH and elevation were the highest correlated variables ($r^2 > 0.5$).

DISCUSSION

Flora

A very low number of taxa were recorded on the Mt Ida Greenstone Belt primarily due to the low number of ephemerals represented in the taxa, with only one recorded. Brooking Hills area had a similar low number of perennial taxa, with a total of 82 perennial taxa and 22 ephemerals (Meissner & Owen, in press). The low number of annuals was attributed to the fact that in the four months preceding the survey, only 54 mm of rainfall was recorded at Bulga Downs, 90km to the north-east, with the average for that period approximately twice that value.

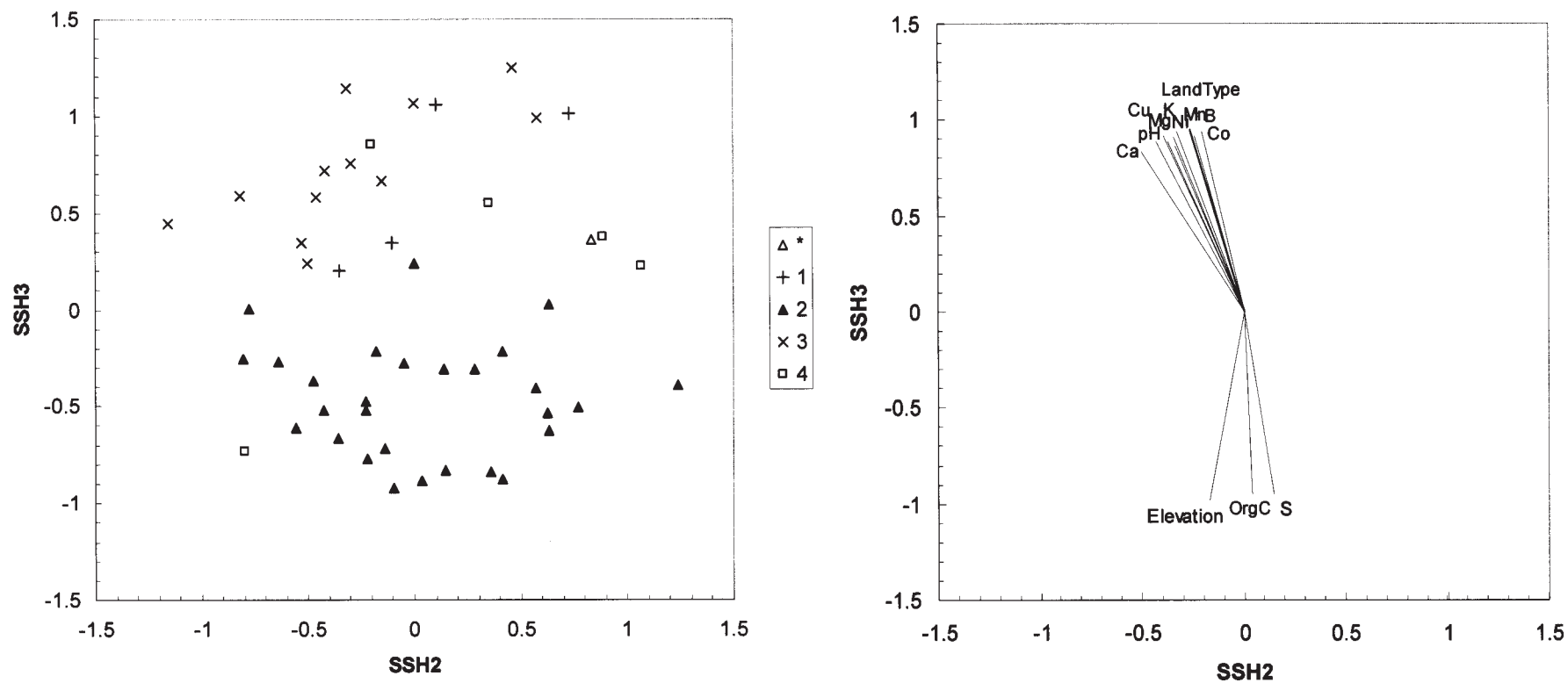


Figure 2. Three dimensional SSH ordination showing Axis 1, 2 and 3 of the 50 quadrats established on the Mount Ida Greenstone Belt. The four communities are shown and lines represent the strength and direction of the best fit linear correlated variables ($P < 0.05$).

Plant Communities

This survey described four plant communities on the Mount Ida greenstone belt and Mt Hope. Pringle et al. (1994) characterised this range within two land systems, Brooking and Bevon, which broadly correlate with the occurrence of Communities 2 and 3, respectively. In this survey, Communities 2 and 3 represented the lowland and upland communities and were characterised by different suites of species. Pringle et al. (1994) did not differentiate between vegetation communities on the upper and lower slopes of the range and classified the vegetation as Stony Ironstone Mulga Shrublands. This study shows that these upland and lowland communities are distinct with different composition and associated with different environmental characteristics.

Community 3 was typified by species characteristic of colluvial and lower slopes of ironstone ranges, such as *E. forrestii*, *Scaevola spinescens* and *A. tetragonophylla*, while Community 2 was typified by species found on outcrops and ridges of ironstone ranges, such as *P. brucei* subsp. *brucei*, *O. humilis* and *E. georgei*. The distribution of nutrients was also typical of erosional environments and similar to patterns found on other ironstone ranges (Meissner et al., 2009a, b). The more mobile elements, Na, Ca, Mg, Co, Ni, Cu and Zn, were all lower in Community 2 due to leaching and weathering (Britt et al. 2001).

Communities 1 and 4 differed slightly in community composition but were intermediate in physical characteristics between Community 2 and 3. Community 1 occurred at similar elevations, intermediate soil fertility between Community 2 and 3 and occurred on the lower slopes and flats. This community had the lowest species richness and was the first division in the dendrogram. It is likely that this community is a species-poor representation of the lowland community (Community 3). Similarly, Community 4 was found on lower terrains on midslopes and crests and is closely related to Community 3. It represents another variation of a lowland community, and is intermediate between Communities 2 and 3, sharing many of the physical characters and typifying species.

There were no communities recorded during the survey that were restricted within the range, with the communities spread across the greenstone belt however the communities found on the Mount Ida greenstone belt were unique to that range. An initial comparison of taxa between the Brooking Hills and this range found only 43 taxa in common. In addition, a preliminary comparison of the communities on the Mount Ida greenstone belt to the nearest ironstone range at Brooking Hills, found that the plant communities were significantly different (ANOSIM Global R = 0.154, P < 0.01, Clarke & Warwick 2001).

Conservation

At the time of the survey, the Mt Ida Greenstone Belt and Mt Hope were not within a conservation estate. This survey has shown that this range had a unique suite of

communities that differ from other ironstone ranges in the region, however, there were no restricted communities and only one priority taxon. Additional surveys during years of higher rainfall may add further annual species. The banded iron formations of the Mt Hope and Mt Ida Greenstone Belt are currently under prospective mining interest.

ACKNOWLEDGEMENTS

We would like to thank the following people: Dave Allen and Katrina Walton, WA Chemcentre for Soil Analysis; Perrinvale Station for their cooperation and help during the field survey; the staff at the Western Australian Herbarium, especially Karina Knight; Rob Davies, Bruce Maslin, Frank Obbens and Barbara Rye on for their taxonomic expertise. Finally, Neil Gibson is thanked for his advice and support. This project was funded by the Western Australian Department of Environment and Conservation's Biodiversity Conservation Initiative.

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APPENDIX

Floristic list for the Mount Ida Greenstone Belt and Mt Hope including all taxa from the sampling quadrats and adjacent areas. Nomenclature follows Paczkowska and Chapman (2000).

Adiantaceae	<i>Acacia murrayana</i>
<i>Cheilanthes brownii</i>	<i>Acacia quadrimarginea</i>
<i>Cheilanthes sieberi</i> subsp. <i>sieberi</i>	<i>Acacia ramulosa</i> var. <i>ramulosa</i>
Amaranthaceae	<i>Acacia sibirica</i>
<i>Ptilotus helipteroides</i>	<i>Acacia tetragonophylla</i>
<i>Ptilotus obovatus</i>	<i>Acacia victoriae</i>
Apocynaceae	Myoporaceae
<i>Alyxia buxifolia</i>	<i>Eremophila forrestii</i> subsp. <i>forrestii</i>
Asclepiadaceae	<i>Eremophila georgei</i>
<i>Marsdenia australis</i>	<i>Eremophila glutinosa</i>
<i>Rhyncharthema linearis</i>	<i>Eremophila latrobei</i> subsp. <i>latrobei</i>
Asteraceae	<i>Eremophila oldfieldii</i> subsp. <i>angustifolia</i>
<i>Olearia humilis</i>	<i>Eremophila platycalyx</i> subsp. <i>platycalyx</i>
<i>Olearia muelleri</i>	<i>Eremophila scoparia</i>
Caesalpiniaceae	Myrtaceae
<i>Senna artemisioides</i> subsp. <i>helmsii</i> x <i>Senna glaucifolia</i>	<i>Aluta aspera</i> subsp. <i>aspera</i>
<i>Senna artemisioides</i> subsp. <i>filifolia</i>	<i>Calytrix erosipetala</i>
<i>Senna cardiosperma</i>	<i>Eucalyptus ewartiana</i>
<i>Senna glaucifolia</i>	<i>Eucalyptus leptopoda</i> subsp. <i>elevata</i>
Casuarinaceae	<i>Eucalyptus lesouefii</i>
<i>Allocasuarina acutivalvis</i> subsp. <i>acutivalvis</i>	<i>Eucalyptus lucasii</i>
<i>Allocasuarina dielsiana</i>	<i>Eucalyptus rigidula</i>
<i>Casuarina pauper</i>	<i>Micromyrtus clavata</i>
Chenopodiaceae	<i>Thryptomene costata</i>
<i>Maireana planifolia</i>	<i>Thryptomene decussata</i>
<i>Maireana triptera</i>	Phormiaceae
<i>Rhagodia drummondii</i>	<i>Dianella revoluta</i> var. <i>divaricata</i>
<i>Sclerolaena fusiformis</i>	Pittosporaceae
Cupressaceae	<i>Bursaria occidentalis</i>
<i>Callitris canescens</i>	Poaceae
Dilleniaceae	<i>Austrostipa</i> sp. indet. BIF
<i>Hibbertia arcuata</i>	<i>Austrostipa</i> aff. <i>trichophylla</i> (R. Meissner & G. Owen 2010)
Goodeniaceae	<i>Austrostipa elegantissima</i>
<i>Scaevola spinescens</i>	<i>Austrostipa scabra</i>
Lamiaceae	<i>Austrostipa trichophylla</i>
<i>Hemigenia</i> sp. Yalgoo (A.M. Ashby 2624)	<i>Eragrostis eriopoda</i>
<i>Prostanthera althoferi</i> subsp. <i>althoferi</i>	<i>Eriachne helmsii</i>
<i>Spartothamnella teucriiflora</i>	<i>Eriachne pulchella</i>
Loranthaceae	Proteaceae
<i>Amyema fitzgeraldii</i>	<i>Hakea recurva</i> subsp. <i>recurva</i>
Malvaceae	Rubiaceae
<i>Hibiscus</i> cf. <i>krichauffianus</i>	<i>Psydrax rigidula</i>
<i>Sida chrysocalyx</i>	<i>Psydrax suaveolens</i>
<i>Sida</i> sp. unisexual (N.H. Speck 574)	Rutaceae
Mimosaceae	<i>Philotheca brucei</i> subsp. <i>brucei</i>
<i>Acacia aneura</i> var. cf. <i>aneura</i>	Sapindaceae
<i>Acacia aneura</i> var. cf. <i>argentea</i>	<i>Dodonaea lobulata</i>
<i>Acacia aneura</i> var. cf. <i>microcarpa</i>	<i>Dodonaea petiolaris</i>
<i>Acacia burkittii</i>	<i>Dodonaea rigida</i>
<i>Acacia cockertoniana</i>	<i>Dodonaea viscosa</i> subsp. <i>mucronata</i>
<i>Acacia duriuscula</i>	Solanaceae
<i>Acacia erinacea</i>	<i>Solanum ashbyae</i>
<i>Acacia minyura</i>	<i>Solanum ellipticum</i>
	<i>Solanum lasiophyllum</i>
	Sterculiaceae
	<i>Brachychiton gregorii</i>

Table 1

Sorted two-way table of quadrats established on the Mount Ida Greenstone Belt showing species by community type. Taxa shaded grey within a community are typifying species identified by SIMPER (Clarke & Warwick 2001) at the 4group level ($P < 0.05$).

	One	Two	Three	Four
<i>Acacia aneura</i> broad				
<i>Casuarina pauper</i>				
<i>Olearia muelleri</i>				
<i>Allocasuarina dielsiana</i>				
<i>Dianella revoluta</i> var. <i>divaricata</i>				
<i>Spartothamnella teucriflora</i>				
<i>Acacia aneura</i> falcate				
<i>Acacia ramulosa</i> var. <i>ramulosa</i>				
<i>Maireana planifolia</i>				
<i>Senna artemisioides</i> subsp. <i>filifolia</i>				
<i>Rhagodia drummondii</i>				
<i>Acacia tetragonophylla</i>				
<i>Solanum lasiophyllum</i>				
<i>Dodonaea rigida</i>				
<i>Sida</i> sp. unisexual (N.H. Speck 574)				
<i>Cheilanthes sieberi</i> subsp. <i>sieberi</i>				
<i>Eremophila oldfieldii</i> subsp. <i>angustifolia</i>				
<i>Dodonaea lobulata</i>				
<i>Scaevola spinescens</i>				
<i>Acacia victoriae</i>				
<i>Hakea recurva</i> subsp. <i>recurva</i>				
<i>Acacia aneura</i> var. cf. <i>aneura</i>				
<i>Eremophila georgei</i>				
<i>Olearia humilis</i>				
<i>Prostanthera althoferi</i> subsp. <i>althoferi</i>				
<i>Acacia aneura</i> var. cf. <i>microcarpa</i>				
<i>Eremophila latrobei</i> subsp. <i>latrobei</i>				
<i>Acacia quadrimarginea</i>				
<i>Eremophila forrestii</i>				
<i>Philotheca brucei</i> subsp. <i>brucei</i>				
<i>Ptilotus obovatus</i>				
<i>Eremophila glutinosa</i>				
<i>Hibbertia arcuata</i>				
<i>Acacia minyura</i>				
<i>Thryptomene decussata</i>				
<i>Marsdenia australis</i>				
<i>Sida chrysocalyx</i>				
<i>Acacia aneura</i> var. cf. <i>argentina</i>				
<i>Acacia cockertoniana</i>				
<i>Psyrax suaveolens</i>				
<i>Solanum ellipticum</i>				
<i>Eucalyptus leptopoda</i> subsp. <i>elevata</i>				
<i>Hemigenia</i> sp. Yalgoo (A.M. Ashby 2624)				
<i>Allocasuarina acutivalvis</i> subsp. <i>acutivalvis</i>				
<i>Austrostipa scabra</i>				
<i>Senna cardiosperma</i>				
<i>Bursaria occidentalis</i>				
<i>Dodonaea petiolaris</i>				
<i>Dodonaea viscosa</i> subsp. <i>mucronata</i>				
<i>Brachychiton gregonii</i>				
<i>Eucalyptus ewartiana</i>				
<i>Eremophila platycalyx</i>				
<i>Hibiscus</i> cf. <i>krichauffianus</i>				

Table 2

Mean values for soil attributes (measured in mg/kg except EC and pH) by plant community type. Differences between ranked values tested using Kruskal–Wallis non-parametric analysis of variance. Standard error in parentheses. a and b represent significant differences between community types at $p < 0.05$ (n = number of quadrats, P = probability).

	Community Type				P
	1	2	3	4	
EC	2.5 (0.5)	3.7 (0.2)	4.8 (1.1)	4.0 (1.1)	0.2522
pH	4.8 (0.2)ab	4.1 (0.1)a	5.3 (0.2)b	4.5 (0.2)ab	<0.0001
P	4.8 (1.0)	11.7 (2.4)	7.4 (3.4)	20.6 (13.1)	0.1877
K	119.8 (25.0)ab	74.6 (6.6)a	170.2 (16.2)b	173.4 (35.7)b	<0.0001
Mg	71.8 (15.0)ab	37.8 (4.6)a	104.0 (11.5)b	37.0 (15.1)ab	0.0002
Org C	0.74 (0.08)ab	1.44 (0.10)a	0.78 (0.09)b	1.09 (0.29)ab	0.0007
Total N	0.058 (0.006)	0.099 (0.006)	0.072 (0.007)	0.092 (0.019)	0.0237
B	0.3 (0.1)ab	0.2 (0.0)a	0.4 (0.0)b	0.4 (0.1)ab	0.0014
Ca	415.0 (101.5)ab	220.2 (29.5)a	642.5 (106.6)b	356.0 (90.2)ab	0.0008
Co	1.4 (0.6)b	0.2 (0.1)a	1.7 (0.3)b	1.0 (0.7)ab	<0.0001
Cu	1.8 (0.3)ab	1.0 (0.1)a	2.3 (0.2)b	2.2 (1.0)ab	<0.0001
Fe	40.3 (3.6)b	76.4 (8.9)a	47.8 (3.4)b	71.8 (23.3)ab	0.0071
Mn	88.0 (31.1)ab	29.9 (6.6)a	104.3 (14.6)b	75.6 (39.4)ab	<0.0001
Na	5.8 (1.3)	4.0 (0.5)	7.0 (1.4)	5.8 (1.6)	0.1258
Ni	0.48 (0.11)ab	0.23 (0.03)a	0.58 (0.06)b	0.56 (0.26)ab	<0.0001
S	7.0 (2.0)ab	15.1 (1.0)a	7.3 (1.1)b	12.0 (2.4)ab	0.0003
Zn	1.4 (0.3)	1.2 (0.1)	1.9 (0.2)	2.1 (0.4)	0.0416
n	4	28	12	5	

Table 3

Mean values for site attributes by plant community type; Elevation (m); Soil depth (1 - skeletal, 2 – shallow, 3 – deep); Coarse fragment (CF) abundance (0 – no coarse fragments to 6 very abundant coarse fragments); Maximum size of coarse fragments (1 – fine gravely to 7 large boulders); Rock outcrop (RO) abundance (0 – no bedrock exposed to 5 – rockland); Runoff (0 – no runoff to 5 – very rapid); Slope (degrees), runoff (0 – No runoff, 1 – very slow, 2 – Slow, 3 – Moderately rapid); Morphology type (1= Crest, 2= Upper Slope, 3= Mid Slope, 4= Lower Slope, 5 = Simple slope, 6 = Hillock); Land type (1 = Hillcrest, 2 = Hill slope, 3 = Footslope, 4 = Summit, 5 = Mount, 6 = Breakaway. Differences between ranks tested using Kruskal–Wallis non-parametric analysis of variance. Standard error in parentheses. a, b and c represent significant differences between community types at $P < 0.05$ (n = number of quadrats, P = probability.).

	Community Type				p
	1	2	3	4	
Elevation (m)	480.8 (19.5)ab	536.1 (5.6)a	472.5 (6.5)b	471.6 (6.6)b	<0.0001
Soil Depth	2.3 (0.3)ab	1.7 (0.1)a	2.2 (0.1)b	2.4 (0.2)b	0.0034
Coarse Fragment Size	3.5 (0.5)b	5.2 (0.1)a	4.1 (0.3)b	4.4 (0.7)ab	0.0061
Rock outcrop abundance	0.0 (0.0)b	2.1 (0.3)a	0.6 (0.3)b	1.8 (0.9)ab	0.0019
Slope	5.0 (1.7)	7.3 (0.8)	6.6 (1.5)	7.2 (2.8)	0.8264
Runoff	1.5 (0.5)	2.0 (0.2)	2.1 (0.3)	2.0 (0.4)	0.8246
CF Abundance	3.3 (0.9)	4.2 (0.1)	3.8 (0.2)	3.6 (0.2)	0.1900
Land Type	4.3 (0.3)b	1.9 (0.2)a	3.3 (0.3)b	2.8 (0.8)ab	0.0007
Morph Type	2.5 (0.5)ab	1.4 (0.1)a	2.1 (0.2)b	1.8 (0.4)ab	0.0060
n	4	28	12	5	

Flora and vegetation of banded iron formations of the Yilgarn Craton: Perseverance Greenstone Belt

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ABSTRACT

The Perseverance Greenstone Belt is located within the Eastern Goldfields Geological Province of Western Australia and is represented by low undulating hills of banded ironstone and basalt. This paper describes the flora and vegetation on these hills. Eighty eight taxa, including seven annuals and no introduced taxa, were recorded. Two priority taxa, *Grevillea inconspicua* and *Baeckea* sp. Melita Station (H. Pringle 2738), were found. Hierarchical classification of species presence/absence data identified four floristic communities. The main floristic differences occurred between communities occurring on basalt, or mafic, substrates (Communities 1 and 4) and those occurring on the ironstone hills (Communities 2 and 3). Significant differences were found in the soil chemistry between these substrates. None of the Perseverance Greenstone Belt is within the Western Australian conservation estate.

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

INTRODUCTION

Banded iron formations (BIF) are finely laminated deposits of alternating iron rich/silica rich layers (Page 2001) laid down approximately 3.8 to 2.5 billion years ago. The conditions and processes that led to the formation of this distinct lithology, whether of sedimentary origin or from secondary diagenetic modification of an unknown rock precursor, or a combination of both, are still being debated (Page 2001). Within Western Australia, BIF are found on the Pilbara and Yilgarn Cratons, part of the earth's crust that have been stable for the past 2.4 billion years. The Yilgarn Craton is considerably larger than the Pilbara Craton with 80% consisting of granite-greenstone terrane (Trendall 1990).

In this study, the BIF occur as part of the Perseverance Greenstone Belt and are expressed as a series of low hills associated with basalt and other mafic bedrock. Extensive mining and exploration have been undertaken in the area, beginning in the late 19th century (Beard 1976). Nickel is the primary focus of mining, with three mining operations: the Mount Keith, Leinster-Perseverance and Yakabindie mines on the Greenstone Belt. The development of mining in the 1930s was followed by the expansion of the pastoral industry, which now one of the primary land uses of the area.

High levels of plant endemism have been shown to occur in the BIF ranges (Gibson *et al.* 2007). Analysis of 25 BIF ranges in the Yilgarn Craton found that 10% of

declared rare flora (DRF) and priority taxa, under the Western Australian Wildlife Conservation Act, occurred on these ranges (Gibson *et al.* 2007). This study is part of a series of papers studying the floristic communities of BIF on the Yilgarn Craton. The aim of this paper is to describe the flora and vegetation communities on the Perseverance Greenstone Belt, focusing on those communities occurring on BIF.

Geology

The ironstone hills described in this study are part of the Perseverance Greenstone Belt in the Eastern Goldfields Province, which occupies the eastern third of the Yilgarn Craton (Griffin 1990). The major component of the Perseverance Greenstone Belt comprises metamorphosed ultramafic and mafic rocks, such as basalts, which include the Violet Range, immediately west of the survey (Fig. 1). Mafic is a term derived by contracting “magnesium” and “ferric”, reflecting that the rocks are high in these minerals (Eggleton 2001). Associated meta-sedimentary rocks, which included BIF, are widespread within the belt but are poorly exposed as a discontinuous ridge. The BIF and chert units of the greenstone belt are generally less than a few metres thick and are commonly associated with shales and quartz mica-schists (Liu *et al.* 1998).

Climate

The climate of the region is desert with bimodal rainfall distribution (Beard 1976). Winter rainfall is generally light and is associated with low pressure systems off the south

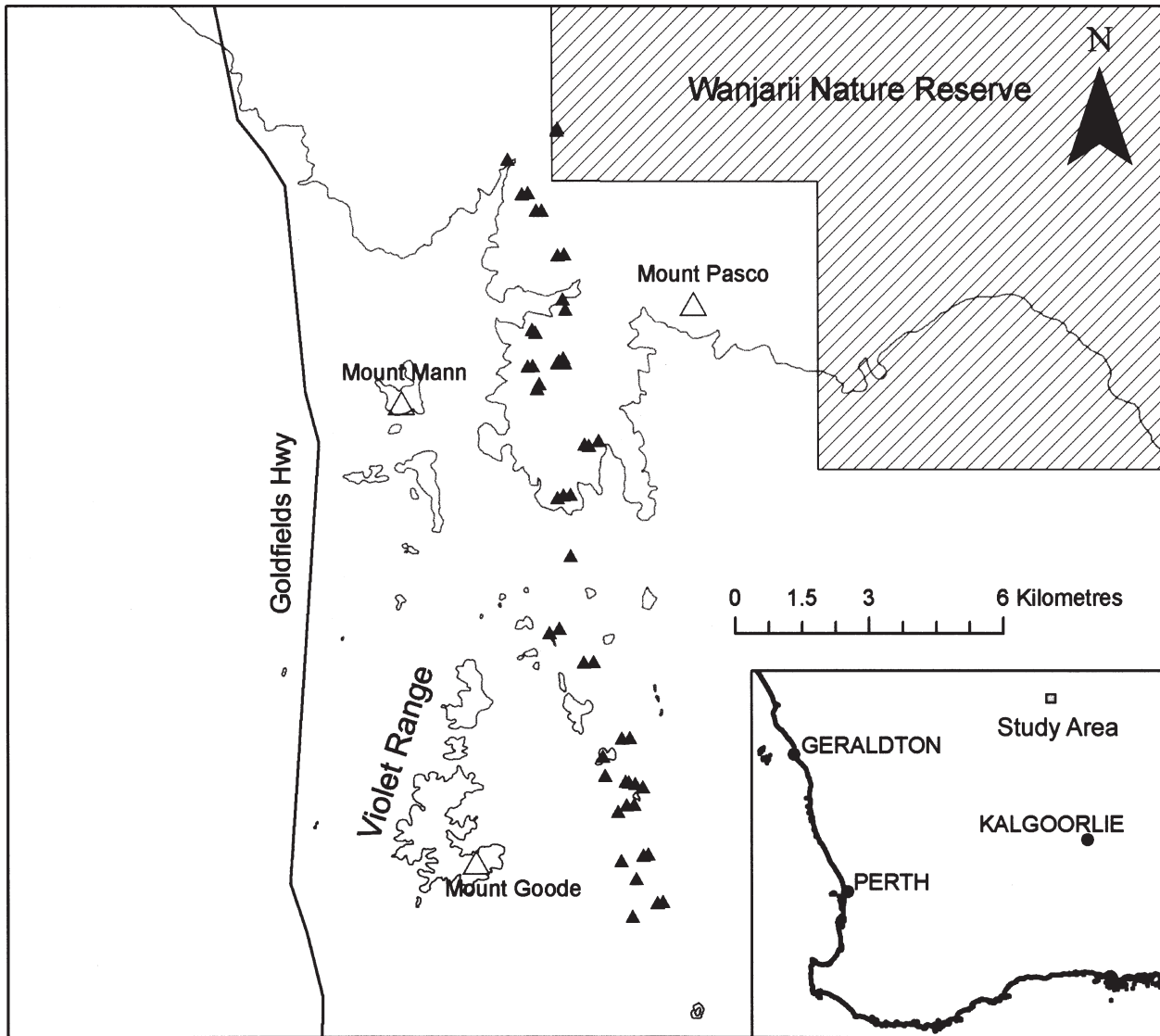


Figure 1. Location of the Perseverance Greenstone Belt study area, showing the location of 50 sites (▲). The 520 m contour is shown with the highest peaks, Mt Mann (554 m), Mount Goode (598 m) and Mount Pasco (549 m).

coast, while summer rainfall events, are usually short and intense, originating from cyclonic events to the north-west which degenerate into rain bearing depressions (Hall & Milewski 1994). Mean annual rainfall at Yeelerie Station (c. 55 km northwest of the survey) is 237.8 mm, with moderate seasonal variation over the 81 years of record (1928–2009: decile 1, 120.9 mm; decile 9, 400.2 mm). Rainfall is spread throughout the year, with little winter–summer difference. The highest maximum temperatures occur during summer, with January the hottest month (mean maximum temperature 37.9°C and a mean of 10.9 days above 40°C -1973–2009). Winters are mild with the lowest mean maximum temperatures of 19.3°C recorded in July. Temperatures occasionally fall below 0°C in winter (a mean 7.7 days below 0°C), with a July mean minimum of 3.5°C.

Vegetation

The Perseverance Greenstone Belt occurs within the Murchison Interim Biogeographic Regionalisation for Australia (IBRA) region (Department of the Environment and Water Resources 2004), dominated by *Acacia aneura* low woodlands and abundant ephemerals. Several biological surveys have been undertaken in the eastern goldfields including Wanjarri Nature Reserve, adjacent to the ironstone hills. Hall *et al.* (1994) described vegetation occurring within broad valleys, undulating plains and breakaways, but did not include any ironstone landforms. The ironstone hills in this survey have been described broadly by Beard (1976), who generalised the vegetation cover as shrublands and mulga scrub and described the rocky hills covered with *A. aneura*, *A. quadrimarginea*,

A. grasbyi and *Hakea lorea* over *Senna* sp., *Eremophila* sp., *Ptilotus obovatus*, *Clianthus formosus*, *Podolepis auriculata*, *Swainsona incei* and *Waitzia aurea*.

The Perseverance belt covers two land systems as described by Pringle *et al.* (1994). A land system describes a combination of landform, soil and vegetation that occur in a recurring pattern (Pringle *et al.* 1994). The Bevon land system covers the northern part of the survey and is described as irregular low ironstone hills with stony lower slopes supporting mulga shrublands. The system includes landforms such as breakaways, footslopes, hillslopes, ridges, stony plains and lateritic plains. To the south, the survey area occurs within the Violet Range land system, named after the Violet Range, which lies west of the current survey. The land system is defined as undulating stony and gravelly plains and low rises, supporting mulga shrublands.

Both land systems are dominated by stony ironstone mulga shrublands (SIMS) vegetation, scattered to moderately close *A. aneura* (mulga) tall shrublands. This vegetation type is characterised by shrublands of *A. aneura*, *Acacia ramulosa* and *Acacia tetragonophylla* and *Eremophila* spp. (*E. fraseri*, *E. forrestii*), *Senna* spp. (*S. artemisioides* subsp. *helmsii*, *S. artemisioides* subsp. *x coriacea* and *S. artemisioides* subsp. *x sturtii*) over shrublands of *Sida calyxhymentia*, *Solanum lasiophyllum*, *Spartothamnella teucrifflorea*, *Maireana* spp. (*M. convexa*, *M. georgei*, *M. triptera*, *M. villosa*) and *Ptilotus* spp. (*P. obovatus* and *P. schwartzii*) (Pringle *et al.* 1994). In both land-systems, SIMS vegetation mainly grades into 'lateritic' hardpan mulga shrublands (LHMS), usually on soils with a conspicuous mantle of ferruginous gravel (Pringle *et al.* 1994). This vegetation is characterised by mulga tall shrublands dominated by *A. aneura* and other *Acacia* spp. (*A. pruinocarpa*, *A. ramulosa* and *A. tetragonophylla*), *Eremophila* spp. (*E. fraseri*, *E. macmillaniana*, *E. forrestii* and *E. margarethae*), *Scaevola spinescens*, *Rhagodia eremaea*, *P. obovatus* and *P. schwartzii*.

METHODS

The methodology employed in this survey follows the standard procedure used in previous vegetation surveys of other ironstone and greenstone ranges in Western Australia (Markey & Dillon 2008a,b; Meissner & Caruso 2008a,b,c). Fifty 20 x 20 m quadrats were established on the crests, slopes and foot slopes of banded ironstone of the Perseverance belt in September 2008 (Fig. 1). The quadrats were established using an environmentally stratified approach to cover the major geographical, geomorphologic and floristic variation but biased (non random) as there were restrictions in access to the range. Each quadrat was permanently marked with four steel fence droppers and its positions were determined using a Global Positioning System (GPS) unit. All vascular plants within the quadrat are recorded and collected for later identification at the Western Australian Herbarium (PERTH). Nomenclature generally follows Paczkowska & Chapman (2000).

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

Twenty soil samples were collected from the upper 10 cm of the soil profile within each quadrat. The soil was bulked and the 2mm fraction analysed for B, Ca, Cd, Co, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S and Zn using the Mehlich No. 3 procedure (Mehlich 1984). The extracted samples were then analysed using Inductively Coupled Plasma - Atomic Emission Spectrometer (ICP-AES). This procedure is an effective and cost-efficient alternative to traditional methods for evaluating soil fertility and has been calibrated for Western Australian soils (Walton & Allen 2004). The pH was measured in 0.01M CaCl₂ at a soil to solution ratio of 1:5. Effective cation exchange capacity (eCEC) was calculated from the sum of exchangeable Ca, Mg, Na and K (Rengasamy & Churchman 1999). Exchangeable Ca, Mg, Na and K were obtained by multiplying the values of Ca, Mg, Na and K obtained from ICP-AES by a standard constant. Organic carbon was measured on soil that was ground to less than 0.15mm using Metson's colorimetric modification of the Walkley and Black method 6A1 (Metson 1956; Walkley 1947). Total Nitrogen was measured using the Kjeldahl method 7A2 (Rayment & Higginson 1992). Electrical conductivity (EC) was based on a 1:5 soil/deionised water extract and measured by a conductivity meter at 25° C (Rayment & Higginson 1992).

Quadrats were classified on the basis of similarity in species composition on perennial species only excluding singletons. This was to facilitate comparison with other analyses of banded ironstone ranges and remove any temporal variations in annual numbers that could confound comparisons (Meissner & Caruso 2008 a,b,c). The quadrat and species classifications were undertaken using the Bray-Curtis coefficient followed by Flexible Unweighted Pair-Group Mean Average (UPGMA) clustering (Clarke & Gorley 2006). The Bray-Curtis coefficient is commonly used in ecological studies especially in presence/absence datasets (Belbin 1989; Clarke *et al.* 2006), while Flexible UPGMA is an effective method of recovering true group structure (Belbin & McDonald 1993). Quadrat classification was followed by similarity profile (SIMPROF) testing to determine the significance of internal group structures using permutation testing (Clarke & Gorley 2006). Indicator species and species assemblages characterising each community were determined following Dufréne & Legendre (1997) using INDVAL routine in PC-ORD (McCune & Mefford 1999).

Quadrats were ordinated using semi-strong hybrid (SSH) multidimensional scaling, a non-parametric approach and not based upon the assumptions of linearity, or any underlying model of species response gradients. Correlations of environmental variables were determined using Principal Component Correlation (PCC) routine

and significance determined by Monte Carlo Attributes in Ordination (MCAO) routine in PATN (Belbin 1989). PCC uses multiple linear regressions of variables in the three dimensional ordination space (Belbin 1989). Statistical relationships between quadrat groups were tested using Kruskal-Wallis non-parametric analysis of variance (Siegel 1956), followed by Dunn's Multiple comparison test (Zar 1999).

RESULTS

Flora

Eighty eight vascular taxa (species, subspecies, varieties, forms and hybrid taxa) were collected within and adjacent to survey plots on the Perseverance Greenstone Belt. The flora consisted of 83 perennials, seven annuals and no introduced taxa in 24 families. The best represented families were Mimosaceae (*Acacia*) (23 taxa), Chenopodiaceae (10 taxa), Caesalpiniaceae (*Senna*) (10 taxa), Myoporaceae (*Eremophila*) (8 taxa) and Malvaceae (6 taxa).

Priority Flora

Two priority species, as defined by Atkins (2008), were collected from the Perseverance Greenstone Belt. Priority taxa are considered to be poorly known, potentially rare or threatened (Atkins 2008). Both taxa have been recorded previously from the area.

- *Baeckea* sp. Melita Station (H. Pringle 2738) (Priority 3) is a myrtaceous shrub growing to 2.5m with characteristic hooked golden green leaves and white flowers. This taxon is an ironstone endemic within the Murchison IBRA region. It was recorded from three sites at the southern end of the hills between crests and lower slopes of banded ironstone.
- *Grevillea inconspicua* (Priority 4) is an intricately branched shrub growing to 2m with white or grey flowers in a terminal raceme. It is commonly found growing on drainage lines along rocky outcrops and creeklines within the Murchison IBRA region. It was found opportunistically growing on a lower slope of a basalt hill with surficial ironstone fragments.

Plant Communities

The similarity profile (SIMPROF) analysis identified four significant groups ($p < 0.05$; Clarke & Warwick 2001). Fifty one perennial taxa, occurring in two or more sites, were analysed. The first division in the dendrogram separated Community 1, found on mafic and ultramafic basalt sites, from the other three communities (Fig. 2). The next division in the dendrogram separated Community 4, found on crests and slopes of basalt hills, from Community 2, found on banded ironstone hills in the southern part of the range, and Community 3 on banded ironstone & chert hills and ferruginous colluvium.

Community One – This community consisted of six

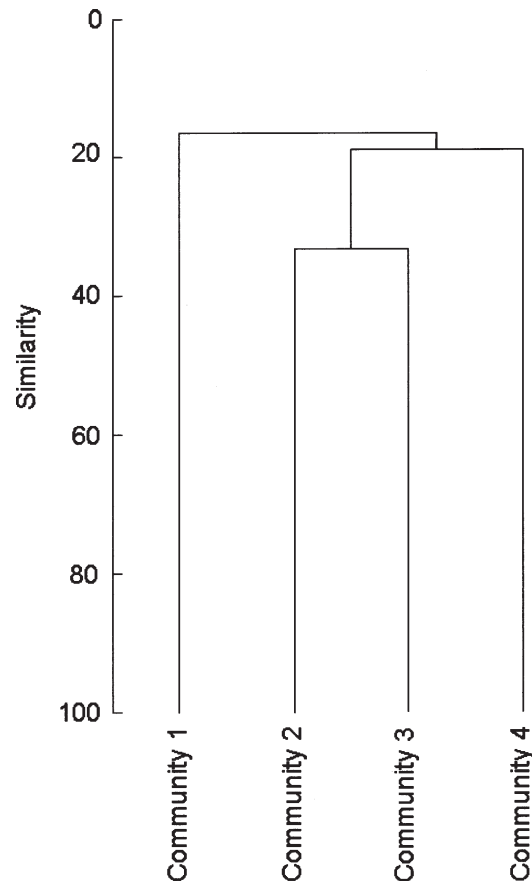


Figure 2. Dendrogram of the 4 group level classification of 50 quadrats established on the Perseverance Greenstone Belt.

sites commonly found on crests and mid-slopes of ultramafic and metabasalt derived hills. This community is described as open to sparse shrubland of *Acacia* cf. *resinimarginea* and *A. grasbyi* over open to sparse shrubland of *Senna* spp. (*S. artemisioides* subsp. *helmsii* and *Senna* sp. Meekatharra (E. Bailey 1–26)) over isolated to open shrubland of *Cheilanthes sieberi* subsp. *sieberi*, *Calytrix desolata* or *Harnieria kempeana* subsp. *muelleri* (Table 1). The community had a mean species richness of 8.7 taxa (± 1.3) per plot and indicator species were *A.* cf. *resinimarginea*, *S. artemisioides* subsp. *helmsii* and *Acacia aneura* var. *fuliginea*.

Community Two – This was the most widespread community on the hills and occurred mostly in the southern part of the range. It occurred mainly on the crests and slopes of banded ironstone and iron-rich chert but also on basalt and felsic rocks. The community is described as open to sparse shrubland of *A. aneura* and *A. quadrimarginea* over isolated to sparse shrubland of *Eremophila* spp. (*Eremophila latrobei*, *Eremophila foliosissima* and *Eremophila galeata*) and *Thryptomene decussata* over isolated to sparse shrubland of *Ptilotus schwartzii* (Table 1). The community had the lowest mean species richness with 7.5 taxa (± 0.4) per plot. There were two indicator species, *Acacia aneura* var. *microcarpa* and *P. schwartzii*.

Community Three – This was the next most widespread community and was found along the entire range on crests and slopes of banded ironstone and iron rich chert. The community is described as open to sparse shrubland of *A. aneura*, *Grevillea berrryana*, and *Acacia* spp. (*A. quadrimarginea*, *A. tetragonophylla* and *A. cf. resinimarginea*) over open to sparse shrubland of *Scaevola spinescens* and *Eremophila latrobei* and *Senna* sp. Meekatharra (E. Bailey 1–26) over isolated to sparse shrublands of *Ptilotus* spp. (*P. obovatus* and *P. schwartzii*) and *M. georgei* (Table 1). This community had the highest mean species richness of 12.3 taxa (± 1.1) per plot and indicator species were *Sida ectogama*, *A. tetragonophylla*, *P. schwartzii*, *Acacia aneura* var. *microcarpa*, *Cymbopogon ambiguus* and *Senna artemisioides* subsp. *x artemisioides*.

Community Four – This community was recorded at eight sites located on the lower slopes and colluvium derived from metabasalt and ultramafic rocks. This community is described as open to sparse dominated *A. aneura* shrublands and other *Acacia* spp. (*A. pruinoarpa*, *Acacia kempeana* and *A. grasbyi*) over open to sparse shrublands of *Sida ectogama*, *S. sp.* Meekatharra (E. Bailey 1–26) and *Eremophila pantonii* over open to sparse shrubland of *M. georgei* and *M. triptera* (Table 1). The community had a mean species richness of 8.5 taxa (± 0.7) per plot and indicator species were *Eremophila oldfieldii*, *M. triptera*, *E. pantonii*, *Acacia oswaldii*, *Hakea preisii* and *A. tetragonophylla*.

Environmental correlates

Prior to analysis, cadmium and molybdenum were removed from the dataset as both were below detectable limits. Non-parametric analysis of variance found ten of the eighteen soil parameters were significantly different between the communities (Table 2) while only one of the eleven site attributes was significant (Table 3). The analyses showed a clear differentiation between Community 2 from Communities 1 and 4. Post-hoc tests failed to discriminate differences between individual community types for iron despite a significant difference ($p < 0.05$).

In terms of site attributes, all communities were similar except for disturbance (Table 3). The plant communities were found in all landscape and morphological types (hill crests, slopes and hillocks) on the Greenstone Belt. The survey area consisted of gentle slopes, low abundance of small surface coarse fragments with very little cover of rock outcrops, on shallow to deep soils.

The soils of the basalt communities (Communities 1 and 4) were less acidic, higher concentrations in elements higher in mafic rocks (Ca, Co, Cu, Mn and K) and higher ECEC than Community 2, which occurred on soils derived from chert and banded ironstone (Table 3). Community 2 occurred on the most acidic sites and less fertile sites. Community 3 had intermediate soil nutrients between the basalt communities (1 & 4) and Community 2 (ironstone). The few exceptions were higher concentrations of potassium and calcium than Community 2 and lower concentrations of copper than Community 1.

The three dimensional SSH ordination (2; stress = 0.1998) showed similar patterns to the univariate analysis. Communities 1 and 4 are well separated from Community 2 on the ordination while Community 3 appears to be intermediate between them (Fig. 3a and 3b). Communities 1 and 4, the basalt communities, correlate with high values of Mg, eCEC, pH, Mn, Cu, Ca, and Co (Fig. 3c and 3d). Community 2 has lower concentrations of these nutrients and correlates with higher disturbance, sulphur and surficial rock (rock outcrop), with the latter not significant in univariate analysis.

DISCUSSION

Flora

The flora of the Perseverance Greenstone Belt was depauperate in comparison to the flora of other ironstone ranges, reflected by the low number of taxa and low species richness. The Booylgoo Range, the nearest surveyed range, 75km to the south-west, recorded 209 taxa, with 142 perennial taxa (Markey & Dillon in press), compared to a total of 88 taxa, with 81 perennial taxa in this survey. Dominance by similar of families was observed in the two areas, with Mimosaceae, Myoporaceae, Chenopodiaceae and Caesalpiniaceae as the dominant perennial families. This composition is typical of communities found in the Murchison IBRA region (Beard 1976, Pringle *et al.* 1994). The paucity of taxa may be associated with increasing aridity expressed as lower rainfall and greater evaporation rates (Hall & Milewski 1994). Low rainfall in the months preceding the survey resulted in the near absence of annuals in the survey.

Endemism and a higher occurrence of priority species are characteristic of some ironstone ranges (Meissner and Caruso 2008 a,b,c; Markey & Dillon 2008 a,b; Gibson *et al.* 2007). Despite the low number of taxa recorded, two priority taxa were recorded during the survey. Both species are regional endemics, with *Grevillea inconspicua* primarily found on rocky mafic substrates within in the Murchison IBRA. *Baeckeia* sp. Melita Station (H. Pringle 2738) has been recorded previously on several ironstone ranges within the Murchison (Markey & Dillon, in press; Meissner *et al.* 2009 b,c). In addition to priority species, several ironstone endemics were also recorded, namely *T. decussata* and *S. ectogama*.

Plant Communities

This survey described four communities found on the Perseverance Greenstone Belt. The greatest floristic differences occurred between the basalt and ironstone communities. The communities on mafic/basalt sites (Communities 1 and 4) and the ironstone communities (2 and 3) were characterised by different species groups and different indicator species. Nearby Booylgoo Range also had floristic differences between communities associated with metabasalt and mafic substrates and those associated with BIF lithologies (Markey & Dillon, in press).

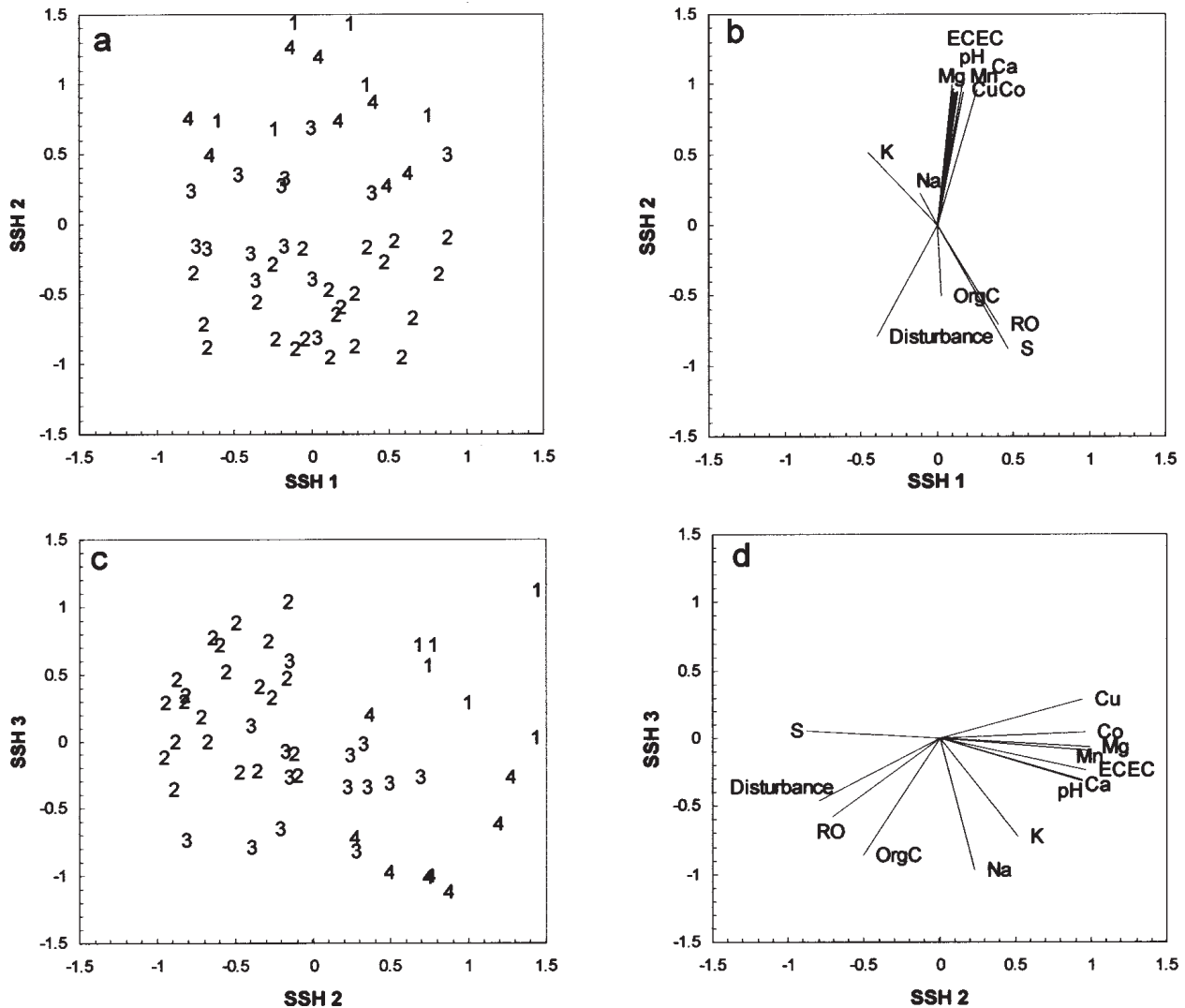


Figure 3. Three dimensional SSH ordination showing SSH Axes 1, 2 and 3 of the 50 quadrats established on Perseverance Greenstone Belt. The four communities are shown and lines represent the strength and direction of the best fit linear correlated variables ($P < 0.05$).

The soil chemical composition reflects the underlying geology of the hills, whether basalt (mafic) or banded ironstone and cherts. Mafic rocks tend to be characterised by higher amounts of trace elements such as cobalt, copper and nickel, as well as higher amounts of calcium, magnesium and potassium. These elements are typical of basalts and tend to increase in availability in the soil as the parent rock becomes more mafic (Gray & Murphy 2001).

In this survey, the relief of the range was gentle occurring as undulating hills, as opposed to the steep strike ridges of other ironstone ranges in the Yilgarn Craton (Markey & Dillon 2008a,b; Meissner & Caruso 2008 a,b,c). The lack of any significant topography is reflected in the absence of any floristic distinction between colluvial slopes or crests of the hills. Previous surveys of ironstone communities have found that topography is also important

in distinguishing communities. The lower colluvial slopes of the ironstone ranges are generally more fertile with more mobile elements and a different community is found here (Markey & Dillon 2008a,b; Meissner & Caruso 2008 a,b,c).

All four communities found on the Greenstone Belt roughly correspond in general terms to the stony ironstone mulga shrublands (SIMS) and share similar dominants with the 'lateritic' hardpan mulga shrublands described in the rangeland condition survey (Pringle *et al.* 1994). However, the rangeland condition survey failed to discriminate between the basalt and ironstone lithologies of the Perseverance belt communities, as the communities were mapped within the same two land systems known as Violet and Bevon. This is not surprising, considering that this survey is at a much finer scale than was mapped for the rangeland condition survey.

Conservation

Although the Wanjarri Nature Reserve is nearby, BIF does not occur within this reserve area (Hall *et al.* 1994). A preliminary comparison of the species recorded within this survey and the Wanjarri Nature Reserve found only 30% similarity based on presence/absence data (Bray-Curtis; Clarke & Gorley 2006). Although several taxa recorded in this survey have been recorded within Wanjarri, a comparison of the floristic communities of Wanjarri with those described here shows no similarity. The ironstone communities are similar in structure to the communities on laterite breakways, characterised as *A. aneura* low woodlands, but the latter lacked of the key indicator species found on the two ironstone communities, such as *P. schwartzii* (Hall & Milewski 1994).

To date, mining tenements cover the entire area and exploration is currently underway in the northern part of the survey area. Although this exploration is not targeting banded iron formation, the ecology of these areas has been adversely affected. None of the ironstone hills within this survey is at present within secure Conservation Reserves.

ACKNOWLEDGEMENTS

We would like to thank the following people: Katrina Walton, WA Chemcentre for Soil Analysis; staff at Mount Keith Operations, BHP; Yakabindie station, the staff at the Western Australian Herbarium, especially Karina Knight; Rob Davies, Paul Wilson and Bruce Maslin for their taxonomic expertise. Finally, Stephen van Leeuwen and Neil Gibson are thanked for their advice and support. Permits for flora collection were issued by the Western Australian Department of Environment and Conservation. This project is part of the Biodiversity Conservation Initiative (BCI) of the Saving Our Species (SOS) Program, and has been funded by the Department of Environment and Conservation, Western Australia.

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APPENDIX

Floristic list for the Perseverance Greenstone Belts, including all taxa from the sampling quadrats and adjacent areas. Nomenclature follows Paczkowska and Chapman (2000).

Acanthaceae

Harnieria kempeana subsp. *muelleri*

Adiantaceae

Cheilanthes brownii

Cheilanthes sieberi subsp. *sieberi*

Amaranthaceae

Ptilotus obovatus

Ptilotus roei

Ptilotus schwartzii

Asclepiadaceae

Marsdenia australis

Asteraceae

Helipterum craspedioides

Rhodanthe maryonii

Brassicaceae

Lepidium oxytrichum

Lepidium platypetalum

Caesalpiniaceae

Senna artemisioides subsp. *filifolia*

Senna artemisioides subsp. *helmsii*

Senna artemisioides subsp. *x artemisioides*

Senna artemisioides subsp. *x sturtii*

Senna charlesiana

Senna glaucifolia

Senna glutinosa subsp. *x luerssenii*

Senna manicula

Senna sp. Meekatharra (E. Bailey 1–26)

Senna stricta *x artemisioides* ssp. *petiolaris* (E.N.S. Jackson 2888)

Casuarinaceae

Casuarina pauper

Chenopodiaceae

Dysphania rhadinostachya subsp. *rhadinostachya*

Enchylaena tomentosa var. *tomentosa*

Maireana convexa

Maireana georgei

Maireana georgei *x Enchylaena tomentosa*

Maireana thesioides

Maireana triptera

Rhagodia eremaea

Sclerolaena eriacantha

Sclerolaena fusiformis

Convolvulaceae

Duperreya sericea

Euphorbiaceae

Euphorbia boophthona

Geraniaceae

Erodium cygnorum

Goodeniaceae

Scaevola spinescens

Lamiaceae

Spartothamnella teucriflora

Malvaceae

Hibiscus cf. *gardneri*

Hibiscus cf. *solanifolius*

Sida ectogama

Sida sp. dark green fruits (S. van Leeuwen 2260)

Sida sp. *Excedentifolia* (J.L. Egan 1925)

Sida sp. Golden calyces glabrous (H.N. Foote 32)

Mimosaceae

Acacia aneura

Acacia aneura var. cf. *argentea* (short phyllode variant) (BRM 9300)

Acacia aneura var. *alata* (flat) (BRM 9689)

Acacia aneura var. *alata/microcarpa* (BRM 9083)

Acacia aneura var. *argentea* (narrow phyllode variant) (BRM 9745)

Acacia aneura var. *argentea* (short phyllode variant) (BRM 9300)

Acacia aneura var. *fuliginea*

Acacia aneura var. *macrocarpa*

Acacia aneura var. *microcarpa*

Acacia aneura var. *microcarpa* (broad, incurved phyllode variant) (BRM 9929)

Acacia aneura var. *tenuis* (BRM 9296)

Acacia aneura var. *tenuis* (flat) (BRM 9353)

Acacia cf. *resinimarginea*

Acacia coolgardiensis

Acacia craspedocarpa

Acacia grasbyi

Acacia kempeana

Acacia oswaldii

Acacia pruinocarpa

Acacia quadrimarginea

Acacia ramulosa

Acacia sibirica

Acacia tetragonophylla

Myoporaceae

Eremophila foliosissima

Eremophila forrestii

Eremophila galeata

Eremophila granitica

Eremophila latrobei subsp. *latrobei*

Eremophila metallicorum

Eremophila oldfieldii subsp. *angustifolia*

Eremophila pantonii

Myrtaceae

Baeckea sp. Melita Station (H. Pringle 2738) Priority 3

Calytrix desolata

Thryptomene decussata

Poaceae

Cymbopogon ambiguus

Enneapogon caeruleus

Eriachne helmsii

Eriachne mucronata

Eriachne pulchella

Proteaceae

Grevillea berryana
Grevillea inconspicua Priority 4
Hakea preissii
Hakea recurva subsp. *recurva*

Rubiaceae

Psydrax latifolia
Psydrax rigidula
Psydrax suaveolens

Santalaceae

Santalum spicatum

Sapindaceae

Dodonaea petiolaris
Dodonaea rigida

Solanaceae

Solanum cf. *lasiophyllum*

Table 1

Sorted two-way table of quadrats established on the Perseverance Greenstone Belt showing species by community type. Taxa shaded grey within a community are indicator species determined by Dufréne and Legendre (1997) at the 4group level ($p < 0.05$).

Species	Community One	Community Two	Community Three	Community Four
<i>Acacia aneura</i> var. <i>argentea</i>	■	■	■	■
<i>Eremophila foliosissima</i>		■	■	■
<i>Psyrax suaveolens</i>	■	■	■	■
<i>Sida</i> sp. Golden calyces glabrous (H.N. Foote 32)		■	■	■
<i>Acacia aneura</i> var. <i>microcarpa</i>	■	■	■	■
<i>Ptilotus schwartzii</i>		■	■	■
A <i>Eremophila latrobei</i> subsp. <i>latrobei</i>	■	■	■	■
<i>Maireana georgei</i>	■	■	■	■
<i>Ptilotus obovatus</i>	■	■	■	■
<i>Eremophila galeata</i>	■	■	■	■
<i>Senna glaucifolia</i>	■	■	■	■
<i>Acacia aneura</i> var. <i>tenuis</i>	■	■	■	■
<i>Acacia tetragonophylla</i>	■	■	■	■
<i>Senna</i> sp. <i>Meeekatharra</i> (E. Bailey 1-26)	■	■	■	■
B <i>Sida ectogama</i>	■	■	■	■
<i>Scaevola spinescens</i>	■	■	■	■
<i>Maireana convexa</i>	■	■	■	■
C <i>Eremophila oldfieldii</i> subsp. <i>angustifolia</i>			■	■
<i>Maireana triptera</i>			■	■
<i>Eremophila pantonii</i>			■	■
<i>Hakea preissii</i>			■	■
D <i>Acacia craspedocarpa</i>		■	■	■
<i>Acacia pruinocarpa</i>		■	■	■
<i>Maireana thesioides</i>		■	■	■
<i>Eremophila granitica</i>	■	■	■	■
<i>Harnieria kempeana</i> subsp. <i>muelleri</i>	■	■	■	■
<i>Psyrax rigidula</i>	■	■	■	■
E <i>Acacia sibirica</i>	■	■	■	■
<i>Senna artemisioides</i> subsp. <i>x artemisioides</i>	■	■	■	■
<i>Cheilanthes sieberi</i> subsp. <i>sieberi</i>	■	■	■	■
<i>Sida</i> sp. <i>Excedentifolia</i> (J.L. Egan 1925)	■	■	■	■
<i>Cymbopogon ambiguus</i>	■	■	■	■
<i>Santalum spicatum</i>	■	■	■	■
<i>Enchylaena tomentosa</i> var. <i>tomentosa</i>	■	■	■	■
<i>Rhagodia eremaea</i>	■	■	■	■
<i>Eriachne helmsii</i>	■	■	■	■
F <i>Cheilanthes sieberi</i> subsp. <i>pseudovellea</i>	■	■	■	■
<i>Marsdenia australis</i>	■	■	■	■
<i>Dodonaea petiolaris</i>	■	■	■	■
<i>Grevillea berryana</i>	■	■	■	■
<i>Eremophila forrestii</i>	■	■	■	■
G <i>Acacia aneura</i> var. <i>fuliginea</i>	■	■	■	■
<i>Acacia</i> cf. <i>resinimarginea</i>	■	■	■	■
<i>Senna artemisioides</i> subsp. <i>helmsii</i>	■	■	■	■
<i>Acacia grasbyi</i>	■	■	■	■
<i>Acacia oswaldii</i>	■	■	■	■
H <i>Acacia quadrimarginea</i>	■	■	■	■
<i>Eriachne mucronata</i>	■	■	■	■
<i>Thryptomene decussata</i>	■	■	■	■
<i>Senna stricta</i> x <i>artemisioides</i> subsp. <i>petiolaris</i> (E.N.S. Jackson 2888)	■	■	■	■
<i>Baeckea</i> sp. <i>Melita Station</i> (H. Pringle 2738)	■	■	■	■

Table 2

Mean values for soil attributes (measured in mg/kg except EC and pH) by plant community type. Differences between ranked values tested using Kruskal–Wallis non–parametric analysis of variance and differences between communities determined using Dunn's *post-hoc* comparison. Standard errors in parentheses. a and b represent significant differences between community types at $p < 0.05$ (n = number of quadrats, p = probability). * *post-hoc* comparison showed no significant differences

Attribute	Community				p–value
	One	Two	Three	Four	
	n=6	n=22	n=14	n=8	
pH(CaCl ₂)	5.5 (0.2) ^a	4.1 (0.0) ^b	4.6 (0.2) ^{ab}	5.7 (0.3) ^a	< 0.0001
ECEC	4.6 (0.6) ^b	1.2 (0.1) ^a	2.0 (0.2) ^{ab}	5.6 (1.1) ^b	< 0.0001
P	7.5 (1.0)	10.0 (3.3)	15.0 (4.4)	8.5 (1.2)	0.1405
K	100 (9) ^a	76 (5) ^b	99 (6) ^a	120 (10) ^a	0.0002
Mg	220 (55) ^{bc}	44 (4) ^a	80 (13) ^{ab}	240 (37) ^c	< 0.0001
Total N	0.044 (0.006)	0.045 (0.003)	0.053 (0.005)	0.053 (0.004)	0.1087
OrgC	0.39 (0.07)	0.46 (0.04)	0.52 (0.06)	0.51 (0.04)	0.0823
B	0.1 (0.0)	0.1 (0.0)	0.1 (0.0)	0.1 (0.0)	0.226
Ca	510 (78) ^a	120 (9) ^b	220 (25) ^a	660 (160) ^a	< 0.0001
Co	2.00 (0.22) ^c	0.21 (0.03) ^a	0.60 (0.24) ^{ab}	1.60 (0.22) ^{bc}	< 0.0001
Cu	1.60 (0.17) ^b	0.68 (0.04) ^a	0.84 (0.22) ^a	1.50 (0.32) ^{ab}	0.0003
Fe*	49 (3)	42 (4)	51 (8)	46 (4)	0.0443
Mn	86 (20) ^b	17 (2) ^a	42 (19) ^{ab}	62 (10) ^b	< 0.0001
Na	1.4 (0.4)	2.0 (0.4)	3.1 (0.8)	11.0 (4.3)	0.0326
Ni	2.1 (0.6)	0.7 (0.1)	1.1 (0.4)	1.6 (0.6)	0.0204
Pb	0.35 (0.06)	0.44 (0.02)	0.51 (0.07)	0.54 (0.12)	0.2903
S	2.3 (0.4) ^a	7.5 (0.5) ^c	5.6 (0.6) ^{bc}	4.0 (1.0) ^{ab}	< 0.0001
Zn	1.7 (0.4) ^{ab}	0.8 (0.1) ^a	1.3 (0.2) ^{ab}	1.7 (0.3) ^b	0.0032

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, 5 – hillock); Land type (1 – hillcrest, 2 – hill slope, 3 – foot slope, 4 – mound); Disturbance (0 – no effective disturbance, 1 – no effective disturbance except grazing by hoofed animals); Maximum size of coarse fragments (CF Size) (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 non–parametric analysis of variance. Standard error in parentheses. a, b and c represent significant differences between community types at $P < 0.05$ (n = number of quadrats, p = probability).

Attribute	Community				p–value
	One	Two	Three	Four	
	n=6	n=22	n=14	n=8	
Aspect	187.5 (49.9)	155.5 (16.7)	173.6 (24.0)	123.8 (40.6)	0.4207
Slope	1.8 (0.5)	3.3 (1.1)	4.1 (1.4)	1.4 (0.3)	0.7133
Morph type	1.8 (0.3)	2.0 (0.2)	2.2 (0.4)	1.9 (0.4)	0.9854
Land type	1.7 (0.2)	1.7 (0.1)	2.0 (0.3)	1.6 (0.2)	0.8454
Disturbance	0.5 (0.2) ^a	1.0 (0.0) ^b	1.0 (0.0) ^b	0.9 (0.1) ^{ab}	0.0006
CF Size	4.5 (0.4)	4.4 (0.2)	4.5 (0.3)	4.0 (0.3)	0.7765
CF Abundance	4.3 (0.2)	4.1 (0.1)	4.4 (0.2)	4.6 (0.2)	0.1897
RO Abundance	0.7 (0.3)	1.2 (0.4)	1.1 (0.4)	0.1 (0.1)	0.2702
Runoff	1.5 (0.2)	1.5 (0.2)	1.6 (0.2)	1.3 (0.3)	0.8511
Soil Depth	1.7 (0.2)	1.8 (0.1)	1.7 (0.2)	1.9 (0.1)	0.8607

Flora and vegetation of banded iron formations on the Yilgarn Craton: south Illaara Greenstone Belt

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ABSTRACT

The Illaara Greenstone Belt is located within the Southern Cross Geological Province, extending discontinuously over 80km in a north-south direction. Previous surveys have been undertaken on the northern part of the greenstone belt. This paper describes the flora and vegetation of the southern ranges of the area. One hundred and forty five taxa, including 31 annuals and no introduced taxa were recorded from the range. One declared rare flora, *Ricinocarpos brevis*, and one priority taxon, *Banksia arborea*, were recorded. Hierarchical classification identified four floristic communities on the range. The main floristic differences occurred between communities found on laterite and banded ironstone (Communities 1 and 2) and communities occurring on a mixture of banded ironstone and mafic substrate. Significant differences were found in the soil chemistry between these substrates. Currently, the southern ranges of the Illaara Greenstone Belt occur on unallocated crown land and not within Western Australian conservation estate.

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

INTRODUCTION

Banded iron formations (BIF) are iron-rich deposits composed of alternating layers of iron and silica-rich layers, formed 3.8 to 2.5 billion years ago, which are hypothesised to have formed through quiet, deep water deposition (Page 2001). In the Yilgarn Craton, BIF are associated with Archaean greenstone belts, such as the Illaara Greenstone Belt, and form distinct ranges and hills within the region.

Greenstone belts in the Yilgarn Craton have historically been mined for gold and other base metals. The discovery of gold at Coolgardie and Kalgoorlie in the 1890s led to an influx of prospectors to the region. Previous mining on the Illaara Greenstone Belt at Metzke Find and Lawrence Find (Wyche 2003) was primarily for gold. However current exploration is being undertaken for iron ore. The range is located on unallocated Crown land where the primary land use is the harvesting of native sandalwood (*Santalum spicatum*).

Previous floristic and vegetation surveys have been undertaken on other ironstone ranges within the Illaara Greenstone Belt to the north of this current survey area. Both earlier surveys found unique floristic communities associated with different substrates and positions in the landscape (Meissner *et al.* 2009, Meissner & Owen in press). The aim of this paper is to describe the flora and vegetation of the southern ranges of the Illaara Greenstone Belt, focussing on banded ironstone formations, as well

as describing relationships with environmental variables. This paper forms part of a continuing series describing the flora and vegetation of BIF of the Yilgarn Craton.

Geology

The Illaara Greenstone Belt occurs within the Southern Cross Province (Griffin 1990) and is located 90km northwest of Menzies (Fig. 1). The greenstone belt extends for a strike length of 80km, in an approximately north-south direction (Wyche 2003), with varying degrees of exposure. Travelling southwards, the greenstone belt is first exposed as Mount Forrest - Mount Richardson, followed by Brooking Hills and then in an unnamed range at the southern extent, which is the subject of this survey. The greenstone belt is not expressed continuously and is separated by several breaks in the strike ridges, Lake Barlee separates Mount Forrest and Mount Richardson from Brooking Hills, and 15km of sandplain and low mulga woodland separate Brooking Hills from the southern ranges of the greenstone belt.

The greenstone belt is composed of a succession of quartzite and quartz-rich metasedimentary rocks, overlain with interval of mafic, ultramafic and meta-sedimentary rocks that includes BIF, chert and shale. Mafic refers to rocks or minerals with a high magnesium-iron content (Eggleton 2001), such as basalts, but they are also high in calcium and sodium (Gray & Murphy 2002). The Illaara Greenstone Belt differs from other greenstone belts in the region in that it contains greater amounts of quartzite and quartz-rich meta-sedimentary rocks.

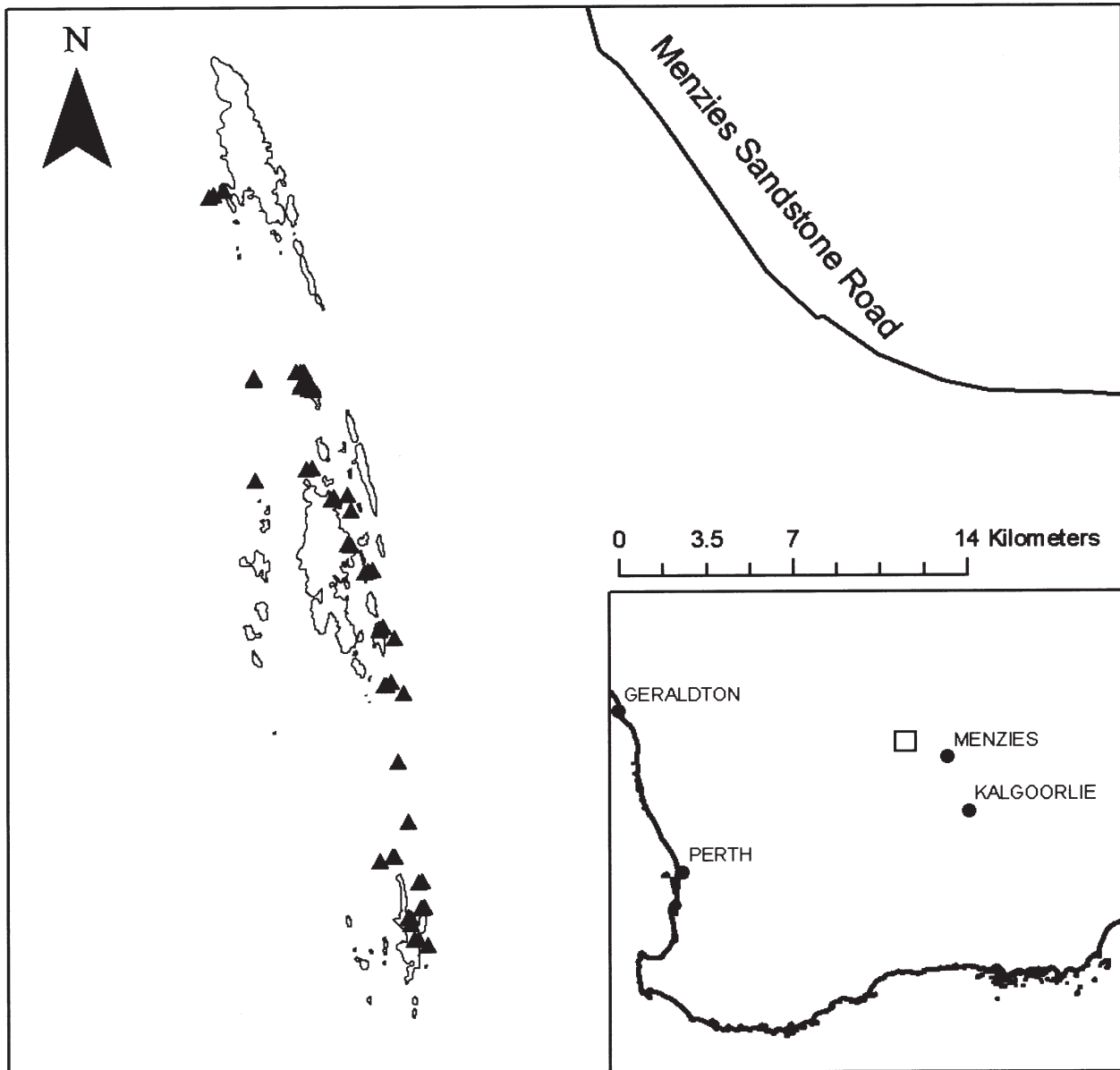


Figure 1. Location of the study area, approximately 90km north west of Menzies. Fifty quadrats (▲) were established on the southern ranges on the Illara Greenstone Belt. The 480m contour is shown.

Climate

The climate of the region is semi-desert Mediterranean with mild wet winters and hot, dry summers (Beard 1990). Mean annual rainfall at Cashmere Downs Station (c. 75km northwest of the range) is 252.9mm, with moderate seasonal variation over the 83 years of record (1919–2002: decile 1, 128.5mm; decile 9, 426.9mm). Mean rainfall is spread throughout the year, with little winter-summer difference. The highest maximum temperatures occur during summer, with January as the hottest month (mean maximum temperature 36°C and mean 6.2 days above 40°C). Winters are mild with a lowest mean maximum temperatures recorded for July 17.5°C. Temperatures rarely fall below 0°C in winter (a mean of 0.9 days below 0°C), with a mean minimum of 5.9°C in July.

Vegetation

Initial vegetation surveys of the Illara Greenstone Belt by Beard (1976) mapped the southern range as shrublands of *Acacia aneura* and *Acacia quadrimarginea* flanked by low woodlands and *A. aneura* on the plains. A rangeland condition survey of the eastern goldfields mapped the area as landsystems, which incorporate information on the vegetation in association with geomorphology and soils (Pringle *et al.* 1994). The ranges in this survey were mapped as the Brooking Landsystem, which is described as prominent ridges of banded ironstone formation supporting mulga shrublands with occasional halophytic communities in the south-east. This landsystem was characterised by Stony Ironstone Mulga Shrublands (SIMS), a vegetation type described as shrublands of *A.*

aneura, *Acacia ramulosa* and *Acacia tetragonophylla* and *Eremophila* spp. (*E. fraseri*, *E. forrestii*), *Senna* spp. (*S. artemisioides* subsp. *helmsii*, *S. artemisioides* subsp. *x coriacea*, *S. artemisioides* subsp. *x sturtii*) over shrublands of *Sida calyxhymenia*, *Solanum lasiophyllum* and *Spartothamnella teucriflora* (Pringle *et al.* 1994).

Previous surveys of the Illaara Greenstone Belt have been undertaken on the northern and central sections of the Illaara Greenstone Belt. Meissner *et al.* (2009) and Meissner & Owen (in press) surveyed Mount Forrest and Mount Richardson in 2006 and Brooking Hills in 2007. The main community recorded on Mount Forrest and Mount Richardson was described as open woodlands and shrublands of *A. aneura*, *A. quadrimarginea*, *A. cockertoniana*, *Callitris columellaris* and *Grevillea berryana* over sparse to open shrubland of *Eremophila glutinosa*, *Drummondita microphylla*, *Thryptomene decussata*, *Baeckea* sp. Melita Station (H. Pringle 2738), *Dodonaea petiolaris*, *Aluta aspera* subsp. *hesperia* (Meissner *et al.* 2009). In contrast, the common community on the Brooking Hills is described as open to sparse shrubland of *A. aneura* over open shrubland of *Eremophila georgei*, *Philotheca brucei* subsp. *brucei* and *Ptilotus obovatus* (Meissner & Owen, in press).

METHODS

The methodology employed in this survey followed the standard procedure used in previous vegetation surveys of other ironstone and greenstone ranges in Western Australia (Meissner & Caruso 2008 a,b,c). Fifty 20 x 20 m quadrats were established on the crests, slopes and foot slopes of south Illaara Greenstone Belt in September 2008 (Fig. 1). The quadrats were established using an environmentally stratified approach to cover the major geographical, geomorphologic and floristic variation but biased (non random) as there were restrictions in access to the range. Each quadrat was permanently marked with four steel fence droppers and its positions were determined using a Global Positioning System (GPS) unit. All vascular plants within the quadrat were recorded and collected for later identification at the Western Australian Herbarium.

Data on topographical position, disturbance, abundance, size and shape of coarse fragments on the surface, the 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 (tall, mid and lower). The quantitative data were used to describe the plant communities following McDonald *et al.* (1990).

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

traditional methods for evaluating soil fertility and has been calibrated for Western Australian soils (Walton & Allen 2004). The soil pH was measured in 0.01M CaCl₂ at soil to solution ratio of 1:5. Effective cation exchange capacity (eCEC) was calculated from the sum of exchangeable Ca, Mg, Na and K (Rengasamy & Churchman 1999). Exchangeable Ca, Mg, Na and K were obtained by multiplying the values of Ca, Mg, Na and K obtained from ICP-AES by a standard constant. Organic carbon was measured on soil that was ground to less than 0.15mm using Metson's colorimetric modification of the Walkley and Black method 6A1 (Metson 1956; Walkley 1947). It involved wet oxidation by a dichromate-sulfuric acid mixture, which produced enough heat to induce oxidation of the organic carbon (Rayment & Higginson 1992). Total Nitrogen was measured using the Kjeldahl method 7A2 (Rayment & Higginson 1992). The nitrogen was measured by automated colorimetry by the nitroprusside/dichloro-S-triazine modification (Blakemore *et al.* 1987) of the Berthelot indophenol reaction reviewed by Searle (1984). Electrical conductivity (EC) was based on a 1:5 soil/deionised water extract and measured by a conductivity meter at 25° C (Rayment & Higginson 1992).

Quadrats were classified on the basis of similarity in species composition using perennial species only and excluding singletons. This was to facilitate comparison with other analyses of banded ironstone ranges and remove any temporal variations in ephemeral numbers that might confound comparisons (Meissner & Caruso 2008 a,b,c). The quadrat and species classifications were undertaken using the Bray - Curtis coefficient followed by Flexible Unweighted Pair-Group Mean Average (UPGMA) clustering (Clarke & Gorley 2006). The Bray-Curtis coefficient is commonly used in ecological studies especially in presence/ absence datasets (Belbin 1989; Clarke *et al.* 2006) while Flexible UPGMA is an effective method of recovering true group structure (Belbin & McDonald 1993). Quadrat classification was followed by similarity profile (SIMPROF) testing to determine the significance of internal group structures using permutation testing (Clarke & Gorley 2006). Indicator species and species assemblages characterising each community were determined following Dufréne and Legendre (1997) using INDVAL routine in PC-ORD (McCune & Mefford 1999). Quadrats were ordinated using semi-strong hybrid (SSH) multidimensional scaling, a non parametric approach, which is not based upon the assumptions of linearity, or any presumed underlying model of species response gradients. Correlations of environmental variables were determined using Principal Component Correlation (PCC) routine and significance determined by Monte Carlo Attributes in Ordination (MCAO) routine in PATN (Belbin 1989). PCC uses multiple linear regressions of variables in the three dimensional ordination space (Belbin 1989). Statistical relationships between quadrat groups were tested using Kruskal-Wallis non-parametric analysis of variance (Siegel 1956), followed by Dunn's multiple comparison test (Zar 1999).

Nomenclature generally follows Paczkowska and Chapman (2000).

RESULTS

Flora

A total of 145 taxa (species, subspecies, varieties, forms and hybrid taxa) from 79 genera and 39 families were recorded from collections within and adjacent to survey plots on the southern ranges of the Illara Greenstone Belt. Dominant families were Mimosaceae (20), Chenopodiaceae (12), Poaceae (12), Asteraceae (11) and Myrtaceae (11). Thirty one of the taxa were ephemerals and no introduced taxa were recorded.

Rare and Priority Flora

One declared rare flora (DRF) and one priority taxon, as defined by Atkins (2008), were recorded from the southern ranges of the Illara Greenstone Belt. Priority taxa are considered to be poorly known, potentially rare or threatened (Atkins 2008). Declared rare flora are taxa that are deemed to be rare or in danger of extinction in accordance with the Western Australian Wildlife Conservation Act 1950.

- *Ricinocarpos brevis* (DRF) was collected from a single specimen during the survey growing on the crest of BIF. *Ricinocarpos brevis* is a monoecious intricately twiggy shrub to 1.8 m, with small white flowers (Halford & Henderson 2007). A targeted survey in the following months found a population close to 3000 individuals on the range (Western Botanical 2008). The nearest population occurs on the Johnston Range, ca. 95km west of the range (Markey & Dillon, in press), but the species is known mainly from the Windarling Range, 105km to the south-west (Halford & Henderson 2007). At each of these locations, it is restricted to outcrops of banded ironstone at higher elevations (Halford & Henderson 2007).
- *Banksia arborea*, commonly known as the Yilgarn Dryandra, is a priority 4 shrub or tree growing to 6m and is endemic to banded ironstone hills in the eastern goldfields area of Western Australia. It was found growing on the crests of banded ironstone in shallow soils. This is the most northerly extent for this species, with the nearest known population occurring on the Yerilgee Hills, 35km to the south west (Markey & Dillon, in review).

Plant Communities

Sixty-one perennial taxa, excluding singletons, were used in the classification. Similarity profile (SIMPROF) analysis identified four significant groups or communities on the southern ranges of the Illara Greenstone Belt ($p < 0.05$; Clarke & Warwick 2001). The main division in the dendrogram separates Communities 1 and 2, found on ferruginous duricrust and crests and slopes of banded ironstone respectively, from Community 3 and 4, occurring on sites of banded ironstone and mafic geology (Fig. 2).

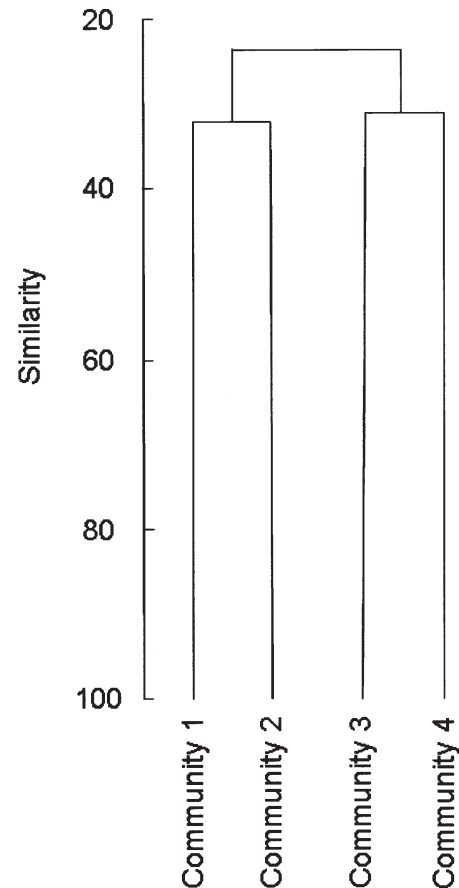


Figure 2. Dendrogram of the four group level classification of 50 quadrats established on southern range of the Illara greenstone belt.

Community One – This community occurred on sites with a ferruginous duricrust. It is described as open to mid-dense shrubland of *Acacia* spp. (*A. cockertoniana*, *A. effusifolia*, *A. stowardii* and *A. aneura*) over open to mid-dense shrubland of *Eremophila forrestii* and *Baeckea elderiana* over sparse to open shrubland of *Prostanthera althoferi* and *Mirbelia microphylla*. The community had the second highest species richness at 15 taxa (± 1.1) per plot. Indicator species were *Acacia aneura* var. *microcarpa*, *Sida* sp. Golden calyces glabrous (H.N. Foote 32), *A. effusifolia*, *Baeckea elderiana*, *Mirbelia microphylla*, *Eragrostis eriopoda*, *Euryomyrtus maidenii*, *Monachather paradoxus* and *Prostanthera althoferi* (Table 1).

Community Two – This community occurred on crests and slopes of banded ironstone on the entire length of the range. It is described as open to mid-dense shrublands of *A. aneura* and other *Acacia* spp. (*A. cockertoniana* or *A. quadrimarginea*) over open to mid-dense shrubland of *Philotheca brucei* subsp. *brucei*, *Olearia humilis* and *Eremophila* spp. (*E. latrobei*, *E. glutinosa* and *E. forrestii*) over isolate to sparse shrubland of *Sida* sp. Golden calyces glabrous (H.N. Foote 32) and *Cheilanthes sieberi* subsp. *sieberi*. This community had the lowest species richness with 12.5 taxa (± 0.4) per plot. Indicator species were *A. aneura* var. *microcarpa*, *Acacia cockertoniana*, *Sida* sp.

Golden calyces glabrous (H.N. Foote 32), *O. humilis*, *A. quadrimarginea* and *E. glutinosa* (Table 1).

Community Three – This was the most prevalent community on the range, composed of over half of the sites surveyed. It was found on the crest and slopes across the range primarily on banded ironstone, but also on a mixture of ironstone and mafic lithologies. It is described as open to sparse shrubland of *A. aneura* and *Acacia* spp. (*A. quadrimarginea* and/or *A. tetragonophylla*) over sparse to open shrublands of *Sida ectogama*, *Dodonaea rigida*, *Eremophila* spp. (*E. latrobei* and *E. forrestii*), *Scaevola spinescens* and *P. brucei* subsp. *brucei* over isolate to sparse shrublands and fernland of *Ptilotus obovatus* and *Cheilanthes sieberi* subsp. *sieberi*. This community had the highest species richness with 17.3 taxa (± 0.8) per plot. Indicator species were *D. rigida*, *A. tetragonophylla*, *P. obovatus*, *S. spinescens* and *S. ectogama* (Table 1).

Community Four – This community occurred on the slopes and crests of banded ironstone and mafic geology. It is described as open to mid-dense mallee woodland and shrubland of *Eucalyptus* spp. (*Eucalyptus salubris* or *Eucalyptus* aff. *griffithsii*) and *Acacia duriuscula* over open to mid-dense shrubland of *Eremophila* spp. (*E. oldfieldii* and *E. pantonii*) and *A. tetragonophylla* over open to sparse shrubland of *P. obovatus* and *Lepidium platypetalum*. Species richness was the lowest of all communities, with 14.2 taxa (± 0.8) per plot. Indicator species were *A. tetragonophylla*, *P. obovatus*, *S. spinescens*, *S. ectogama*, *A. duriuscula*, *Enchylaena tomentosa*, *Eucalyptus salubris*, *L. platypetalum*, *Eremophila pantonii*, *Olearia muelleri* and *S. spicatum* (Table 1).

Environmental correlates

Prior to analysis, soil cadmium and molybdenum were removed, as both were below detectable limits. Non-parametric analysis of variance found that 14 of the 17 soil elements were significantly different (Table 2), while only one of 12 site attributes were significantly different between the four communities (Table 3). Slope was significant but post-hoc comparison did not show any differences, although Communities 1 and 3 tended to occur on gentler slopes. The main differences occurred between Community 1, on the ferricrete community, and Community 4, the *Eucalyptus* woodland community. Communities 2 and 3, the main communities on the range, were intermediate between Communities 1 and 4.

Community 1 occurred on the most acidic (mean pH 4.2) and the least fertile sites on gentle slopes, generally on the footslopes of the range. This community had lower amounts of phosphorous, potassium and magnesium than Community 4 (*Eucalypt* woodland) while having the lowest amount of trace elements (Table 2). Community 4 had the highest fertility of all communities and was less acidic with more abundant trace elements.

Community 2, found only on ironstone, and Community 3, occurring on a mixture of ironstone and mafic substrates, showed intermediate soil chemistry between Communities 1 and 4. Community 2 was similar to Community 1, with similar acidic soils, and low fertility,

but showed no significant differences in soil chemistry to Community 3, apart from higher amounts of sulphur and more acidic soils. Community 3 had similar soil chemistry to Community 4. It was less acidic, but more fertile, with significantly higher amounts of phosphorous, and potassium than Community 1.

The three-dimensional SSH ordination (Fig. 3; stress = 0.1653) shows a gradual species turnover from Community 1 through to Community 4 and a similar pattern to the univariate analysis. The ordination also confirms the results of the univariate analysis and is best seen in Fig. 3a and b. The floristic communities grade from Community 1 in the upper right quadrant, through to Communities 2 and 3, which also overlap with Community 4 the lower left quadrant (Fig. 3b). Similar patterns of soil chemistry are also shown in the ordination, where Community 4 is correlated with higher levels of Na, Mn, Zn, Cu, Ni, Mg, K and Ca but is lower in S, while Community 1 shows the opposite trend (Fig. 3 c & d).

DISCUSSION

Flora

This survey completes the floristic survey of the Illaara Greenstone Belt, adding to floristic surveys of Mount Forrest-Mt Richardson (Meissner *et al.* 2009) and Brooking Hills (Meissner & Owen, in press). The flora of the southern ranges of the Illaara Greenstone Belt are comparable in terms of the number of taxa recorded within the nearby Yerilgee Hills (183 taxa; Markey & Dillon, in review) but more than in Brooking Hills to north (104 taxa; Meissner & Owen, in press) and Mount Forrest-Mount Richardson (114 taxa; Meissner *et al.* 2009).

While the southern ranges had a higher number of taxa compared to the rest of the greenstone belt, they had similar dominant families, namely Mimosaceae, Myoporaceae, Myrtaceae and Poaceae (Table 4). These families are typical of communities found in the Murchison Interim Biogeographic Regionalisation for Australia (IBRA) (Beard 1976). In total, 242 taxa have been recorded for the entire Illaara greenstone from the three surveys, with only 37 taxa common to all three ranges. Furthermore, nearly half of the flora in this survey (71 taxa) are unique to the southern ranges. This shift in species composition has been noted on other extensive BIF ranges (Markey & Dillon 2008) and on granite outcrops (Hopper *et al.* 1997) within Western Australia.

Endemic, rare and priority taxa are commonly found on the ironstone ranges within the Yilgarn Craton (Gibson *et al.* 2007). Several species in this survey are defined as endemic to the ironstone ranges, found only in BIF or ironstone. However, there were no taxa endemic to the southern ranges of the Illaara Greenstone Belt. *Banksia arborea* and *Ricinocarpos brevis* are both endemic to banded ironstone but are also classed as regional endemics, found only in a small area within the Eastern Goldfields. Such localised and restricted distributions associated with

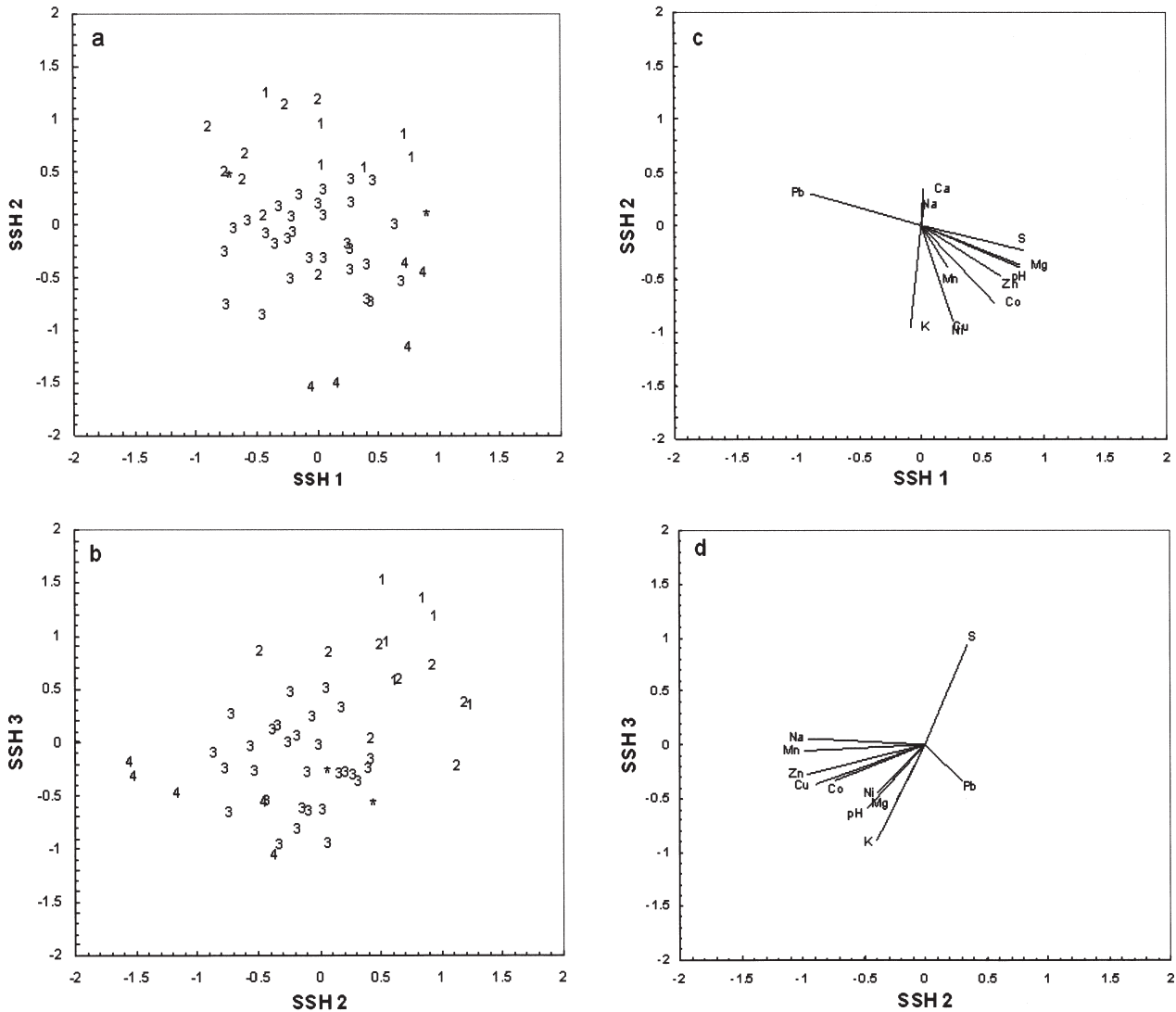


Figure 3. Three dimensional ordination showing Axes 1, 2 and 3 of the 50 quadrats established on southern ranges of the Illaara Greenstone Belt. The four communities are shown and lines represent the strength and direction of the best fit linear correlated variables ($P < 0.05$).

ironstone ranges are hypothesised to be the result of the ranges acting as refugia during periods of cooler and drier climates at glacial maxima (Byrne 2008).

Plant communities

Unlike previous surveys, topography and other site attributes, such as surficial rock, were not significantly correlated with the different communities. These relationships have been found on other ironstone ranges, including nearby Yerilgee Hills (Markey & Dillon, in review b). The greatest distinction occurred between communities on ironstone substrates and those on a mixture of ironstone and mafic substrate. This is reflected in the chemical composition of the soils, with mafic and ironstone communities high in calcium, magnesium, potassium and manganese, that are characteristic of soils derived from mafic substrates (Gray & Murphy 2002).

The two common communities found on the range, Communities 2 and 3, both correspond to the stony ironstone mulga shrublands (SIMS) described by Pringle *et al.* (1994). However, at a finer scale, these communities are quite distinct from each other, with differences in their understorey with *O. humilis* and *E. glutinosa* in Community 2 and *D. rigida* and *S. ectogama* in Community 3.

Communities 2 and 3 were similar in terms of soil chemistry, with the exceptions of soil pH and sulphur. Differences between the two communities seemed to be based upon substrate lithology, with Community 2 occurring mainly on BIF, while Community 3 was found on a mixture of BIF and mafic bedrock. A gradual shift in species composition between the communities can be seen in the ordination and soil chemistry was intermediate between the extremes of mafic and laterite lithologies.

The most distinct community recorded was that

restricted to small areas flanking the range on ferruginous duricrust, or ferricrete (Community 1). This community was distinctive in terms of several taxa, notably *A. effusifolia*, *Baeckea elderiana*, *Mirbelia microphylla* and *Euryomyrtus maidenii*. This community occurred on the least fertile sites, which is not surprising given that ferricrete is a product of deep weathering of the greenstone in the Tertiary, which would lead to the leaching of mobile elements (Britt *et al.* 2001). In contrast, the eucalypt woodland (Community 4) occurred on the most fertile sites. This pattern has been observed on other ranges such as Koolanooka Hills (Meissner & Caruso 2008a), where the eucalypt woodlands occurred on richer and deeper soils.

The southern ranges of the Illaara Greenstone Belt share communities similar to those recorded on the Brooking Hills and Mount Forrest-Mount Richardson, as discussed previously. Meissner and Owen (in press) hypothesised that the survey of southern part of the Illaara Greenstone Belt would find different set of communities indicating further species turnover. A preliminary analysis combining all the survey data collected for the entire greenstone belt found that each section had significantly different communities from each other (ANOSIM Global $R = 0.321$, $P < 0.01$, Clarke and Warwick 2001). This species turnover from north to south along the range is probably due to the primary environmental gradients of increasing rainfall and decreasing aridity (Beard 1976).

Conservation

Currently, the southern ranges of the Illaara Greenstone Belt occur on unallocated Crown Land and are not located within Western Australian conservation estate. Mining exploration is being undertaken in the region but currently the major land use within the range is sandalwood extraction, which requires an extensive system of tracks through the vegetation.

ACKNOWLEDGEMENTS

We would like to thank the following people: Katrina Walton, WA Chemcentre for Soil Analysis; the staff at the Western Australian Herbarium, especially Karina Knight; Bruce Maslin, Rob Davies and Paul Wilson for their taxonomic expertise. Stephen van Leeuwen and Neil Gibson are also thanked for their advice and support. Permits for flora collection were issued by the Western Australian Department of Environment and Conservation. This project is part of the Biodiversity Conservation Initiative (BCI) of the Saving Our Species (SOS) Program, and has been funded by the Department of Environment and Conservation, Western Australia.

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APPENDIX

Flora list for the southern ranges of the Illaara Greenstone Belt, including all taxa from the sampling quadrats and adjacent areas. Nomenclature follows Paczkowska and Chapman (2000). R = declared rare flora

Adiantaceae

- Cheilanthes brownii*
Cheilanthes sieberi subsp. *sieberi*

Amaranthaceae

- Ptilotus aevoides*
Ptilotus exaltatus
Ptilotus gaudichaudii var. *gaudichaudii*
Ptilotus helipteroides
Ptilotus obovatus

Anthericaceae

- Thysanotus manglesianus*

Apocynaceae

- Alyxia buxifolia*

Asclepiadaceae

- Marsdenia australis*

Asteraceae

- Brachyscome ciliocarpa*
Calotis hispidula
Helipterum craspedioides
Lawrencella rosea
Myriocephalus guerinae
Olearia humilis
Olearia muelleri
Podolepis gardneri
Rhodanthe battii
Vittadinia humerata
Waitzia acuminata var. *acuminata*

Brassicaceae

- Lepidium platypetalum*

Caesalpiniaceae

- Senna artemisioides* subsp. *filifolia*
Senna artemisioides subsp. *x artemisioides*
Senna artemisioides subsp. *x artemisioides x filifolia*
Senna charlesiana
Senna glutinosa subsp. *chatelainiana x charlesiana*

Casuarinaceae

- Allocasuarina acutivalvis* subsp. *acutivalvis*
Casuarina pauper

Chenopodiaceae

- Enchylaena lanata*
Enchylaena tomentosa
Maireana convexa
Maireana georgei
Maireana planifolia
Maireana triptera
Rhagodia eremaea
Sclerolaena eriacantha
Sclerolaena eurotioides
Sclerolaena fusiformis
Sclerolaena gardneri

Convolvulaceae

- Duperreya sericea*

Crassulaceae

- Crassula tetramera*

Cupressaceae

- Callitris columellaris*

Epacridaceae

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

Euphorbiaceae

- Euphorbia tannensis* subsp. *eremophila*
Ricinocarpos brevis R

Geraniaceae

- Erodium cygnorum*

Goodeniaceae

- Brunonia australis*
Dampiera roycei
Goodenia havilandii
Goodenia macropectra
Goodenia mimuloides
Scaevola spinescens
Velleia hispida
Velleia rosea

Haloragaceae

- Gonocarpus nodulosus*
Haloragis odontocarpa forma *octoforma*
Haloragis trigonocarpa

Lamiaceae

- Prostanthera althoferi*
Prostanthera althoferi subsp. *althoferi x campbellii*
Spartothamnella teucriiflora
Wrixonia prostantheroides

Lobeliaceae

- Isotoma petraea*

Loranthaceae

- Amyema miquelii*
Amyema nestor
Lysiana casuarinae

Malvaceae

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

Mimosaceae

- Acacia aneura* green (Meissner & Wright 2555)
Acacia aneura hybrid
Acacia aneura var. *alata/microcarpa* (BRM 9083)
Acacia aneura var. *argentea* (BRM 9713.)
Acacia aneura var. *argentea* (narrow phyllode variant) (BRM 9745)
Acacia aneura var. *argentea* (short phyllode variant) (BRM 9300)
Acacia aneura var. *microcarpa* (BRM 9794)

Acacia aneura var. *microcarpa* (broad, incurved phyllode variant) (BRM 9929)
Acacia aneura var. *microcarpa* hybrid
Acacia aneura var. *tenuis* (BRM 9296)
Acacia burkittii
Acacia cf. *oswaldii*
Acacia cockertoniana
Acacia duriuscula
Acacia effusifolia
Acacia exocarpoides
Acacia quadrimarginea
Acacia ramulosa var. *linophylla*
Acacia ramulosa var. *ramulosa*
Acacia tetragonophylla

Myoporaceae

Eremophila alternifolia
Eremophila forrestii subsp. *forrestii*
Eremophila georgei
Eremophila glutinosa
Eremophila latrobei subsp. *latrobei*
Eremophila oldfieldii subsp. *angustifolia*
Eremophila pantonii

Myrtaceae

Baeckea elderiana
Eucalyptus aff. *griffithsii* (Meissner & Wright 2590)
Eucalyptus ebbanoensis subsp. *ebbanoensis*
Eucalyptus leptopoda subsp. *subluta*
Eucalyptus oleosa subsp. *oleosa*
Eucalyptus orbifolia
Eucalyptus salubris
Euryomyrtus maidenii
Melaleuca leiocarpa
Micromyrtus flaviflora
Verticordia interioris

Papilionaceae

Mirbelia microphylla
Swainsona kingii

Phormiaceae

Dianella revoluta var. *divaricata*

Pittosporaceae

Bursaria occidentalis
Pittosporum angustifolium

Poaceae

Aristida contorta
Austrostipa elegantissima
Austrostipa scabra
Austrostipa sp.
Austrostipa trichophylla
Enneapogon caerulescens
Eragrostis eriopoda
Eragrostis lacunaria
Eriachne mucronata
Eriachne pulchella subsp. *pulchella*
Monachather paradoxus
Paspalidium basicladum

Proteaceae

Banksia arborea
Grevillea haplantha subsp. *haplantha*
Grevillea nematophylla subsp. *supraplana*
Hakea recurva subsp. *recurva*

Rhamnaceae

Cryptandra connata

Rubiaceae

Psydrax latifolia
Psydrax suaveolens

Rutaceae

Philothea brucei subsp. *brucei*

Santalaceae

Santalum spicatum

Sapindaceae

Dodonaea lobulata
Dodonaea petiolaris
Dodonaea rigida

Solanaceae

Solanum ellipticum
Solanum ferocissimum
Solanum lasiophyllum
Solanum nummularium

Sterculiaceae

Brachychiton gregorii

Violaceae

Hybanthus floribundus subsp. *curvifolius*

Zygophyllaceae

Zygophyllum eichleri

Table 1

Sorted two-way table of quadrats established on southern ranges of the Illaara Greenstone Belt showing species by community type. Taxa shaded grey within a community are indicator species determined by INDVAL (Dufréne & Legendre 1997) at the four group level ($p < 0.05$).

	One	Two	Three	Four
<i>Abutilon cryptopetalum</i>			■	
<i>Solanum ellipticum</i>			■	
<i>Rhagodia eremaea</i>			■	
<i>Acacia burkittii</i>			■	
<i>Amyema nestor</i>			■	
<i>Abutilon oxycarpum</i>			■	
<i>Psyrax suaveolens</i>			■	
<i>Spartothamnella teucriflora</i>			■	
<i>Acacia aneura</i> var. <i>argentea</i>	■	■	■	■
<i>Cheilanthes sieberi</i> subsp. <i>sieberi</i>	■	■	■	■
<i>Dodonaea rigida</i>	■	■	■	■
<i>Eremophila latrobei</i> subsp. <i>latrobei</i>	■	■	■	■
<i>Eremophila forrestii</i>	■	■	■	■
<i>Acacia ramulosa</i>	■	■	■	■
<i>Marsdenia australis</i>	■	■	■	■
<i>Solanum lasiophyllum</i>	■	■	■	■
<i>Sida</i> sp. dark green fruits (S. van Leeuwen 2260)	■	■	■	■
<i>Acacia tetragonophylla</i>	■	■	■	■
<i>Ptilotus obovatus</i>	■	■	■	■
<i>Scaevola spinescens</i>	■	■	■	■
<i>Sida ectogama</i>	■	■	■	■
<i>Eremophila oldfieldii</i> subsp. <i>angustifolia</i>	■	■	■	■
<i>Senna artemisioides</i> subsp. <i>filifolia</i>	■	■	■	■
<i>Dodonaea lobulata</i>	■	■	■	■
<i>Dianella revoluta</i> var. <i>divaricata</i>	■	■	■	■
<i>Hakea recurva</i> subsp. <i>recurva</i>	■	■	■	■
<i>Lysiana casuarinae</i>	■	■	■	■
<i>Maireana planifolia</i>	■	■	■	■
<i>Solanum ferocissimum</i>	■	■	■	■
<i>Acacia aneura</i> var. <i>microcarpa</i>	■	■	■	■
<i>Brachychiton gregorii</i>	■	■	■	■
<i>Eremophila georgei</i>	■	■	■	■
<i>Acacia cockertoniana</i>	■	■	■	■
<i>Sida</i> sp. Golden calyces glabrous (H.N. Foote 32)	■	■	■	■
<i>Olearia humilis</i>	■	■	■	■
<i>Acacia exocarpoides</i>	■	■	■	■
<i>Acacia quadrimarginea</i>	■	■	■	■
<i>Philotheca brucei</i> subsp. <i>brucei</i>	■	■	■	■
<i>Dodonaea petiolaris</i>	■	■	■	■
<i>Dryandra arborea</i>	■	■	■	■
<i>Eremophila glutinosa</i>	■	■	■	■
<i>Austrostipa trichophylla</i>	■	■	■	■
<i>Melaleuca leiocarpa</i>	■	■	■	■
<i>Acacia duriscula</i>	■	■	■	■
<i>Casuarina pauper</i>	■	■	■	■
<i>Enchylaena tomentosa</i>	■	■	■	■
<i>Eucalyptus salubris</i>	■	■	■	■
<i>Lepidium platypetalum</i>	■	■	■	■
<i>Allocasuarina acutivalvis</i> subsp. <i>acutivalvis</i>	■	■	■	■
<i>Eremophila pantonii</i>	■	■	■	■
<i>Olearia muelleri</i>	■	■	■	■
<i>Santalum spicatum</i>	■	■	■	■
<i>Austrostipa scabra</i>	■	■	■	■
<i>Eucalyptus</i> aff. <i>griffithsii</i>	■	■	■	■
<i>Acacia effusifolia</i>	■	■	■	■
<i>Baeckea elderiana</i>	■	■	■	■
<i>Mirbelia microphylla</i>	■	■	■	■
<i>Eragrostis eriopoda</i>	■	■	■	■
<i>Euryomyrtus maidenii</i>	■	■	■	■
<i>Monachather paradoxus</i>	■	■	■	■
<i>Prostanthera althoferi</i>	■	■	■	■

Table 2

Mean values for soil attributes (measured in mg/kg except EC and pH) by plant community type. Differences between ranked values tested using Kruskal-Wallis non-parametric analysis of variance. Standard errors in parentheses. a, b and c represent significant differences between community types at $P < 0.05$ determined by Dunns *post-hoc* test (n = number of quadrats, P = probability). * *post-hoc* test showed no significance.

Attribute	Community				P-value
	One n = 6	Two n = 8	Three n = 29	Four n = 5	
pH	4.2 (0.03) ^a	4.3 (0.1) ^a	4.9 (0.1) ^b	6.1 (0.2) ^b	< 0.0001
P	4.8 (1.5) ^a	6.9 (0.8) ^{ab}	10.4 (1.3) ^b	8.6 (1.0) ^b	0.002
K	64 (8) ^a	130 (9) ^{ab}	170 (10) ^b	210 (20) ^b	< 0.0001
Mg	18 (1) ^a	49 (7) ^{ab}	105 (18) ^{bc}	250 (43) ^c	< 0.0001
OrgC	0.79 (0.06)	1.4 (0.1)	1.2 (0.1)	1.3 (0.1)	0.064
Total N*	0.062 (0.003)	0.098 (0.007)	0.086 (0.01)	0.10 (0.01)	0.0236
B	0.075 (0.025) ^a	0.15 (0.02) ^{ab}	0.16 (0.01) ^b	0.32 (0.07) ^b	0.0019
Ca	104 (11) ^a	255 (40) ^{ab}	533 (69) ^{bc}	1300 (368) ^c	< 0.0001
Co	0.065 (0.001) ^a	0.36 (0.15) ^{ab}	1.34 (0.24) ^{bc}	3.7 (0.62) ^c	< 0.0001
Cu	0.8 (0.1) ^a	1.3 (0.2) ^{ab}	2.0 (0.2) ^{bc}	5.0 (1.4) ^c	< 0.0001
Fe	40 (2)	56 (7)	53 (6)	60 (4)	0.149
Mn	13 (2) ^a	48 (16) ^{ab}	93 (17) ^{bc}	248 (59) ^c	< 0.0001
Na	0.58 (0.08) ^a	2.8 (1.8) ^{ab}	2.9 (0.4) ^{bc}	14.0 (3.8) ^c	0.0004
Ni	0.15 (0.02) ^a	0.35 (0.08) ^{ab}	0.71 (0.13) ^{bc}	1.5 (0.2) ^c	< 0.0001
Pb	0.57 (0.03)	0.74 (0.11)	0.65 (0.05)	0.5 (0.1)	0.251
S	14.8 (0.9) ^a	14.5 (1.4) ^a	8.1 (0.7) ^b	9.8 (1.0) ^{ab}	0.0001
Zn	0.76 (0.09) ^a	1.34 (0.14) ^{ab}	2.02 (0.12) ^b	2.9 (0.7) ^b	< 0.0001

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, 5 – hillock); Land type (1 – hillcrest, 2 – hill slope, 3 – foot slope, 4 – mound); Disturbance (0 – no effective disturbance, 1 – no effective disturbance except grazing by hoofed animals); Maximum size of coarse fragments (CF Size) (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 non–parametric analysis of variance. Standard errors in parentheses. **post-hoc* test showed no significance.

Attribute	Community 1 n = 6	Community 2 n = 8	Community 3 n = 29	Community 4 n = 5	P-value
Aspect	217.5 (53.8)	196.9 (45.8)	184.7 (21.1)	207.0 (58.0)	0.925
Slope*	2.0 (0.4)	7.5 (1.2)	3.9 (0.8)	8.0 (1.5)	0.0084
Morph Type	2.7 (0.6)	2.5 (0.5)	2.7 (0.2)	2.8 (0.7)	0.9665
Landtype	0.3 (0.2)	0.3 (0.2)	0.3 (0.1)	0.2 (0.2)	0.9008
Disturbance	1.2 (0.2)	1.1 (0.1)	1.2 (0.1)	1.4 (0.4)	0.9695
CF_Abundance	4 (0.3)	4.5 (0.3)	3.8 (0.1)	4.4 (0.2)	0.0757
CF_Size	3.5 (0.5)	4.0 (0.3)	4.0 (0.2)	5.0 (0.3)	0.1913
RO_Abundance	0.3 (0.2)	1.3 (0.5)	0.9 (0.3)	0.6 (0.2)	0.75
Runoff	1.5 (0.2)	2.3 (0.3)	1.8 (0.2)	2.2 (0.5)	0.3837
Soil Depth	1.8 (0.2)	1.8 (0.3)	2.0 (0.1)	2.2 (0.2)	0.6057
%Leaf_Litter	1.8 (0.2)	2.0 (0.3)	1.9 (0.1)	2.4 (0.2)	0.4318
%Bare_Ground	4.0 (0)	3.8 (0.2)	3.7 (0.1)	3.8 (0.2)	0.4619

Table 4

A comparison of the floristic data on the Illaara Greenstone Belt.

	This survey	Brooking Hills	Mount Forrest - Mount Richardson
Flora	145	104	114
DRF	1	-	-
Priority	1	-	4
Ephemerals	31	22	34
<i>Eucalyptus</i>	6	0	7
<i>Acacia</i>	20	13	9
<i>Eremophila</i>	7	8	13
<i>Senna</i>	5	9	2

Flora and vegetation of banded iron formations of the Yilgarn Craton: western Narryer Terrane

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ABSTRACT

The Narryer Terrane is the oldest component of the Yilgarn Craton, located in the north-western part of the Murchison Interim Biogeographic Regionalisation of Australia (IBRA) region. Previous work has surveyed the flora and vegetation of Jack Hills, the main greenstone belt within the terrane. This paper describes the flora and vegetation of the remaining occurrences of banded iron formations on the Narryer Terrane. One hundred and fifty one taxa were recorded from the western Narryer Terrane, with two species of conservation significance, *Philothea citrina* and *Calytrix erosipetala*. Three range extensions were recorded including *Swainsona rotunda*, previously only known from the type specimen. Four communities were determined from hierarchical classification and the distribution of plant communities was correlated with soil nutrients. The most widespread community occurred across all positions in the landscape, on sites with greater fertility and less acidic soil. All communities occurred on relatively low terrain, characterised by gently inclined slopes, low rock cover and shallow soils. Vegetation within the survey region was in poor condition due to grazing by feral goats. The ironstone ranges are currently within mining tenements but no current exploration is underway. None of the ranges are within the Western Australian conservation estate.

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

INTRODUCTION

The Narryer Terrane is the most ancient known component of the Yilgarn Craton and contains the oldest known rocks and zircon crystals in metasedimentary rocks in Australia, dating to c. 3.73 Ga (Kinny *et al.* 1998) and c.4.4 Ga (Wilde *et al.* 2001) respectively. The terrane is located in the north western part of the Murchison Interim Biogeographic Regionalisation of Australia (IBRA) (Environment Australia 2000) region, with pastoralism the predominant land use in the area.

Previous surveys in the area have concentrated upon broadscale descriptions of the vegetation (Beard 1976, Curry *et al.* 1994). A more recent survey of the Terrane has described the flora and vegetation of Jack Hills (Meissner & Caruso 2008a), the main greenstone belt within Narryer Terrane. The remaining occurrences of banded iron formation (BIF) on the terrane occur west of the Murchison River, from Mt Narryer to Mt Nairn, across three pastoral leases, and are the focus of this paper.

The objective of the study is to describe the flora and plant communities of the banded ironstone ranges on the western Narryer Terrane and their relationships with environmental variables, and to provide baseline information for future management.

Geology and Geomorphology

The Narryer Terrane is composed mainly of granite rocks and granitic gneisses from early to middle Archaean (>2.2 Ga) interbedded with minor deformed and metamorphosed banded iron formations, mafic and ultramafic intrusive rocks and metasedimentary rocks (Cassidy *et al.* 2006). Banded iron formations occur either within the Mindle metasedimentary rocks as orthopyroxene-bearing BIF, cropping discontinuously as thin bands in gneisses northeast of Mount Narryer, or within Meeberrie and Dugel gneisses, as metamorphosed banded and granular iron formations (Williams & Myers, 1987). The occurrences of BIF increase around Meegea Hill and north towards Mount Nairn (Williams *et al.* 1983).

The geomorphology of the region is variable, dominated by areas of low relief to localised areas of high relief composed of more resistant rocks. Mount Dugel and Mt Narryer form the highest points at the southern and northern ends of a low strike ridge, composed mainly of quartzites and gneisses, 27km long and 3km wide (Williams & Myers 1987).

Climate

The climate of the region is classified as arid and characterised by hot, dry summers and mild winters. Rainfall is bimodal, with significant rainfall events

occurring in winter and summer. The two highest mean monthly rainfalls at Errabiddy Station (120 km NE of Mt Dugel) occur in January and June (31.2 mm and 30.5 mm respectively), with the highest ever daily rainfall of 143.8 mm occurring in January 1963. Mean annual rainfall at Errabiddy is 210.3 mm, with much variation (80.9 mm 1st decile; 354.0 mm 9th decile; recorded 1936 to 2005).

Summer rainfall is influenced by cyclonic activity off the north-west coast of Western Australia and convectional activity bringing either isolated thunderstorms in localised areas, or widespread rainfall (Curry *et al.* 1994). In contrast, winter rainfall is associated with low pressure systems originating in the Southern Ocean. The cold fronts arising from the south west systems often weaken as they move inland and result in isolated showers and strong winds (Curry *et al.* 1994).

The highest maximum temperatures occur during summer (January mean maximum temperature 39.7 °C and mean 16.4 days above 40 °C). Winters are mild with lowest mean maximum temperatures recorded for July of 20.6 °C. Temperatures rarely fall below 2 °C in winter, with a mean minimum of 7.4 °C in July.

Vegetation

The Narryer Terrane occurs within the Byro sub-region of the Murchison phytogeographic region (Beard 1976). The Byro sub-region is dominated by *Acacia aneura* (mulga) in the northeast, occurring as continuous sparse woodlands, or as scattered trees in *Acacia ramulosa* scrub (Beard 1976). In particular, Beard (1976) mapped the hills around Mt Narryer, Mt Dugel, Meegea Hill and Mt Nairn as various associations of *A. aneura* scrub. The most common association was characterised by *A. aneura*, *Acacia atopa*, *Acacia ramulosa*, *Acacia kempeana*, *Eremophila fraseri*, *Eremophila foliosissima*, *Eremophila platycalyx*, *Schoenia cassiniana*, *Myriocephalus guerinae* and *Podolepis auriculata*.

A flora and vegetation survey of Jack Hills, the nearest ironstone range approximately 50 km to the east of Mt Narryer, described six vegetation communities (Meissner & Caruso, 2008a). These communities were characterised by *A. aneura* shrublands with associations of different *Acacia* spp. and *Eremophila* spp. An unusual and restricted spinifex community was recorded on the higher elevations, and was composed of a different suite of species to communities recorded elsewhere across the range.

The present study area includes four different land systems, the Agamemnon, Mindura, Narryer and Thomas, as defined by Curry *et al.* (1994). Land systems describe an area based on landform, geological features and major vegetation types. All four land systems have similar landforms and geomorphology that encompass a catenary sequence of rocky hills and ridges, rounded summits, stony slopes to stony plains, drainage flats, floors and channels.

The rocky hills, low hills and breakaways of Agamemnon, Mindura and Thomas land systems support Rocky Hill Mixed Shrublands characterised by *Acacia grasbyi*, *Eremophila glutinosa*, *Solanum ashbyae*, *Tribulus platypterus*, *Cheilanthes austrotenuifolia* and *Spyridium*

sp. (Curry *et al.* 1994). These give way to Stony Mulga Mixed Shrubland on the stony slopes, footslopes and plains, dominated by *A. aneura*, *A. pruinocarpa*, *A. grasbyi*, *Eremophila macmillaniana*, *E. spathulata*, *E. fraseri*, *E. freelingii*, *E. spathulata*, *Solanum lasiophyllum*, *Ptilotus rotundifolius*, *Senna helmsii*, *Ptilotus obovatus* and *Ptilotus schwartzii*. Footslopes of Narryer and Thomas land systems are typified by Stony Snakewood Shrubland, characterised by *A. aneura*, *A. victoriae* and *Hakea preissii* with either *Senna* or *Eremophila* species as mid-stratum and high cover of chenopod species in the lower stratum (Curry *et al.* 1994).

METHODS

The study area encompasses three pastoral leases, Mt Narryer, Milly Milly and Boolardy Stations. Fifty one 20 x 20 m quadrats were established on the crests, slopes and foot slopes of the ironstone hills on the pastoral leases, in August 2007 (Fig. 1). The quadrats were established using an environmentally stratified approach to cover the major geographical, geomorphologic and floristic variation but biased (non random) as there were restrictions in access to the range. Each quadrat was permanently marked with four steel fence droppers and its position was determined using a Global Positioning System (GPS) unit. All vascular plants within the quadrat were recorded and collected for later identification at the Western Australian Herbarium.

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

Twenty soil samples were collected from the upper 10 cm of the soil profile within each quadrat. The soil was bulked and the 2 mm fraction analysed for B, Ca, Cd, Co, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S and Zn using the Mehlich No. 3 procedure (Mehlich 1984). The extracted samples were then analysed using Inductively Coupled Plasma - Atomic Emission Spectrometer (ICP-AES). This procedure is an effective and cost-efficient alternative to traditional methods for evaluating soil fertility and has been calibrated for Western Australian soils (Walton & Allen 2004). pH was measured in 0.01 M CaCl₂ at soil to solution ratio of 1:5.

Quadrats were classified on the basis of similarity in species composition on perennial species only, to be consistent with previous studies of banded ironstone ranges (Gibson 2004 a, b). The quadrat and species classifications were undertaken using flexible UPMGA of Bray and Curtis similarities (unweighted pair-group mean average; $\beta = 0$; Belbin 1989). The quadrat classification was followed by similarity profile (SIMPROF) testing to determine the significance of internal group structures using permutation testing (Clarke & Gorley 2006).

Similarity percentages (SIMPER), based upon a Bray and Curtis similarity resemblance matrix, were used to

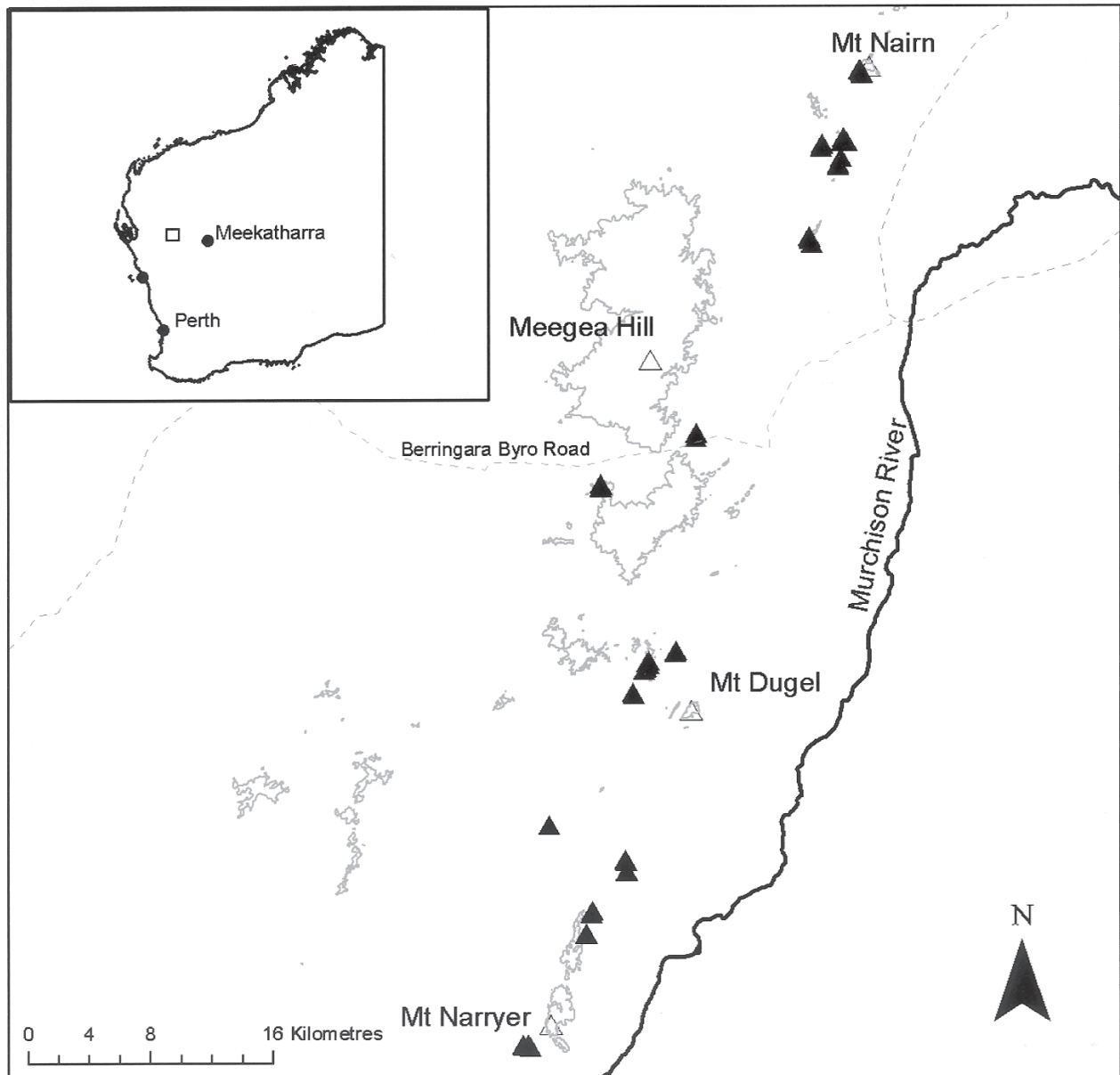


Figure 1. Location of the western Narryer Terrane study area, showing the location of the 51 sites (▲). The 340 m contour is shown with the highest peaks, Mt Narryer (514m) and Mt Dugel (461m).

determine typifying species for each community. SIMPER analyses the contribution of individual species to the average similarity within groups and average dissimilarity between groups (Clarke & Warwick 2001).

Quadrats were ordinated using semi-strong hybrid (SSH) multidimensional scaling, correlations of environmental variables were determined using Principal Component Correlation (PCC) routine and significance determined by Monte-Carlo Attributes in Ordination (MCAO) routine in PATN (Belbin 1989). PCC is a routine that runs multiple linear regressions on the variables and the ordination coordinates, resulting in a vector for each variable within the ordination plot. The MCAO is a Monte-Carlo permutation test that determines the robustness of the PCC results by randomly assigning values

of variables to objects and then running the PCC routine (Belbin 1989).

Statistical relationships between quadrat groups were tested using Kruskal-Wallis non parametric analysis of variance (Siegel 1956), followed by non-parametric comparison (Zar 1999).

Nomenclature generally follows Paczkowska and Chapman (2000).

RESULTS

Flora

A total of 151 species within 74 genera and 38 families were recorded on the ironstone ranges of the terrane. Forty

one taxa were ephemerals and no introduced taxa were recorded. The flora was dominated by Asteraceae (nine taxa), Chenopodiaceae (13), Mimosaceae (18), Myoporaceae (13) and Poaceae (12). Seven taxa were unidentifiable due either to grazing by goats, resulting in stunted growth, or in the case of the ephemeral genera, they had not begun to flower.

A. aneura, commonly known as mulga, was the dominant species within the vegetation, occurring in nearly every plot. Mulga is a highly variable species, consisting of *A. aneura* and close relatives, and can be difficult to identify in the field and the herbarium (Miller *et al.* 2002). Currently, a project is underway to clarify the genetic relationships and determine characters for identification of *A. aneura* variants (B. Maslin, pers. comm.¹). To this end, we have classified our collections of mulga into morphotypes, based upon phyllode dimensions and shape, presence of glands on new growth, and ribbing on the branchlets, that may prove to be useful characters (B. Maslin pers. comm.²).

Taxonomic interest

Two taxa were collected that had sufficient material to be of taxonomic interest. *Acacia* sp. Yellow Pulvinus (R. Meissner & G. Owen 1607) is a shrub to 5m and is possibly related to *Acacia coolgardiensis*. It has a distinctive bright yellow pulvinus at least 1mm at the base of a terete phyllode and was found growing on a small laterised banded ironstone hill near Mount Narryer.

Wurmbea sp. Boolardy (Meissner & Owen 1502) was originally identified as *Wurmbea deserticola* but upon further examination by the taxonomic authority on *Wurmbea*, it was found to be a unique species (Macfarlane pers. comm.^{2,3}). It was collected on the laterite crest and is a cormous, perennial herb to 25 cm, with three leaves. It was fruiting at the time of collection. This is the only known collection of this taxon and may be an endemic to the area.

Rare and Priority Flora

Priority taxa are considered to be poorly known, potentially rare or threatened taxa (Atkins 2008). Two priority species were collected during the survey, *Philotheca citrina* (Priority 1) and *Calytrix erosipetala* (Priority 3).

Philotheca citrina (P1) is a perennial shrub to 1.3 m with pale yellow flowers. It was discovered in 1985 during a survey of the Murchison Basin (Wilson 1992). It is restricted to a small area of the northwest Murchison IBRA region, mainly growing on laterite breakaways and granite outcrops. It has been collected previously from the area, on Byro and Milly Milly Stations. In this survey, it was found growing in laterite breakaway in the Mt Dugel area.

Calytrix erosipetala (P3) is a low shrub to 60 cm with pink flowers. It is closely related to *Calytrix warburtonensis*, but differs in having an erose to suberose petal margin, sub-orbicular thecae and longer hypanthium with a shorter free region (Craven 1987). The erose to suberose petal margin is characteristic of this species and is known in only two other species found in the Northern Territory (Craven 1987). It was recorded on laterised ironstone breakaway, a characteristic habitat, in the Mt Dugel area. As well as an additional population record, the collection also marks a range extension, with the nearest population 200km to the south east.

Range Extensions

This survey recorded range extensions for three species are defined as any new record more than 100km from the nearest population.

Swainsona rotunda is a leguminous prostrate herb with lilac flowers. It was previously known only from the type specimen, collected near the Pink Hills, 150km north of the collections from this survey. This species is characterised by medifixed hairs and 1–4 flowers per inflorescence (Thompson 1993). In addition, previous collections from Jack Hill were redetermined as *S. rotunda*.

Dodonaea pinifolia is a dioecious shrub to 1 m, flowering from October to January, growing on laterite on hills, granite or sandstone outcrops. In this survey, the specimens collected were heavily grazed and found growing near Mount Dugel, on ironstone and sandstone hills. The nearest know populations is located 250km to the southwest.

Iseilema eremaicum, or Flinders Grass, is a tufted grass to 29 cm, collected mostly on clay soils and seasonally wet areas. It also occurs in South Australia, Northern Territory and Queensland. The nearest populations occur 200km north-east and 200km north-west of the study area.

Plant Communities

One hundred and forty three taxa were recorded in the 51 quadrats with twelve taxa removed due to taxonomic uncertainty (ie. unidentifiable to species level). Ephemerals and singletons were removed resulting in a total of seventy taxa used in the final analysis. Eight taxa were combined into four species groups, such as *Eremophila phyllopoda* subsp. *phyllopoda* and *Eremophila phyllopoda* combined into *E. phyllopoda*.

Four communities were determined by SIMPROF ($p < 0.05$). The first division in the dendrogram separates Communities 1 and 2 from Communities 3 and 4 at approximately 17 % similarity (Fig. 2). Community 1, found at two sites, then splits from Community 2, found on the upper slopes and crests of the western Narryer Terrane. The remaining two communities, separate at c. 20% similarity. Community 3 was found mainly on laterite breakaways while Community 4 was the most widespread community on slopes and crests of the terrane.

Community 1 consisted of two sites found on a lower slope near Meegea Hills and a mid-slope on Mt Nairn.

¹ ² Bruce Maslin, Western Australian Herbarium, Department of Environment and Conservation, Kensington

² ³ Terry Macfarlane, Department of Environment and Conservation, Manjimup.

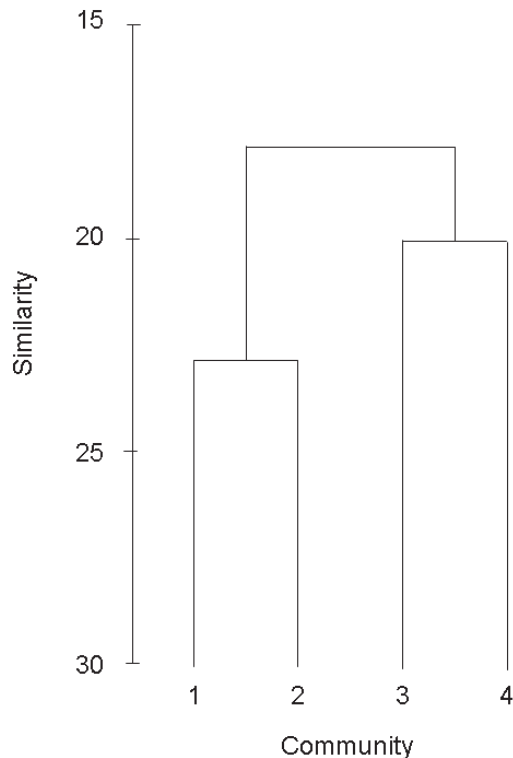


Figure 2. Dendrogram of the 4 group level classification of 51 quadrats established on the western Narryer terrane.

This community was characterised by open shrublands of *A. aneura* over shrublands of *E. phyllopoda* with a mean species richness of 9.5 ± 3.5 taxa per site. This community had the lowest species richness and may be a species poor representation of Community 2. The typifying species of Community 1 were *E. phyllopoda*, *Wurmbea inframediana* and *A. aneura* (terete/compressed morphotype; Table 1).

Community 2 comprised six sites found across the range on upper slopes and crests with low cover of rock outcrop. It can be described as open shrublands of *A. aneura* and *Grevillea berryana* over shrublands of *Eremophila latrobei* subsp. *latrobei* and *E. glutinosa* over sparse grassland of *Monachather paradoxus*. The community shares the highest species richness of 16.0 ± 5.7 taxa per site. It was characterised by key species of *M. paradoxus*, *E. latrobei* subsp. *latrobei*, *E. glutinosa* and *G. berryana* (Table 1).

Community 3 was found on slopes and summits of laterised ironstone breakaways and consisted of nine sites with five of the sites occurring in surrounding area of Mt Dugel. The community was characterised by sparse to open woodlands and shrublands of *A. aneura*, *Acacia citrinoviridis* and *Acacia pruinocarpa* over sparse to open shrublands of *E. phyllopoda*, *Dodonaea viscosa* subsp. *mucronata*, *Micromyrtus sulphurea*, *Calytrix erosipetala*, *Philotheca citrina*, *Philotheca brucei* subsp. *cinerea*, *Eremophila georgei*, *Thryptomene decussata* and *Ptilotus obovatus*. The community had a species richness of 15.0 ± 4.6 taxa per site and typifying taxa were *Ptilotus*

obovatus, *Solanum ashbyae* / *lasiopetalum* complex, *A. aneura* (ribbed morphotype) and *Monachather paradoxus* (Table 1).

Community 4 was the most common community found on the ironstone hills with 35 sites on slopes and crests. It is described as sparse to open woodlands and shrublands of *A. aneura* and other *Acacia* spp. (*Acacia citrinoviridis*, *Acacia tetragonophylla*, *Acacia quadrimarginea*, *Acacia pruinocarpa*, *Acacia demissa* and *Acacia rhodophloia*), *Hakea preissii*, *Grevillea berryana* and *E. macmillaniana* over sparse to open shrublands of *Eremophila* spp. (*E. phyllopoda*, *Eremophila spathulata*, *E. glutinosa*, *E. jucunda* subsp. *jucunda*, *E. latrobei* subsp. *latrobei* and *Eremophila galeata*), *Senna* spp. (*Senna artemisioides* subsp. *petiolaris*, *Senna artemisioides* subsp. *helmsii*, *Senna* sp. Meekatharra (E. Bailey 1–26) and *Senna glaucifolia*), *Acacia craspedocarpa* and *Dodonaea viscosa* subsp. *mucronata* over isolated grasslands of *Cymbopogon ambiguus*. The community shared the highest species richness of 16.0 ± 4.7 taxa per quadrat with Community 2. The characteristic taxa were *A. aneura* (glandular morphotype), *E. macmillaniana*, *Acacia tetragonophylla*, *Ptilotus obovatus*, *E. phyllopoda* and *Wurmbea inframediana* (Table 1).

Physical Parameters

Community 1 consisted of two sites and as a consequence was not included in the statistical analysis. Community 1 was generally lower in nutrients than the other sites, with the lowest values for phosphorus, organic carbon and nitrogen, but the highest mean value for potassium.

Non-parametric analysis of variance found significant differences between Communities 2, 3 and 4. Community 4 was significantly different in 12 of the 17 soil nutrients. It was more fertile than Community 2 and 3, with higher values of P, K, Mg, and Total N, with K and Mg statistically significant (Table 2). In addition, soils were also significantly higher concentrations of Ca, Co, Cu, Fe, Mn, Ni and Zn and had significantly levels of lower Na and S (Table 2).

Communities 2 and 3 were similar in soil chemical composition (Table 2). Soils from both communities were more acidic than Community 4 and lower in major and trace elements (Table 2). Sodium concentration was the only significant difference between the two, with Community 3 having significantly higher concentrations than Community 2 (Table 2).

All three communities had similar site attributes (Table 3). The communities were relatively low in the landscape, with a mean elevation of 368.2 ± 3.3 m above sea level. In comparison, the highest points in the area are Mt Narryer (514m) and Mt Dugel (461m). The sites can be characterised as generally gently inclined (6.4 degrees ± 0.6), rock outcrop cover up to 20%, moderate cover of coarse fragments (20–50%) and mainly shallow soils. Only coarse fragment size was significantly different between communities. Community 3 had significantly higher abundance of surface fragments than Community 4 with Community 2 intermediate between the two (Table 3).

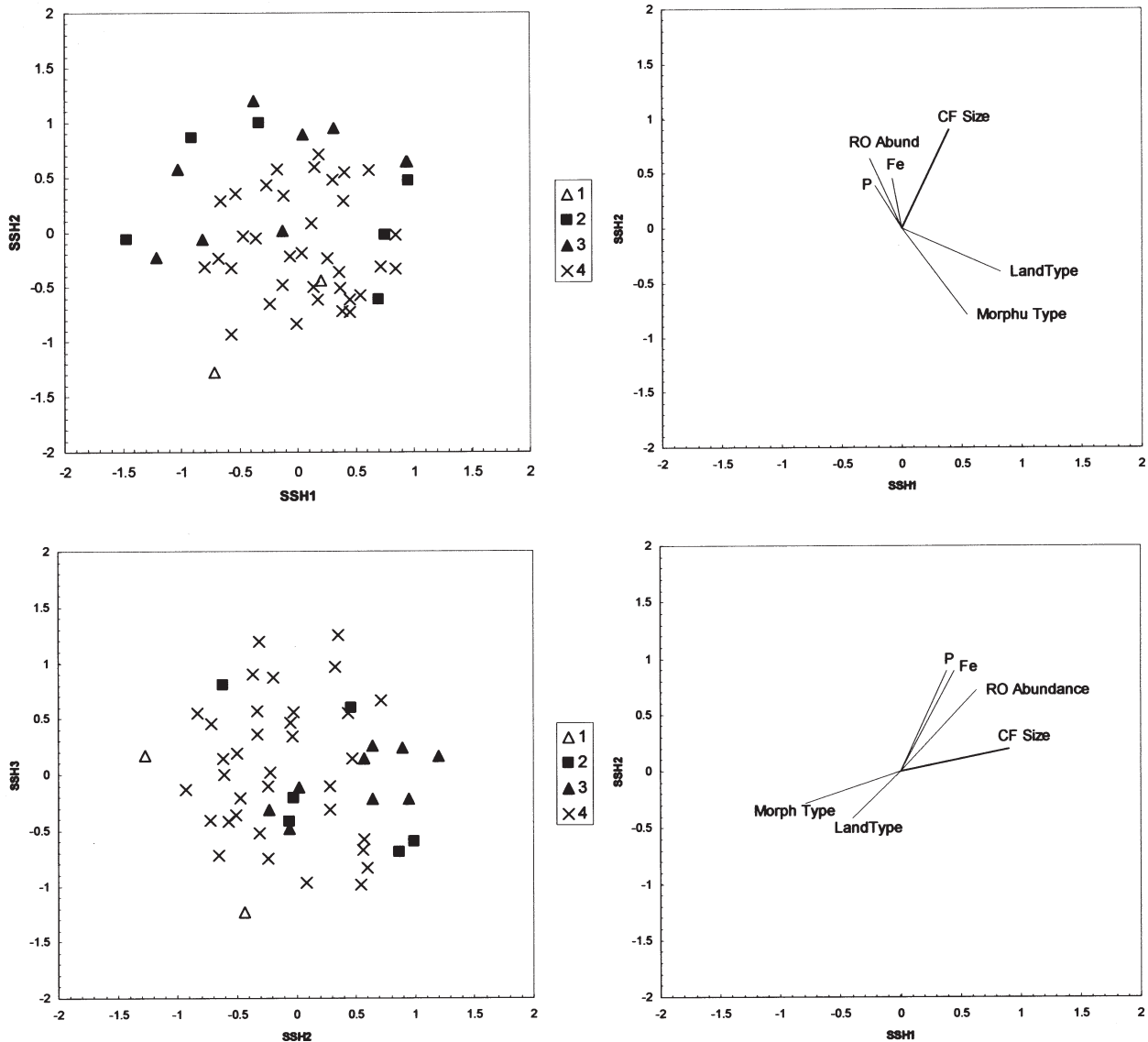


Figure 3. Three dimensional SSH ordination showing Axis 1, 2 and 3 of the 51 quadrats established on the western Narryer Terrane. The four communities are shown and lines represent the strength and direction of the best-fit linearly correlated variables ($P < 0.05$).

The three dimensional SSH ordination shows some overlap between communities (stress = 0.1938; Fig. 3). Community 4, commonly found across the terrane, is concentrated in the centre of the ordination on all 3 axes (Fig. 3). Community 3, on the lateritic sites and breakaways, partly overlaps Community 4 indicating some commonality. It occurs in the upper (Fig. 3a) and right quadrants (Fig. 3b). Community 2 also overlaps Community 4, but is more widely dispersed than community 3, while Community 1 in lower left quadrant on axes 2 and 3 (Fig. 3b).

The relationships between the three dimensional SSH ordination and the environmental variables were poor, with correlations between 0.15 and 0.2. This was most probably due to a non-linear relationships with Community 4, located in the middle of the ordination, it has higher concentrations of soil nutrients than the

communities spread around the edge. Rock outcrop abundance, coarse fragment size, phosphorus and iron are all higher in the upper half of the ordination (Fig. 3a). Morphology and land type generally increase in the opposite direction, with sites on upper parts of the range, such as crests and summits, occurring in the lower right quadrant.

DISCUSSION

Flora

Prior to the survey, Jack Hills was the only ironstone range on the Narryer Terrance that had been surveyed for flora and plant communities (Meissner & Caruso 2008a). A total of 202 taxa were recorded at Jack Hills, with over 50%

ephemeral taxa (Meissner & Caruso 2008a). In comparison, the current survey recorded 151 taxa with only 105 taxa common to both areas. The western Narryer Terrane recorded less than 30% ephemeral taxa, mainly due to poor rainfall prior to the survey.

Endemism and high occurrence of priority species are characteristic of some ironstone ranges (Meissner & Caruso 2008 a,b,c; Markey & Dillon 2008 a,b). In this survey, one endemic taxon was found, *Wurmbea* sp. Boolardy (R.Meissner & G. Owen 1502), and several priority species were recorded. In addition, taxa commonly associated with ironstone were recorded, such as *E. latrobei*, *E. jucunda* and *Thryptomene decussata*. More importantly, new collections were made of *S. rotunda*, a species previously known only from the holotype.

Plant Communities

This survey described four floristic communities on the west Narryer Terrane. Communities 2 and 4 roughly correspond to the Rocky Hill Mixed Shrublands and Stony Mixed Mulga Shrublands of Curry *et al.* (1994). However, these communities were broadly described and applied on other ranges. Curry *et al.* (1994) also described the vegetation on Jack Hills and the Weld Range as predominantly Rocky Hill Mixed Shrublands, both part of the same land system. Detailed surveys of Jack Hills and the Weld Range showed the communities on these ironstone ranges were very different and characterised by different suites of species (Markey & Dillon 2008b, Meissner & Caruso 2008a). A preliminary comparison of the community composition between the western Narryer Terrane and Jack Hills found the same pattern; the floristic communities on the two ranges were significantly different (ANOSIM Global R = 0.306, P < 0.01, Clarke and Warwick 2001).

The distribution of the communities within the western Narryer Terrane was largely influenced by soil nutrients, which in turn was influenced by the landform. The lateritic community (Community 3) was clearly distinguished from the other communities and contained species, such as *Philotheca citrina*, which did not occur elsewhere. These sites were characterised by a high abundance of pisoliths, as well as ferruginous duricrust and low levels of soil fertility (Cornelius *et al.* 2007).

In previous studies of ironstone ranges, the greatest floristic differences were often found between lowland and upland communities (Markey & Dillon 2008 a,b; Meissner & Caruso 2008 a,b,c). In this study, no differentiation was found between the lowland and upland communities. The most common community recorded, Community 4, characterised the landscape of the ironstone ranges of the western Narryer Terrane. It was found on the sites with greater fertility and less acidity that occurred in all positions in the landscape from colluvial areas and lower slopes to the crests of the ironstone hills.

Higher elevations have also previously been correlated with the occurrence of endemic and restricted communities on other ironstone ranges (Meissner & Caruso 2008b; Meissner *et al.* 2009). The communities

were more uniform when compared to Jack Hills and there was no difference in elevation between communities.

The topography of the study area is more subdued than that of Jack Hills, where Mount Hale (697m) is the highest peak, and the location of the restricted spinifex community. In comparison, the highest peak of banded ironstone was Mt Nairn (430m). Although Mt Narryer (514m) is higher, it is composed of metamorphic gneiss, not ironstone, and was therefore not surveyed. The lower elevations and lack of extreme elevations of the ironstone hills may reduce the number of available habitats to support specialised communities such as Jack Hills.

Despite the general lack of topographic zonation of the vegetation, Community 2 was clearly a community only found on the upper slopes and crests within the terrane. This community had the lowest fertility, lowest trace element concentration and most acidic soils. The typifying species, *E. glutinosa* and *E. latrobei*, are taxa commonly associated with ironstone ranges. These sites are typically lower in fertility (Markey & Dillon 2008 a,b; Meissner & Caruso 2008 a,b,c), and are probably the result of leaching by runoff as evidenced by lower concentrations of the more mobile elements, magnesium, calcium and sodium (Cornelius *et al.* 2007).

Conservation

The banded iron formations are a minor landform in a region dominated by granite and granitic gneiss ranges, such as Mount Narryer. To date, mining tenements cover the entire area but there is no current exploration. None of the ironstone ranges of this survey are currently within secure Conservation Estate.

The vegetation of the western Narryer Terrane was found to be in poor condition, with extensive evidence of grazing by feral goats. Grazing was greatest on the rocky hills, especially summits and crests, where extensive goat manure and high numbers of increaser species, such as *Chenopodium melanocarpum*, were recorded. Presence of feral goats, in addition to livestock, can prevent the regeneration of woody perennial species (Tiver & Andrew 1997). Currently, the elevated levels of herbivory by goats on the rocky hills can potentially have a large impact on the communities found in this survey.

ACKNOWLEDGEMENTS

We would like to thank the following people: Dave Allen and Katrina Walton, WA Chemcentre for Soil Analysis; Sandy McTaggart at Mt Narryer Station, Simon and Natalie Broad at Milly Milly, and Mark Halleen at Boolardy Station for their cooperation and help during the field survey; the staff at the Western Australian Herbarium, especially Karina Knight; Rob Davies, Bruce Maslin, Frank Obbens and Barbara Rye on for their taxonomic expertise. Finally Neil Gibson is thanked for his advice and support. This project was funded by the Department of Environment and Conservation, Western Australia.

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APPENDIX

List of the flora for Mt Narryer Terrane, including all taxa from the sampling quadrats and adjacent areas. Nomenclature follows Paczkowska and Chapman (2000).

Adiantaceae

Cheilanthes brownii
Cheilanthes sieberi subsp. *sieberi*

Aizoaceae

Tetragonia sp. indet

Amaranthaceae

Ptilotus aervoides
Ptilotus exaltatus
Ptilotus helipteroides
Ptilotus obovatus
Ptilotus roei
Ptilotus rotundifolius
Ptilotus schwartzii

Anthericaceae

Thysanotus manglesianus
Thysanotus speckii

Apiaceae

Trachymene pilbarensis

Asteraceae

Actinobole oldfieldianum
Brachyscome sp. indet
Brachyscome iberidifolia
Calotis hispidula
Helipterum craspedioides
Podolepis gardneri
Pogonolepis stricta
Rhodanthe battii
Rhodanthe maryonii

Boraginaceae

Heliotropium inexplicitum

Brassicaceae

Lepidium oxytrichum
Stenopetalum sp. indet
Stenopetalum anfractum
Stenopetalum filifolium

Caesalpiniaceae

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

Chenopodiaceae

Chenopodium melanocarpum
Chenopodium saxatile
Dysphania rhadinostachya subsp. *rhadinostachya*
Enchylaena tomentosa var. *tomentosa*
Maireana planifolia x *villosus*
Maireana sp. indet
Maireana georgei
Maireana planifolia
Maireana thesioides

Maireana triptera
Maireana villosa
Rhagodia eremaea
Sclerolaena cuneata

Colchicaceae

Wumbea cf. *densiflora*
Wumbea densiflora
Wumbea deserticola
Wumbea inframediana

Cuscutaceae

Cuscuta cf. *epithymum*

Droseraceae

Drosera macrantha subsp. *macrantha*

Euphorbiaceae

Euphorbia boophthona
Sauropus crassifolius

Frankeniaceae

Frankenia sp. 1 indet
Frankenia sp. 2 indet
Frankenia sp. 3 indet

Geraniaceae

Erodium cygnorum

Goodeniaceae

Goodenia tenuiloba
Scaevola spinescens

Haloragaceae

Haloragis trigonocarpa

Lamiaceae

Spartothamnella teucriflora

Loranthaceae

Amyema fitzgeraldii

Malvaceae

Abutilon sp. indet
Hibiscus burtonii
Sida sp. indet
Sida aff. *atrovirens*
Sida atrovirens
Sida cf. sp. unisexual (N.H. Speck 574)
Sida chrysocalyx

Mimosaceae

A. aneura (ribbed morphotype) (R. Meissner & G. Owen 1611)
A. aneura (terete/compressed morphotype) (R. Meissner & G. Owen 1608)
A. aneura (wide morphotype) (R. Meissner & G. Owen 1615)
A. aneura (glandular morphotype) (R. Meissner & G. Owen 1613)
Acacia citrinoviridis
Acacia craspedocarpa
Acacia cuthbertsonii subsp. *cuthbertsonii*

Acacia demissa
Acacia grasbyi
Acacia kempeana
Acacia palustris
Acacia pruinocarpa
Acacia quadrimarginea
Acacia ramulosa var. *linophylla*
Acacia rhodophloia
Acacia sp. Yellow Pulvinus (R. Meissner & G. Owen

1607)

Acacia synchronicia
Acacia tetragonophylla

Myoporaceae

Eremophila compacta
Eremophila exilifolia
Eremophila forrestii
Eremophila galeata
Eremophila georgei
Eremophila glutinosa
Eremophila jucunda
Eremophila jucunda subsp. *jucunda*
Eremophila latrobei subsp. *latrobei*
Eremophila macmillaniana
Eremophila phyllopoda
Eremophila phyllopoda subsp. *phyllopoda*
Eremophila spathulata

Myrtaceae

Aluta aspera subsp. *hesperia*
Calytrix desolata
Calytrix erosipetala (P3)
Micromyrtus sulphurea
Thryptomene decussata
Verticordia interioris

Nyctaginaceae

Boerhavia coccinea

Papilionaceae

Glycine canescens
Indigofera monophylla
Mirbelia rhagodioides
Swainsona rotunda

Poaceae

Aristida contorta
Austrostipa elegantissima
Cymbopogon ambiguus
Enneapogon caerulescens
Eriachne helmsii
Eriachne mucronata
Eriachne pulchella
Iseilema eremaeum
Monachather paradoxus
Neurachne minor
Paspalidium basicladum
Tripogon loliiformis

Portulacaceae

Calandrinia eremaea complex
Calandrinia sp. The Pink Hills (F. Obbens FO 19/06)
Portulaca oleracea

Proteaceae

Grevillea berryana
Grevillea deflexa
Grevillea striata
Hakea preissii
Hakea recurva subsp. *arida*

Rubiaceae

Psydrax latifolia
Psydrax rigidula
Psydrax suaveolens

Rutaceae

Philotheca brucei subsp. *cinerea*
Philotheca citrina (P1)

Santalaceae

Santalum spicatum

Sapindaceae

Dodonaea petiolaris
Dodonaea pinifolia
Dodonaea viscosa subsp. *mucronata*

Solanaceae

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

Stackhousiaceae

Stackhousia muricata

Stylidiaceae

Stylidium longibracteatum

Tiliaceae

Corchorus crozophorifolius

Zygophyllaceae

Tribulus suberosus
Zygophyllum kochii

Table 1

Sorted two-way table of quadrats established on the western Narryer Terrane showing species by community type. Taxa shaded grey within a community are typifying species identified by SIMPER (Clarke & Warwick 2001) at the 4group level ($p < 0.05$).

	1	2	3	4
<i>Acacia aneura</i> (glandular morphotype)				
<i>Eremophila macmillaniana</i>				
<i>Acacia tetragonophylla</i>				
<i>Ptilotus obovatus</i>				
<i>Solanum ashbyi/lasiophyllum</i> complex				
<i>Eremophila phyllopoda</i>				
<i>Senna artemisioides</i> subsp. <i>helmsii</i>				
<i>Senna</i> sp. Meekatharra (E. Bailey 1-26)				
<i>Eremophila glutinosa</i>				
<i>Eremophila latrobei</i> subsp. <i>latrobei</i>				
<i>Senna glaucifolia</i>				
<i>Wurmbea inframediana</i>				
<i>Ptilotus schwartzii</i>				
<i>Cheilanthes sieberi</i> subsp. <i>sieberi</i>				
<i>Cheilanthes brownii</i>				
<i>Acacia aneura</i> (terete/compressed morphotype)				
<i>Eremophila galeata</i>				
<i>Eremophila jucunda</i>				
<i>Wurmbea densiflora</i>				
<i>Eremophila spathulata</i>				
<i>Psyrax suaveolens</i>				
<i>Acacia aneura</i> (wide morphotype)				
<i>Scaevola spinescens</i>				
<i>Sida atrovirens</i> complex				
<i>Acacia palustris</i>				
<i>Calytrix desolata</i>				
<i>Acacia quadrimarginea</i>				
<i>Corchorus crozophorifolius</i>				
<i>Dodonaea pinifolia</i>				
<i>Eremophila exilifolia</i>				
<i>Cymbopogon ambiguus</i>				
<i>Enchylaena tomentosa</i> var. <i>tomentosa</i>				
<i>Senna glutinosa</i> subsp. <i>x luerssenii</i>				
<i>Tribulus suberosus</i>				
<i>Hakea preissii</i>				
<i>Maireana triptera</i>				
<i>Sclerolaena cuneata</i>				
<i>Rhagodia eremaea</i>				
<i>Acacia aneura</i> (ribbed morphotype)				
<i>Acacia ramulosa</i> var. <i>linophylla</i>				
<i>Senna artemisioides</i> subsp. <i>petiolaris</i>				
<i>Acacia citrinoviridis</i>				
<i>Neurachne minor</i>				
<i>Maireana villosa</i>				
<i>Monachather paradoxus</i>				
<i>Acacia pruinoarpa</i>				
<i>Calytrix erosipetala</i>				
<i>Dodonaea petiolaris</i>				
<i>Philotheca citrina</i>				
<i>Mirbelia rhagodioides</i>				
<i>Dodonaea viscosa</i> subsp. <i>mucronata</i>				
<i>Thryptomene decussata</i>				
<i>Eremophila georgei</i>				
<i>Philotheca brucei</i> subsp. <i>cinerea</i>				
<i>Wurmbea deserticola</i>				
<i>Aluta aspera</i> subsp. <i>hesperia</i>				
<i>Sida chrysocalyx</i>				
<i>Acacia</i> sp. Yellow Pulvinus				
<i>Hibiscus burtonii</i>				
<i>Grevillea berryana</i>				
<i>Thysanotus manglesianus</i>				
<i>Acacia cuthbertsonii</i> subsp. <i>cuthbertsonii</i>				
<i>Acacia demissa</i>				
<i>Acacia kempeana</i>				
<i>Indigofera monophylla</i>				
<i>Acacia rhodophloia</i>				
<i>Senna stricta</i>				
<i>Maireana planifolia</i> x <i>villosus</i>				
<i>Ptilotus rotundifolius</i>				
<i>Boerhavia coccinea</i>				

Table 2

Mean values for soil attributes (measured in mg/kg except EC and pH) by plant community type. Differences between ranked values tested using Kruskal –Wallis non-parametric analysis of variance. Standard error in parentheses. a and b represent significant differences between community types at $p < 0.05$ (n = number of quadrats, p = probability, ns = not significant). Community 1 was excluded from analysis due to low quadrat number.

	Community Type				P
	1	2	3	4	
EC	2.0 (0.0)	2.0 (0.0)	3.7 (0.9)	4.3 (0.9)	0.1854
pH	4.6 (0.2)	4.2 (0.0)a	4.3 (0.1)a	5.2 (0.1)b	<0.001
P	8.0 (1.0)	15.5 (4.5)	20.6 (6.2)	20.9 (5.4)	0.4653
K	265.0 (35.0)	117.5 (19.8)a	112.3 (26.2)a	209.0 (16.7)b	0.0010
Mg	90.5 (19.5)	39.7 (6.3)a	55.6 (9.5)a	158.2 (16.2)b	<0.0001
Org C	0.32 (0.02)	0.40 (0.04)	0.51 (0.08)	0.40 (0.03)	0.2404
Total N	0.035 (0.001)	0.036 (0.003)	0.041 (0.005)	0.043 (0.003)	0.6850
B	0.18 (0.13)	0.05 (0.00)	0.07 (0.01)	0.13 (0.02)	0.0465
Ca	145.0 (15.0)	85.0 (12.4)a	129.9 (26.8)a	316.7 (30.2)b	<0.0001
Co	0.85 (0.57)	0.15 (0.04)a	0.08 (0.02)a	1.55 (0.19)b	<0.0001
Cu	0.55 (0.15)	0.50 (0.03)ab	0.37 (0.02)a	0.84 (0.08)b	<0.0001
Fe	36.5 (3.5)	36.0 (3.6)a	52.9 (9.8)ab	56.7 (4.7)b	0.0433
Mn	47.5 (28.5)	16.8 (2.9)a	9.8 (1.6)a	70.9 (7.9)b	<0.0001
Na	12.0 (10.0)	1.3 (0.4)a	6.2 (1.6)b	9.0 (3.9)b	0.0080
Ni	0.20 (0.10)	0.09 (0.01)a	0.12 (0.03)a	0.48 (0.07)b	<0.0001
S	3.5 (1.5)	6.7 (1.3)ab	7.9 (0.7)a	4.9 (0.6)b	0.0017
Zn	0.95 (0.15)	0.65 (0.10)a	0.80 (0.20)a	1.64 (0.18)b	0.0002
n=	2	6	9	35	

Table 3

Mean values for site attributes by plant community type; Elevation (m); soil depth (1 – skeletal, 2 – shallow, 3 – deep); Coarse fragment (CF) abundance (0 – no coarse fragments to 6 very abundant coarse fragments); Maximum size of coarse fragments (1 – fine gravely to 7 large boulders); Rock outcrop (RO) abundance (0 – no bedrock exposed to 5 – rockland), runoff (0 – no runoff to 5 – very rapid); Slope (degrees); Runoff (0 – no runoff, 1 – very slow, 2 – slow, 3 – moderately rapid); Morphology type (1 – crest, 2 – upper Slope, 3 – mid Slope, 4 – lower Slope, 5 – simple slope, 6 – hillock); Land type (1 – hillcrest, 2 – hill slope, 3 – footslope, 4 – summit, 5 – mount, 6 – breakaway). Differences between ranks tested using Kruskal –Wallis non-parametric analysis of variance. Standard error in parentheses. a, b and c represent significant differences between community types at $P < 0.05$ (n = number of quadrats, P = probability, ns = not significant).

	Community Type				p
	1	2	3	4	
Elevation (m)	373.5 (13.5)	371.3 (9.5)	371.6 (7.3)	366.5 (4.2)	0.7970
Soil Depth	2.0 (0.0)	1.5 (0.2)	1.8 (0.1)	1.9 (0.1)	0.1265
Coarse Fragment Size	4.5 (0.5)	5.0 (0.4)	4.7 (0.3)	4.7 (0.2)	0.7326
CF Abundance	4.5 (0.5)	4.7 (0.4)ab	5.0 (0.0)a	4.3 (0.1)b	0.0274
Rock outcrop abundance	0.0 (0.0)	1.3 (0.5)	2.2 (0.5)	1.5 (0.3)	0.3397
Slope	5.5 (3.5)	5.3 (1.6)	5.4 (1.2)	6.8 (0.8)	0.6553
Runoff	2.0 (1.0)	1.7 (0.4)	1.7 (0.2)	1.9 (0.2)	0.8522
Morphology Type	3.5 (0.5)	2.0 (0.7)	2.0 (0.4)	2.9 (0.3)	0.1723
Landform Type	3.0 (0.0)	2.3 (0.2)	2.3 (0.6)	2.6 (0.2)	0.5255
n=	2	6	9	35	