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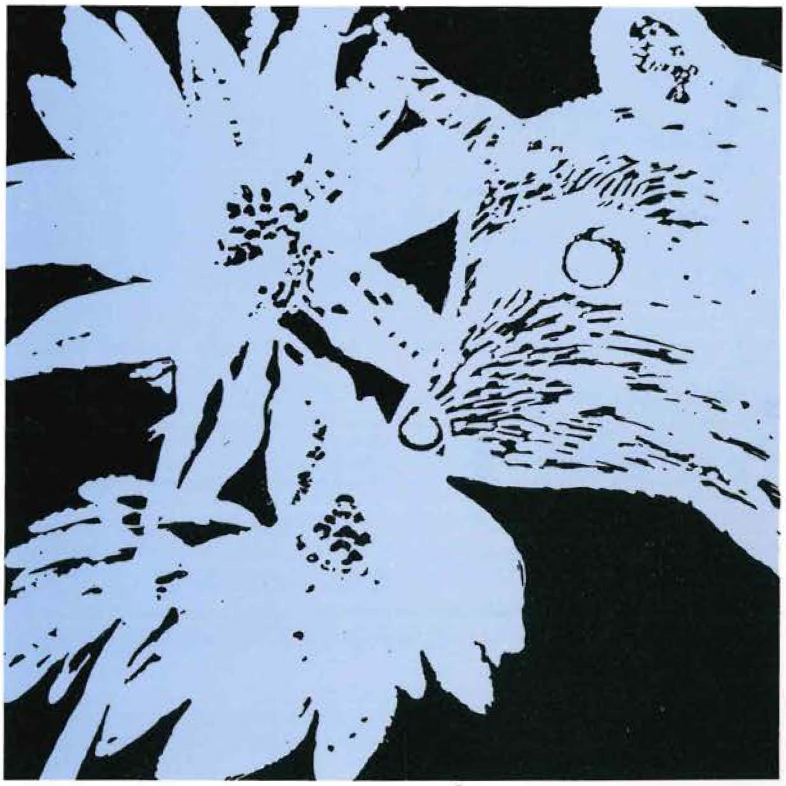
science

VOLUME TWO NUMBER TWO DECEMBER 1996



WESTERN AUSTRALIAN JOURNAL OF
CONSERVATION AND LAND MANAGEMENT

DEPARTMENT OF CONSERVATION
AND LAND MANAGEMENT

CALMScience

Published by the Department of Conservation and Land Management, Locked Bag 104, Bentley Delivery Centre, Western Australia 6983

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CALM
science
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WESTERN AUSTRALIAN
JOURNAL OF CONSERVATION
AND LAND MANAGEMENT

CALMScience 2 (2): 113-118 (1996)

Performance of 30 mm regrowth jarrah laminated signboards under exterior conditions

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SUMMARY

Regrowth jarrah (*Eucalyptus marginata* Donn ex Sm.) signboards 200 x 30 x 850 mm were glued with one of three proprietary brands of waterproof exterior adhesive, i.e. 'Bondtite 145' (B145), Timbachem 'Resobond A3' (RA3) and Timbachem 'Resobond 440' (R440), and sealed with one of four different paint systems. They were stored under water-sprays in a log stockpile for three years, during which the boards were sprayed with water for 15 minutes every two hours. Dry cleavage tests, as specified in Australian Standard AS 1328-1987, were conducted at the beginning of the trial before applying a paint finish, and then after one year and after three years, while wet cleavage tests were done after three years only.

After three years the dry cleavage tests showed that glueline strengths had declined with all adhesives, and both wet and dry tests indicated that RA3 gluelines were significantly stronger than those of B145 and R440. All gluelines satisfied the requirements of the Standard. R440 and B145 gluelines performed similarly in terms of mean percentage wood failure, but twice the number of panels glued with R440 failed the wet cleavage test.

No significant differences in percentage wood failure were found between paint systems or the interaction of adhesive and paint, but the small sample size of two replications per treatment was a constraint. The overall condition of the signboards, in terms of checking and splitting, showed that RA3 gluelines performed better than those of B145 and R440. Consequently, RA3 is recommended for gluing regrowth jarrah signboards for use in exposed outdoor conditions. Further trials using an increased sample size would be required to evaluate the performance of different paint systems.

INTRODUCTION

A panel product manufactured by edge-and-face gluing of thin boards has been developed at the Department of Conservation and Land Management's (CALM) Timber Utilisation Centre (TUC). The system enables the processing of timber from small regrowth eucalypt thinnings into a value-added product for use in furniture manufacture, and was developed to enable the forest products industry to meet the demand for furniture wood by supplementing solid timber supplies (Siemon 1990).

The product is principally used in interior applications, for example, furniture components, panelling, bench and table tops and cupboard doors. Exterior or high equilibrium moisture content (EMC) applications are possible, as in signboards, but in outdoor applications a waterproof glue (e.g. resorcinol formaldehyde) and a reliable paint system are required. Adhesives used in exterior applications are generally three to four times the cost of the interior adhesives, which increases the overall cost of the panels.

The present trial assessed the performance of regrowth jarrah signboards glued with one of three exterior adhesives, and finished with one of four paint systems or left untreated, and then stored in a water-spray stockpile where they received regular wetting and drying over three years.

MATERIALS AND METHODS

Thirty 850 x 200 x 30 mm signboards (ten per adhesive) were manufactured by edge-and-face gluing with one of three proprietary brands of waterproof exterior adhesive:

'Bondtite 145' (B145):	Polyphenolic (tannin) resorcinol formaldehyde
Timbachem 'Resobond A3' (RA3):	Resorcinol formaldehyde
Timbachem 'Resobond 440' (R440):	Phenol/resorcinol formaldehyde (heat cured) resin.

B145 is manufactured by Bondtite Adhesives Pty Ltd in South Africa, and supplies in Western Australia (WA) at the time of the trial were from Harcros Chemicals Pty Ltd.

The adhesive is now available from Polymer Coatings and Adhesives Pty Ltd. RA3 and R440 are manufactured by Bunnings Timbachem, a Division of Bunnings Forest Products Pty Ltd. Panels were glued according to the manufacturer's specifications as given in technical information sheets, i.e. B145 - Mydrin Australia (1994), and RA3 or R440 - Bunnings Timbachem (1990a) and (1990b) respectively.

Board moisture contents before gluing were between 8 and 10 per cent, based on oven-dry weight. Each edge was dressed immediately prior to gluing, allowing a maximum time of one hour between dressing and gluing. An 'Orma' glue press with an oil-heated platen was used for edge-gluing, and a cold press for face-gluing. Details of temperature, vertical and horizontal pressures, and curing time are regarded as part of the intellectual property of the process. Face glueline strength was assessed on the panels before exposure, according to the requirements of the AS1328-1987 (Standards Association of Australia 1987) dry cleavage test. The percentage of wood failure compared with adhesive failure was estimated for each glueline.

Two of the ten signboards in each glue type were then randomly allocated to one of the following treatments:

- unpainted (control)
- water based primer
- oil based primer
- water based primer and acrylic paint ('Mission brown')
- oil based primer and acrylic paint ('Mission brown').

Signboards were then placed in the TUC stockpile in October 1990 under a watering schedule of 15 minutes in every two hours. Boards were supported on their edges on a flat wooden surface about 300 mm above the ground, giving an orientation of 90° to the sun, and allowing some water trapping, which was intended to accelerate deterioration.

Visual assessments of the condition of the gluelines after one year (November 1991) and three years (November 1993) were conducted using the following classifications:

1 - excellent - no defective gluelines
2 - good - no more than two hairline splits greater than 150 mm long
3 - average - no limit on hairline splits
4 - poor - splits wider than 1 mm.

After this assessment, a detailed examination of the glueline was done by inspecting the freshly cut ends of each sample after cleavage samples had been docked. Grading was by the following classification:

0 - no checks
1 - hairline checks <1 mm
2 - checks >1 mm
3 - splits from one surface to another surface.

Although the 1990 and 1991 assessments were done by Mr S.L. Ward and the 1993 assessment by the other authors, the quantitative systems reduced the possibility of operator bias by different interpretations of board conditions.

Dry cleavage tests as described in AS 1328 -1987 (Standards Association of Australia 1987) were done in 1991. The cut ends of the signboards were then resealed and the boards re-positioned in the TUC stockpile. Wet and dry cleavage tests were done at the completion of the trial in November 1993, and board condition was rated using the above criteria. Analysis of variance was used to determine whether there was a difference between glues and treatments, both within the same year and between years.

RESULTS AND DISCUSSION

Tables 1 and 2 show the mean percentage wood failure for face joints and the percentage of gluelines failing the dry or wet cleavage tests for each adhesive. The initial dry cleavage tests (before applying the paint systems and commencing the exposure phase of the trial) indicated that R440 gluelines had significantly less strength ($p<0.01$) than those of RA3 and B145. Mean percentage wood failure for R440 gluelines was 72 per cent and those of RA3 and B145 gluelines 100 per cent.

Newby and Siemon (1989) had assessed the performance of a range of commercially available adhesives used by the furniture industry in WA. They found that when edge-gluing 60-year-old regrowth jarrah, four of the five adhesives tested, i.e. urea formaldehyde ('Grasp'), melamine-fortified urea formaldehyde, pure resorcinol formaldehyde (RA3) and melamine formaldehyde gave very good results from the dry cleavage test outlined in AS 1328 - 1987 (Standards Association of Australia 1987). The fifth adhesive, polyvinylacetate or PVA, could not be recommended.

After one year's exposure the strength of all glues decreased, with RA3 gluelines showing greater strength than those of R440 and B145 gluelines. A significant difference was found between the R440 and RA3 gluelines ($p<0.05$), but no difference in wood failure percentage occurred between the paint systems.

Exposing the signboards for another two years resulted in the dry cleavage tests showing a 12 per cent decrease in glue strength for B145 gluelines, and a 6 per cent increase in strength for R440 gluelines, although this may reflect the different assessor's interpretations of wood failure, and no change for RA3 gluelines. Wet cleavage tests require samples to be subjected to a six-hour vacuum-and-pressure cycle in an autoclave before cleaving each glueline with a chisel, hence it is a more severe test of strength, and recommended for assessing waterproof glues. Wet and dry cleavage results were similar in terms of the mean percentage of wood failure (Table 2), but more panels glued with RA3 or R440 failed the wet cleavage test.

Dry and wet cleavage tests indicated that RA3 gluelines were significantly stronger than those of both B145 and R440 ($p<0.01$). RA3 gluelines had a mean

TABLE 1
Effect of adhesive on percentage wood failure in face-glued regrowth jarrah signboards after one or three years exposure (dry cleavage test).

ASSESSMENT (YEAR)	ADHESIVE	WOOD FAILURE (%)				PANEL FAILURE (%)
		MEAN	S.D.	RANGE	No.	
0	B145	100	0	-	6	0
	RA3	100	0	-	6	0
	R440	72.0	29.6	30-100	6	0
1	B145	82.0	27.5	5-100	39	20
	RA3	88.2	22.8	0-100	40	10
	R440	62.4	31.2	0-100	40	30
3	B145	70.4	29.3	0-100	80	20
	RA3	89.0	17.5	25-100	80	0
	R440	68.6	26.6	10-100	80	20

TABLE 2
Effect of adhesive on percentage wood failure in face-glued regrowth jarrah signboards after three years exposure (wet cleavage test).

ADHESIVE	WOOD FAILURE (%)				PANEL FAILURE (%)
	MEAN	S.D.	RANGE	No.	
B145	66.3	29.2	0-100	80	20
RA3	85.0	20.1	10-100	80	10
R440	60.3	26.6	10-100	80	40

percentage wood failure of 89 per cent (dry) and 85 per cent (wet), and 10 per cent of signboards failed the wet cleavage test after three years exposure. The B145 gluelines had mean percentage wood failures of 70.4 per cent (dry) and 66.3 per cent (wet), and 20 per cent of signboards failed the wet cleavage test after three years exposure. In comparison, R440 gluelines had a mean percentage wood failure of 68.6 per cent (dry) and 60.3 per cent (wet), and 40 per cent of signboards failed the wet cleavage test.

Appendix 1 lists the condition of individual gluelines for each adhesive and paint system after three years exposure. No significant differences were found between paint systems or the combination of adhesive and paint finish, although the small sample size should be taken into consideration.

RA3 gluelines are performing better than both R440 and B145 in terms of mean percentage wood failure and the number of panels failing. R440 and B145 gluelines performed similarly in terms of mean percentage wood failure, but twice the number of panels glued with R440 failed the wet cleavage test after three years exposure.

For the combined dry cleavage results of all adhesives, the results showed significant decreases in glueline strength from year 0 to year 1 ($p<0.01$), and from year 0 to year 3 ($p<0.001$). However, only B145 gluelines showed a significant strength decrease from year 0 to year 3 ($p<0.01$). RA3 and R440 gluelines had no significant loss in strength over the period. The initial dry cleavage results for R440 indicated a lower glueline strength.

The dry cleavage results of the paint system for all years indicated a significant difference ($p<0.05$) between R440 sealed with oil primer and acrylic paint and RA3 sealed with water primer or water primer plus paint. These significant differences could be due to the varying performances between R440 and RA3 affecting the paint systems.

Table 3 lists the condition of the edge-and-face gluelines after three years exposure. Signboards glued with RA3 performed better than those glued with B145 or R440, with a small percentage of signboards with checks greater than 1 mm and no signboards with splits. Face gluelines on the exposed or unexposed edges of all boards performed similarly. Consequently, RA3 is considered to give the best results in gluing regrowth jarrah signboards for use in exposed outdoor conditions. Further trials using an increased sample size would be required to evaluate the performance of different paint systems.

TABLE 3

Glueline performance of edge-and-face jointed 30 mm regrowth jarrah signboards glued with one of three different adhesives after three years exposure to exterior conditions (% in parentheses).

ADHESIVE	GLUELINE PERFORMANCE CODE[a]	EXPOSED FACE GLUELINES[b]	UNEXPOSED FACE GLUELINES[b]	EDGE 1	EDGE 2
B145	0	8 (40)	15 (75)	23 (50)	28 (61)
	1	4 (20)	2 (10)	5 (11)	4 (9)
	2	6 (30)	1 (5)	6 (13)	1 (2)
	3	2 (10)	2 (10)	12 (26)	13 (28)
RA3	0	17 (85)	19 (95)	48 (100)	47 (100)
	1	2 (10)	0	0	0
	2	1 (5)	1 (5)	0	0
	3	0	0	0	0
R440	0	12 (60)	15 (79)	45 (90)	38 (79)
	1	2 (10)	2 (10.5)	2 (4)	2 (4)
	2	5 (25)	2 (10.5)	1 (2)	2 (4)
	3	1 (5)	0	2 (4)	6 (13)

[a] Code 0 - no checks
1 - hairline checks <1 mm
2 - checks >1 mm
3 - splits from one surface to another surface

[b] Number of gluelines with a particular code and percentages in parentheses are given. (Assessment was done on edges after cutting cleavage samples, enabling clear identification of gluelines.)

In subsequent research on gluing jarrah and karri (*E. diversicolor* F. Muell.), Balfas (1993) found that sanding with a coarse abrasive (80 grit paper) prior to gluing substantially increased wettability and dry bond strength of jarrah and karri in both the dry and wet conditions. He also found that surface treatment with sodium hydroxide (NaOH) also improved wettability and glueline strength with the dry cleavage test, but only slightly increased glueline strength when the wet cleavage test was applied. A combination of coarse sanding (80 grit paper) and NaOH treatment increased wettability and bond strength gave better results. In addition, Balfas (1994) found that surface activation using lithium and sodium hydroxides significantly increased wettability and glueline strength when gluing jarrah and karri. Results from these studies need to be included in future trials assessing the overall performance of glued panels exposed under exterior conditions.

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APPENDIX 1

Effect of adhesive and paint system on glueline performance of edge-and-face jointed 30 mm regrowth jarrah laminated signboards after three years exposure to exterior conditions (% in parentheses).

GLUELINE PERFORMANCE CODE[a]	EXPOSED FACE[b]	UNEXPOSED FACE[b]	EDGE 1	EDGE 2
		B145		
		Untreated (control)		
0	0 (0)	1 (25)	0	0
1	1 (25)	2 (50)	0	0
2	3 (75)	1 (25)	1 (12.5)	1 (12.5)
3	0 (0)	0 (0)	7 (87.5)	7 (87.5)
TOTAL	4 (100)	4 (100)	8 (100)	8 (100)
		Oil primer		
0	2 (50)	4 (100)	5 (50)	5 (50)
1	0	0	2 (20)	2 (20)
2	1 (25)	0	0	0
3	1 (25)	0	3 (30)	3 (30)
TOTAL	4 (100)	4 (100)	10 (100)	10 (100)
		Water primer and paint		
0	3 (75)	4 (100)	6 (75)	6 (75)
1	0	0	1 (12.5)	1 (12.5)
2	1 (25)	0	0	0
3	●	0	1 (12.5)	1 (12.5)
TOTAL	4 (100)	4 (100)	8 (100)	8 (100)
		Water primer		
0	1 (25)	4 (100)	7 (70)	10 (100)
1	1 (25)	0	2 (20)	0
2	2 (50)	0	1 (10)	0
3	0	0	0	0
TOTAL	4 (100)	4 (100)	10 (100)	10 (100)
		Oil primer and paint		
0	1 (25)	4 (100)	5 (50)	7 (70)
1	2(50)	0	0	1 (10)
2	0	0	4 (40)	0
3	1 (25)	0	1 (10)	2 (20)
TOTAL	4 (100)	4 (100)	10 (100)	10 (100)
		R440		
		Untreated (control)		
0	0	1 (33)	7 (70)	3 (30)
1	2 (50)	2 (67)	1 (10)	0
2	1 (25)	0	0	1 (10)
3	1 (25)	0	2 (20)	6(60)
TOTAL	4 (100)	4 (100)	10 (100)	10 (100)
		Oil primer		
0	3 (75)	4 (100)	10 (91)	10 (100)
1	0	0	1 (9)	0
2	1 (25)	0	0	0
3	0	0	0	0
TOTAL	4 (100)	4 (100)	11 (100)	10 (100)
		Water primer and paint		
0	4 (100)	4 (100)	9 (100)	7 (78)
1	0	0	0	1 (11)
2	0	0	0	1 (11)
3	0	0	0	0
TOTAL	4 (100)	4 (100)	9 (100)	9 (100)

Appendix 1 (continued)

GLUELINE PERFORMANCE CODE[a]	EXPOSED FACE[b]	UNEXPOSED FACE[b]	EDGE 1	EDGE 2
		R440 (continued)		
		Water primer		
0	3 (75)	4 (100)	10 (91)	10 (91)
1	0	0	0	0
2	1 (25)	0	1 (9)	1 (9)
3	0	0	0	0
TOTAL	4 (100)	4 (100)	11 (100)	11 (100)
		Oil primer and paint		
0	2 (50)	2 (50)	9 (100)	9 (100)
1	0	0	0	0
2	2 (50)	2 (50)	0	0
3	0	0	0	0
TOTAL	4 (100)	4 (100)	9 (100)	9 (100)
		RA3		
		Untreated (control)		
0	4 (100)	4 (100)	9 (100)	8 (100)
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
TOTAL	4 (100)	4 (100)	9 (100)	8 (100)
		Oil primer		
0	3 (75)	4 (100)	9 (100)	9 (100)
1	0	0	0	●
2	1 (25)	0	0	0
3	0	0	0	●
TOTAL	4 (100)	4 (100)	9 (100)	9 (100)
		Water primer and paint		
0	4 (100)	3 (75)	10 (100)	10 (100)
1	0	0	0	0
2	0	1 (25)	0	0
3	0	0	0	0
TOTAL	4 (100)	4 (100)	10 (100)	10 (100)
		Water primer		
0	2 (50)	4 (100)	9 (100)	9 (100)
1	2 (50)	0	0	0
2	0	0	0	0
3	0	0	0	0
TOTAL	4 (100)	4 (100)	9 (100)	9 (100)
		Oil primer and paint		
0	4 (100)	4 (100)	11 (100)	11 (100)
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
TOTAL	4 (100)	4 (100)	11 (100)	11 (100)

[a] Code 0 - no checks
1 - hairline checks < 1 mm
2 - checks > 1 mm
3 - splits from one surface to another surface

[b] Number of gluelines with a particular code and percentages in parentheses are given. [Assessment was done on edges after cutting cleavage samples, enabling clear identification of gluelines.]

Treating four-year-old Tasmanian blue gum posts with pigment emulsified creosote

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SUMMARY

Tasmanian blue gum (*Eucalyptus globulus* Labill. ssp. *globulus*) posts cut from four-year-old trees growing in an agroforestry trial at Middlesex, 15 km south of Manjimup, were treated with Pigment Emulsified Creosote (PEC) or High Temperature Creosote (HTC).

A hot and cold bath treatment process with temperatures between 95°C and 100°C and without mechanical shearing or agitation, caused the PEC to sediment in the base of the treatment drum. Subsequent reheating did not result in increased preservative retentions in retreatments. Posts treated with HTC required three hot and cold bath cycles to achieve the required retention and depth of penetration to between 30 and 45 mm. PEC costs about 50 per cent more than HTC. This trial demonstrated the need for a method of preservative agitation to maintain a stable emulsion, if PEC is to be used effectively in this process. HTC is a suitable preservative to treat Tasmanian blue gum fence posts using the hot and cold bath process for the butts and cold soaking the crowns.

INTRODUCTION

The Department of Conservation and Land Management (CALM) and private land owners have entered into partnerships with two overseas companies in which the Department will establish Tasmanian blue gum (*Eucalyptus globulus* Labill. ssp. *globulus*) plantations over 10 years. The first partnership is with the Japanese consortium Oji-Itochu to establish 20 000 ha, centring mainly on private land on the south coast around Albany. The second partnership is with Hansol Forest Products of Korea, with 10 000 ha of Tasmanian blue gums to be planted in the Wellington catchment near Collie (CALM 1993). Although planted primarily as a source of pulpwood, the plantation can reduce the effects of salination and eutrophication through soil rehabilitation and can provide habitats for fauna (Shea and Bartle 1988).

In addition, the species can provide sawlogs for structural or appearance grade timber, if the stands are well managed. Fence posts and strainers from thinnings are an alternative product, provided they are treated with preservatives to enhance their durability, when used in contact with the ground. Previous trials involved treating two-year-old and 2.5-year-old Tasmanian blue gum (Brennan 1992; Brennan and Pitcher 1993) using High Temperature Creosote (HTC) manufactured according to AS 1143 (Standards Association of Australia 1973) using the hot and cold bath process or cold soaking.

Pigment Emulsified Creosote (PEC) is a relatively new and unique formulation which contains a micronized finely dispersed pigment, the function of which is to lock the creosote into the wood structure and inhibit subsequent bleeding or sweating of the preservative (Chin *et al.* 1986), which is commonly experienced with HTC-treated timber. PEC is manufactured as an oil-in-water emulsion, by simultaneously bringing together and emulsifying the prepared aqueous and oil phases under conditions of ultra high shear (Chin *et al.* 1986). However, prior to use in the treatment process it is inverted to a water-in-oil emulsion in which the pigment particles distribute around the water droplets. Their deposition within the structure of the timber obviates bleeding and produces a dry clean surface upon weathering. PEC has been jointly patented by CSIRO Division of Forest Products and Koppers Australia Pty Ltd in Australia (Watkins 1977 Patent No. 514897; Watkins *et al.* 1989 Patent No. 570984). Chemically, PEC is composed of 65 per cent creosote, 30 per cent water and 5 per cent surfactants, stabilizers and finely dispersed, micronized pigment (Greaves *et al.* 1986). Unlike HTC, PEC does not crystallize and presents no problems with loss of active creosote components, or with the removal and disposal of crystallized products from work and storage tanks, or from the treatment cylinder, pump lines and valves. The odour in and around treatment plants is reduced significantly and there is reduced ground pollution. In addition, weathered PEC-treated commodities are odourless and do not bleed, even at elevated ambient temperatures.

PEC-treated timber and posts exhibit relatively dry oil-free surfaces, and therefore are much easier to handle than timber treated with HTC. PEC does not emit irritating vapours like HTC and can be used to treat wood at temperatures of 30° C lower than those used with HTC. After pressure impregnation, PEC-treated posts exhibit a rust colour when weathered, whereas HTC-treated timber is a dark to black colour. Additional pigment or colourant (white, brown, etc. pigment) can be added to PEC for aesthetic reasons, to further reduce the dark creosote colour.

PEC is designed for use in pressure impregnation treatment plants with poles being commercially treated with PEC at Kopper's Grafton plant in New South Wales. If PEC is left standing in storage tanks for long periods, sedimentation can occur. A mechanical agitator or a pump to occasionally circulate PEC and an in-line homogenizer called a Dispax Reactor® is required to maintain a homogenized emulsion. PEC is stable up to a practical working temperature of 95° C, and in commercial situations PEC can be heated to 90° C when a Dispax Reactor® is used (Hawkins[1] personal communication).

In the 1950s the CSIRO Division of Forest Products developed three on-farm methods for treating fence posts; cold soaking, low-pressure soaking and the hot and cold bath process (CSIRO 1955). The hot and cold bath process involves heating the dry posts in steam, hot water or hot liquid preservative to drive out any air in the posts, followed by cooling in preservative, when atmospheric pressure assists capillary forces in moving the liquid to replace the air driven out (Dale 1967). Heating to just below 100° C in water, or to higher temperatures in oil or steam, is most effective. In this trial the dry posts were treated by the hot and cold bath process with the butts immersed in hot PEC or HTC.

In the hot and cold bath process used in on-farm treatments, a relatively small volume of PEC would be heated to between 90°C and 95°C, with some agitation achieved by putting posts in and out of the treatment drum. The aim of this trial was to determine whether PEC could be heated to between 90°C and 95°C without sedimenting, in order to treat four-year-old Tasmanian blue gum posts using the hot and cold bath process. Posts treated with HTC were used as a control.

MATERIALS AND METHODS

Approximately 65 Tasmanian blue gum posts, 50 to 130 mm small end diameter under bark (s.e.d.u.b.) and 1.7 to 2.0 m long were cut from four-year-old trees growing in an agroforestry trial at the old agricultural research station, Middlesex, approximately 15 km south of Manjimup. The trees were planted in June 1989 at 330 stem ha^{-1} in rows 15 m apart and spaced at 2 m. A 1992 thinning reduced this to 165 stem ha^{-1} and remaining trees were pruned to 2 m.

Trees were felled on 15 March 1993, docked into posts and delivered to the Wood Utilisation Research Centre (now Timber Utilisation Centre - TUC) in Harvey the following day. Posts were debarked within three days of felling by manually striking the posts with the back of an axe and removing the bark by hand or the axe blade. After strip stacking, the posts were dried to below fibre saturation point (f.s.p.), about 25 per cent moisture content (based on oven-dry weight), by a combination of air and kiln drying. After five months all posts were below f.s.p. (mean moisture content 17.7 per cent) and were considered suitable for treatment using the hot and cold bath process.

Preparation

After drying, posts were sorted into diameter classes and randomly allocated to different treatment batches. Approximately 8 per cent of posts were severely split as a result of drying and were considered unsuitable for treatment.

Prior to treatment all posts had small and large end diameters under bark, and sapwood width, measured in four positions. Sapwood and total post volumes were then calculated. The mass of posts before and after treatment was measured to determine PEC uptake. Immediately before treatment, 20 mm was removed from the ends of each post as the end grain can become blocked with kino and dirt, restricting the longitudinal movement of liquids. Air-dry densities and initial moisture contents were assessed.

Equipment

The following equipment was used for treating 1.8 m posts with creosote:

- a 205 L drum (760 mm high) for butt treatment and an extended drum (1300 mm high) to treat the crowns;
- draining troughs made by cutting a drum (205 L) in half lengthwise;
- leaning rails to support the posts standing in the draining troughs;
- electric base hot plate with a thermostat to control temperature and a multimeter or thermometer to monitor temperature;
- insulation to wrap around the treatment vessel, e.g. R 2.0 batts;
- steel mesh or a metal grid cut to fit the base of the drum, to elevate the posts off the bottom of the drum, thus allowing creosote to readily penetrate the ends of the posts;
- temporary roofing erected over the treatment drums in wet weather, as any water entering the treatment drum would cause inaccuracies when estimating preservative uptake;
- dipstick with a lineal tape attached for measuring change in creosote levels, and a measuring jug;
- safety wear of full length clothing, gloves, shoes and hat and UV barrier cream for applying to exposed skin.

When cold soaking the electric base hot plate was removed.

[1] Mr Terry Hawkins, Koppers Timber Preservation Pty Ltd, North Sydney.

Although PEC or HTC can be heated in a 205 L drum over an open fire, creosote is flammable and use of an open fire is not recommended.

Butt Treatment

The butts (760 mm) were treated using the hot and cold bath process. This process involves heating dry posts in hot creosote to drive out some air (and additional water) in the posts, followed by cooling overnight in the treatment drum, when atmospheric pressure assists capillary forces in moving the liquid into the posts, to replace the air driven out (Dale 1967). Mean moisture contents at treatment were approximately 18 per cent for the three batches treated. Appendix 1 lists the schedules for treating the butt sections for each of the batches.

During the cold cycle, creosote was absorbed into the posts, causing the preservative level to drop. Measured amounts of creosote were added to keep the level at approximately 775 mm (above the critical level of 760 mm), but at least 75 mm below the top of the drum, to allow for expansion of the preservative when heated.

The CSIRO Division of Forest Products (1961) recommended a sapwood retention of 160 kg m^{-3} of creosote (146 L m^{-3}) for the butt ends, and between 48 to 64 kg m^{-3} (44 to 58 L m^{-3}) for the crowns. The butt end retention of 160 kg m^{-3} was specified 34 years ago and is higher than the current Australian standard of 99 kg m^{-3} for posts treated to hazard level 4 (H4) (Standards Australia 1993). The volume of PEC or HTC required to achieve these retentions was estimated from sapwood volume estimates. When the butts had absorbed the estimated volume of creosote the posts were removed, and excess creosote drained into troughs, measured and returned to the treatment drum. This amount was subtracted from the initial calculation to give the actual volume of creosote absorbed by the butts. The gain in mass for each post was used to accurately determine the PEC or HTC uptake for the butt sections.

Crown Treatment

After butt treatment, posts were inverted and placed in a 205 L drum extended to 1300 mm high to allow the full length of the posts to be treated. Crown treatment involved cold soaking instead of the hot and cold bath process, owing to the lower decay hazard in the above ground section. Based on the sapwood volume and the required preservative retention, the amount of PEC or HTC needed to treat the crowns was estimated. Batch 1 required 13 days and Batch 2 seven days soaking in PEC and Batch 3 required nine days soaking in HTC to adequately treat the crown sections. After crown treatment, posts were removed and any excess preservative was drained, measured and returned to the treatment drum.

Two or three sample posts per batch were cross-cut at 100 mm, 300 mm, 450 mm, 600 mm, 700 mm and 760 mm from the butt and the sections then split longitudinally with an axe. A visual assessment of the pattern and distribution of creosote treatment on both the transverse and radial longitudinal sections was used to determine whether further treatments were required. Insufficient radial penetration of creosote into the sapwood was indicated, therefore retreatment was required. Photographic records were made of transverse and radial longitudinal sections.

All posts were individually weighed and preservative retention was estimated by gain in mass for the butts, crowns and total lengths.

Chemical Analysis

Two 20 mm diameter cores were taken 600 mm from the butt of twelve posts (four from each batch) for chemical analysis by the Chemistry and Wood Preservation Laboratory of the Queensland Forest Service. Creosote retentions in percentage mass/mass and kg m^{-3}, depth of penetration, sample moisture contents and air-dry density were determined. Analysis was carried out according to AS 1605 - 1974 (Standards Association of Australia 1974). Creosote has been found to be more difficult to extract from PEC-treated samples than from HTC-treated samples, and often the PEC-treated samples required a longer extraction period (Kennedy[2] personal communication).

Post Identification

Following treatment with PEC or HTC, posts were tagged as follows:

Batch 1 (PEC)	1-1, 1-3, 1-5, 1-6, 1-7 and 1-11 to 1-19 (14 posts);
Batch 2 (PEC)	2-1 to 2-3, 2-5 to 2-14, 2-16, 2-18 to 2-20 (17 posts);
Batch 3 (HTC)	3-1 to 3-5 and 3-8 to 3-18 (16 posts).

The gaps in the sequence are because some posts were cut to examine creosote distribution during treatment, as discussed above.

Assessment

Posts have been placed in-service at a CALM share farming property in the Busselton District to assess long term performance.

RESULTS AND DISCUSSION

Air-dry Density and Moisture Content

The air-dry densities and moisture contents for four-year-old Tasmanian blue gum posts determined before and after treatment are given in Table 1.

[2] Mr Michael Kennedy, Queensland Department of Primary Industries, Forest Service, Indooroopilly, Queensland.

Air-dry densities measured in this trial for four-year-old Tasmanian blue gums is lower than the mean density of 727 kg m^{-3} determined by Kingston and Risdon (1961), but higher than the mean air-dry density of 475 kg m^{-3} for two-year-old Tasmanian blue gums measured by Brennan and Pitcher (1993). The standard deviation of 70 kg m^{-3} indicates greater variation between samples than the 47 kg m^{-3} quoted by Kingston and Risdon (1961). The differences in age between the trees assessed in this trial, and those assessed by Kingston and Risdon (1961) and Brennan and Pitcher (1993), would contribute to the difference in densities. Low mean air-dry densities indicate thin cell walls and large cavities within cells, which should allow a greater uptake of creosote, particularly PEC, where complex surface chemistry plays a role.

Moisture contents before treatment were well below fibre saturation point (f.s.p.), indicating that the cell cavities contained no free water, which could restrict preservative uptake. Moisture contents after treatment indicated slight moisture loss during the hot and cold bath treatment process. The moisture content before and after treatment was used to calculate PEC or HTC retentions based on mass loss using a formula described by Markstrom and Gjovik (1992), and is reported below.

Butt and Crown Retentions

Table 2 lists the butt retentions in percentage mass/mass and kg m^{-3}, and depth of penetration based on chemical analysis of sample cores taken 600 mm from the butt.

TABLE 1

Air-dry densities and moisture contents before and after treating four-year-old Tasmanian blue gum posts with PEC or HTC.

BATCH	AIR-DRY DENSITY (kg m^{-3})			MOISTURE CONTENT (%)					
				BEFORE TREATMENT			AFTER TREATMENT		
	Mean	S.D.	Range	Mean	S.D.	Range	Mean	S.D.	Range
1	640	70	550-790	17.8	0.7	17.0-18.9	12.8	2.5	9-14
2	640	70	550-790	17.4	1.2	16.1-19.8	12.5	1.9	11-15
3	640	70	550-790	17.9	0.7	17.3-19.2	9.8	0.5	9-10

TABLE 2

Creosote retentions in percentage mass/mass and kg m^{-3} for four-year-old Tasmanian blue gum posts, based on chemical analysis.

SAMPLE No.	BATCH 1 (PEC) RETENTION[a]			BATCH 2 (PEC) RETENTION[a]			BATCH 3 (HTC) RETENTION[a]		
	% m/m	kg m^{-3}	Depth of penetration (mm)	% m/m	kg m^{-3}	Depth of penetration (mm)	% m/m	kg m^{-3}	Depth of penetration (mm)
1	12.4	80	35 - 40	9.1	90	30 - 35	11.0	70	40 - 45
2	14.2	90	40 - 45	9.5	60	35 - 40	15.3	100	35 - 40
3	11.0	70	40 - 45	13.8	90	35 - 40	6.1	40	30 - 35
4	14.3	90	> 40	28.9	185	45 - 50	1.3	10	30 - 40
Mean	13.0	82.5	35 - 45	15.3	106.2	30 - 50	8.4	55.0	30 - 45

[a] Creosote retention (% mass/mass) = $\frac{\text{Mass of preservative}}{\text{Mass of core analysed}} \times 100$

Creosote retention (kg m^{-3}) = Creosote retention (% m/m) × $\frac{\text{Air-dry density}}{100}$

where air-dry density is the density of the sample analysed

Australian standard AS1604 -1993 requires hardwoods to be treated to hazard level 4 (H4) to have a retention of 10 per cent mass/mass or 99 kg m^{-3} mass/volume. Hazard level 4 (H4) is for timber that is used in ground contact and subjected to severe wetting and leaching, for example, fencing, greenhouses, pergolas and landscaping timbers (Standards Australia 1993). The 99 kg m^{-3} estimate is based on the air-dry density of spotted gum (*E. maculata* Hook.). Batches 1 and 2 had mean preservative retentions greater than 10 per cent mass/mass and passed the H4 requirement, whereas the lower retention of 8.4 per cent mass/mass for Batch 3 was owing to the low creosote retentions in samples 3 and 4. AS 1604 requires the retention in 90 per cent of test pieces selected from the treatment batch to be not less than 10 per cent mass/mass and 90 per cent shall pass the requirement of full sapwood penetration. Only four samples in each batch were analysed, with two samples in Batch 2 just below the required minimum retention with retentions of 9.1 and 9.5 per cent mass/mass. Two samples in Batch 3 were below the required minimum retention, particularly sample 4 which had a retention of 1.3 per cent mass/mass. Further analyses would be an advantage because of the small sample size. Errors associated with this method of estimating preservative retentions are discussed below.

All the test samples must show evidence of preservative penetration across the full sapwood band. Although starch tests were not conducted, the young age of the trees would indicate the posts consisted of sapwood. Microscopic examination did not reveal any tyloses, which indicated that there was no heartwood or transition wood present. In comparison, Nicholls and Phillips (1970) reported that heartwood formation takes place in manna gum (*E. viminalis* Labill.) when the sapwood is about 4-years-old. Penetration depths are listed in Table 2 and indicate PEC and HTC penetrating greater than 30 mm with some samples up to 50 mm. Retentions in the first 25 mm, which represents more than half the radii of the posts, would be substantially higher than in the inner portion of the analytical zone, giving the posts a greater overall strength and a longer life in ground contact. Despite these penetration depths, low retentions were still recorded and retentions based on mass gain or reduction in creosote level while the posts were immersed, gave a better overall estimation of preservative uptakes. PEC is difficult to extract by the Dean and Stark method outlined in AS 1605 -1974 (Standards Association of Australia 1974) and chemical analysis may indicate lower retentions.

The mean percentage of treated sapwood (based on the full cross section) for the butt samples analysed were :

Batch 1	59 to 76 per cent
Batch 2	54 to 90 per cent
Batch 3	55 to 82 per cent

All samples had creosote penetrating the outer 50 per cent of the sapwood and in some samples as much as 90 per cent. In AS 1604 - 1993, the requirement for H4 is for all sapwood to be treated, and the preliminary redraft of AS 2209 - 1979 requires hardwood poles of durability class 4 to have a minimum depth of penetration of 20 mm and softwood poles 35 mm (Local Government Electricity Association of New South Wales 1992). Sapwood is non durable, i.e. lower durability than class 4 heartwood. In addition, where a species has a wide sapwood band but the inner portion is refractory, creosote is required to penetrate a minimum of 20 mm or 75 per cent of the sapwood thickness, whichever is the greater (Local Government Electricity Association of New South Wales 1992). All samples indicate penetrations greater than 30 mm and some as high as 50 mm, satisfying the requirements of the redrafted AS 2209 but not achieving the full sapwood penetration requirement in AS 1604. Achieving a mean preservative treatment band of 30 mm to 50 mm should give protection to any untreated sapwood in the centre of the post and give the post an adequate residual strength in the treated annulus to ensure structural integrity.

The pole standard (redraft of AS 2209 - 1979) specifies the size of the treated sapwood band for poles used for overhead lines, where strength and durability are critical, and therefore the depth of preservative penetration is important. Fence posts do not have the same load bearing requirements and safety factors as transmission poles, and it is not as critical to achieve a minimum sapwood penetration of 20 mm or 35 mm, but to have a treated envelope of sufficient penetration to protect any untreated heartwood. Without pressure impregnation it is difficult to achieve full sapwood penetration, and in some commercial situations it would be uneconomical to treat the full sapwood bands of posts similar to those treated in this trial, owing to chemical costs.

Retentions based on mass gain for the butts, crowns and full lengths are listed in Table 3. The retention level of each post was calculated using the following equation given in Markstrom and Gjovik (1992):

$$Y = \frac{W(100 + M_1) - X(100 + M_2)}{Z(100 + M_1)}$$

Y = retention of creosote (kg m^{-3})
W = weight of treated post (kg)
X = weight of untreated post at time of moisture content determination on sample posts
Z = volume of post (m^3)
M_1 = average moisture content, oven-dry weight, of five sample posts before treatment (%)
M_2 = average moisture content, oven-dry weight, of five sample posts after treatment (%).

Individual post retentions were used to calculate the mean retentions for each batch.

Table 4 lists the post dimensions, preservative uptake and costs based on the reduction in creosote level while treating the posts. Retentions determined using Markstrom and Gjovik's (1992) formula (Table 3) are similar to those given in Table 4, but as expected are greater than those determined by chemical analysis. The

TABLE 3
PEC and HTC retentions based on mass gain for butts, crowns and full lengths.

BATCH	RETENTION (kg m^{-3})								
	BUTT			CROWN			FULL LENGTH		
	Mean	S.D.	Range	Mean	S.D.	Range	Mean	S.D.	Range
1 (PEC)	170	25	135-225	92	14	65-117	127	17.4	99-165
2 (PEC)	160	26	107-236	62	10	47-83	107	17	78-148
3 (HTC)	98	18	74-143	66	11	55-89	81	12	67-105

butt retentions estimated by the reduction in creosote level while posts were immersed and mass gain methods are between two and 2.5 times greater than those estimated by chemical analysis of a small specimen. The reduction in creosote level method was 1.3 times the mass gain retentions. When estimating crown retentions, the reduction in creosote level while the posts were immersed and mass gain methods gave similar results. All methods indicated that posts treated with HTC (Batch 3) had lower retentions than posts treated with the PEC emulsion (Batches 2 and 3). Despite the lower retentions of posts in Batch 3, the retentions estimated by mass gain, and reduction in creosote level while the posts were immersed indicated retentions above the minimum requirement for H4 in AS 1604 - 1993.

All three methods have potential for errors to occur. Measuring the reduction in the creosote level with posts immersed required reading a dipstick to the nearest millimetre, but owing to the large surface area of the treatment drum a difference of one or two millimetres leads to inaccuracies. Measurements needed to be taken at similar temperatures because of the amount of creosote expansion experienced at different temperatures. Inaccuracies can occur in determining sapwood volume, because generally the boundary between sapwood and heartwood is very difficult to see in posts cut from young trees. However, the young posts treated in this trial contained all sapwood, and as stated previously, microscopic examination did not find the tyloses associated with transition wood.

The mass gain method is the more accurate method because individual posts are weighed before and after treatment, and any additional weight gain is predominantly the result of preservative uptake. Any moisture loss during treatment was between 5 and 8 per cent for the different batches and is accounted for in Markstrom and Gjovik's formula. Retentions based on this method should be used for indicating post and batch retentions and a land owner could use scales to determine weight gain and preservative uptake. Chemical analysis was based on sampling four posts per batch and the retention for the butt section was determined by two small 20 mm diameter cores taken at one position. The results of analysis of retention at that position should be accurate, but only an indication of retentions in the whole butt section.

An alternative method to determining preservative uptake by the change in the creosote level in the treatment vessel with the posts immersed, is the 'top-up method' described by CSIRO (1955) which involves :

(1) Estimating the amount of preservative that a batch of posts should absorb during butt or crown treatment (based on sapwood volume).
(2) Measuring this quantity of preservative into a container.
(3) Marking on a dipstick the level of the preservative in the drum at the beginning of the butt treatment (use a metal dipstick because the creosote will be absorbed into a dry wooden stick, leading to errors).
(4) Ensuring the level is approximately 775 mm (which is above the critical level of 760 mm), but at least 75 mm below the top of the drum, to allow for expansion when heated.
(5) As the treatment proceeds, add measured quantities of creosote from the container to the drum, bringing the level back to the original.
(6) When all the preservative from the container has been used, treatment is complete.

The 'top-up method' allows the creosote level to be maintained at a set level and ensures that no untreated gaps occur. However, regular monitoring is required during treatment, particularly if using the hot and cold bath process, to ensure that the required retentions are achieved.

In the present trial, crowns were cold soaked for 13 days (Batch 1), 7 days (Batch 2) and 9 days (Batch 3). Seventy-five per cent of the PEC absorbed into the crowns treated in Batch 1 occurred in the first five days, therefore Batch 2 was soaked for only 7 days. Batch 3 had 80 per cent of the HTC absorbed into the crowns in the first six days and 20 per cent in the next three days. Retentions determined by the mass gain or reduction in creosote level while the posts were immersed gave similar results (Tables 2 and 3). All batches passed the minimum retention requirement of 48 to 64 kg m^{-3} given by the CSIRO Division of Forest Products (CSIRO 1961).

PEC is subject to sedimentation if left standing without agitation. When treating posts by cold soaking, homogeneity is easily restored by stirring. As stated previously, PEC is an emulsion composed of creosote,

TABLE 4

Post dimensions, preservative uptake based on reduction in creosote level in treatment vessel, and cost of treating four-year-old Tasmanian blue gum posts with PEC or HTC.

Batch	No. of posts treated	Mean s.e.d.u.b. (cm)	Total sapwood volume (m^3)	Total log volume (m^3)	Preservative uptake (L)									Preservative costs ($)		
					Butt			Crown			Post					
					Total	Per post	Per m^3	Total	Per post	Per m^3	Total	Per post	Per m^3	Per litre	Per post	Per m^3
1	16	9.1	0.27	0.27	21.5	1.3	189 (L m^{-3})	10.0	0.6	64 (L m^{-3})	31.5	1.9	117 (L m^{-3})	1.77	3.36	207.09
(PEC)							207 (kg m^{-3})			70 (kg m^{-3})			128 (kg m^{-3})			
2	18	8.2	0.25	0.25	20.8	1.2	198 (L m^{-3})	10.5	0.6	72 (L m^{-3})	31.3	1.7	125 (L m^{-3})	1.77	3.02	221.25
(PEC)							217 (kg m^{-3})			79 (kg m^{-3})			137 (kg m^{-3})			
3	17	8.6	0.25	0.25	12.5	0.7	119 (L m^{-3})	9.4	0.6	65 (L m^{-3})	21.9	1.3	88.6 (L m^{-3})	1.18	1.53	103.84
(HTC)							130 (kg m^{-3})			71 (kg m^{-3})			96 (kg m^{-3})			

Retentions are based on the reduction in creosote level while treating the posts.

water, surfactants, micronized pigment and stabilizers. When PEC is heated to 95°C in a commercial pressure impregnation treatment process a homogenizer is required, i.e. the emulsion is sheared through multiple teeth generators in a Dispax Reactor® and in storage tanks an agitator is used to stir the emulsion. When PEC is used without shearing either during or after treatment, the emulsion will tend to sediment in the base of the storage cylinder.

Batches 1 and 2 required three treatments to produce the required PEC penetration and retention, however, with each subsequent hot and cold cycle it appears to become more difficult to treat the posts. The build-up of deposits (concentrated emulsion/pigments) on the post surfaces can restrict radial movement. Stirring the solution between treatments and agitating by placing posts in and out of the treatment drum did not reconstitute the PEC, with sediment remaining at the base of the drum.

Some bleeding of PEC was observed when the posts were placed in direct sunlight, which could be caused by high creosote loadings, degraded emulsion as indicated above, or air in the posts expanding when heated and thus expelling some PEC. The pigment particles are deposited within the wood structure when a vacuum is applied and the emulsion breaks within the wood cells. The pigment has the critical role of both stabilizing the emulsion and producing the clean surface of the treated commodity, upon drying and weathering. The actual colour would be regarded as a bonus. The posts remain grey until they dry, then brown as the creosote is baked on the surface of the pigment particles by heat and, more importantly, ultra violet radiation. The brown colour is caused by the weathering of dried oxidized creosote on the surface of the pole. Eventually the posts weather to appear as if they are not treated at all, that is the colour becomes grey/white. The surface of a pole treated with PEC in a pressure impregnation process normally develops a rust colour instead of the dark colour of a HTC-treated pole. This rust colour was not observed on the posts treated in this trial.

Costs

A 205 L drum of PEC was donated by Koppers Australia, as PEC is not sold commercially in 205 L drums, and a wholesale price cannot be given. However, an estimated cost of PEC is probably an additional 50 per cent above the cost of HTC, i.e. about $1.77 per L (Hawkins personal communication). This price of $1.77 per L in 205 L drums includes the cost of transportation to Western Australia and can be significantly reduced when purchased in bulk commercial volumes of 20 000 to 25 000 L. Table 4 lists the cost per cubic metre and per post based on the uptakes determined by the reduction in creosote level while posts were immersed. The amount of PEC used to treat an 80 mm to 90 mm s.e.d.u.b. post in this trial cost between $3.02 and $3.36 per post ($221 and $207 per m^3) and HTC cost $1.53 per post ($104 per m^3). Preservative costs based on retentions determined by mass gain would be slightly less, i.e. $2.36 and $3.33 per post ($172 to $205 per m^3) for PEC and $1.29 per post ($88 per m^3) for HTC. For example, the difference in retentions caused the PEC cost in Batch 2 to be reduced by $0.66 per post. The retail price in the south-west of WA of a similar size CCA-treated pine post is approximately $6.90 (based on purchasing a bundle of posts), which is double the cost of a PEC-treated post and five times that of a HTC-treated post. Transport, plant, labour and posts (if not readily available to the land owner) would be additional costs.

When PEC is used to treat posts by the hot and cold bath process or cold soaking, simple agitation equipment is required to maintain a homogeneous emulsion. This equipment is not expensive and could be economical for land owners treating fence posts. The agitation equipment could be constructed by attaching a shaft and propellor to an electric motor, with a voltage regulator used to provide a variable stirring speed. Similar low cost equipment has been built by CSIRO Division of Forest Products to stir small volumes of PEC used in experimental trials. Because the cost of PEC is an estimated 50 per cent higher than the cost of HTC, and 35 per cent more PEC is necessary to get an equivalent HTC retention, this makes PEC-treated posts expensive.

Emulsified creosote (EC), is similar to PEC except it has no pigment, and is principally used for brush-on applications for poles in ground-line maintenance operations. EC could be used as a remedial treatment for treated posts at significantly less cost (Hawkins personal communication). Commercial potential could be realized if PEC or EC were manufactured in Western Australia. At present, the indications are that commercially treated copper-chrome-arsenic (CCA)-treated pine posts are competitive, and preservative penetration would be better.

Durability In-service

Regular assessments, every one to two years for the first five years, then every three to five years, will indicate the performance of the posts in-service at the Busselton property. This will give a comparison between posts treated with PEC and HTC. The overall post condition, whether it is still serviceable and the reason/s for any post failures will be recorded. Assessments will be carried out by manually pushing each post, with the assessor maintaining a uniform loading. A close inspection of the posts below ground-line, after scraping away the soil, will indicate the presence of any fungal or insect attack. Any damage to the exposed section of the post from weathering or mechanical means will also be recorded.

Conclusions

Fence posts cut from Tasmanian blue gum trees can be effectively treated with HTC by the hot and cold bath process for the butts, and cold soaking the crowns, to retentions suitable for use in ground contact. PEC can sediment when heated and when left standing for long periods without agitation, and under these conditions would be unsuitable for land owners treating posts by the hot and cold bath process or cold soaking. PEC requires shearing or simple agitation for this application either during or after the treatment. This trial indicated a need to purchase or make up simple agitation equipment to maintain a homogeneous emulsion. The requirement for agitation and the additional cost of PEC indicates that PEC-treated posts will not be as practical and competitive as posts treated with HTC by the hot and cold bath process. Regular assessments of posts treated with either PEC or HTC will indicate the performance in-service. Posts are in-service at a property in Busselton District, and regular inspections will be made, as explained.

ACKNOWLEDGEMENTS

Koppers Australia are thanked for their kind donation of the drum of Pigment Emulsified Creosote (PEC) used in the trial. Dr Graeme Siemon is thanked for editing this report.

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APPENDIX 1

Schedules for treating the butt sections for Batches 1 and 2 (treated with PEC) and Batch 3 (treated with HTC) are listed below.

BATCH 1 (PEC)

TREATMENT	TEMPERATURE (°C)	TIME (h)
Hot cycle	29 - 55	1.5
	81	1.5
	90	0.75
Hold at 90°C for 2 h	90	1.5
		5.15
Cold cycle	85	1.0
(overnight cool)	72	2.5
	40	14.0
	32	4.0
		21.5
First retreatment	32.61	2.0
Hot cycle	82	1.5
	89	0.5
	93	1.0
Hold at 93°C for 1 h	93	1.0
		6.0
Cold cycle	93 - 48	14.5
(overnight cool)		
Second retreatment	32 - 65	1.5
Hot cycle	73	0.5
	80	0.5
	90	1.0
	96	0.5
Hold at 96°C for 1 h	96	1.0
		5.0
Cold cycle	99 - 91	1.5
(overnight cool)	45	15.5
		17.0

BATCH 2 (PEC)

TREATMENT	TEMPERATURE (°C)	TIME (h)
Hot cycle	50 - 60	1.0
	79	1.0
	89	0.5
	99	0.5
Hold at 99°C for 1 h	99	1.0
		4.0
Cold cycle	99 - 92	0.5
(overnight cool)	89	1.0
	41	16.0
		17.5
First retreatment	37 - 59	1.5
Hot cycle	96	2.0
Hold at 96°C for 2 h	96	2.0
		5.5
Cold cycle	96 - 88	2.0
* (2 days)	40	16.0
	14	48.0
		66.0
Second retreatment	13 - 64	3.5
Hot cycle	77	1.0
	86	0.5
	90	0.5
	98	1.0
Hold at 98°C for 1 h	98	1.0
		7.5
Cold cycle	98 - 31	16.5
(overnight cool)		

* Longer cold cycle was used as posts were cooled in the treatment drum over a weekend.

BATCH 3 (HTC)

TREATMENT	TEMPERATURE (°C)	TIME (h)
Hot cycle	73 - 96	2.0
	103	0.5
	107	0.5
Hold at 107°C for 1 h	107	1.0
		4.0
Cold cycle	107 - 83	1.5
(overnight cool)	62	2.0
	27	13.5
		17.0
First retreatment	27 - 89	2.5
Hot cycle	95	1.0
	106	1.0
Hold at 106°C for 1 h	106	1.0
		5.5
Cold cycle	106 - 94	1.5
(overnight cool)	58	3.5
	24	16.0
		21.0
Second retreatment	29 - 90	3.5
Hot cycle	113	2.0
Hold at 113°C for 2 h	113	2.0
		7.5
Cold cycle	113 - 16	51.5
* (2 days)		

* Longer cold cycle was used as posts were cooled in the treatment drum over a weekend.

CALMScience 2(2): 129-132 (1996)

Growth of young *Eucalyptus globulus* in plantations after manual defoliation simulating insect herbivory

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ABSTRACT

The impact of three levels of manual defoliation in spring, summer or autumn on growth of young plants of *Eucalyptus globulus* Labill. was studied over one year. No extraordinary mortality owing to defoliation treatments resulted. Fifty per cent defoliation in autumn significantly reduced initial height growth, unlike 50 per cent defoliation in spring or summer. One hundred per cent defoliation in any season significantly reduced height growth. Basal area growth remained significantly reduced in September 1992 after 100 per cent defoliation in the previous spring or autumn.

These findings indicate that single 50 per cent or less defoliations of *E. globulus* by insects should be tolerable in spring or summer, but not in autumn, and that 100 per cent defoliation is unacceptable at any time.

INTRODUCTION

The Western Australian Department of Conservation and Land Management (CALM) has initiated plantings of *Eucalyptus globulus* Labill. in excess of 6000 ha throughout the south-west of Western Australia (WA) (CALM 1992). Most of the planted area is on cleared farmland or water catchments, established and managed under sharecropping arrangements between the landholder and CALM.

Defoliating insects are an unpredictable risk to yields from eucalypt plantations. Since 1988, 10 species of insect have been recorded as damaging *E. globulus* plantings in WA (Abbott 1993). Knowledge of the intensity and duration of defoliation effects on tree growth is important because insects are capable of inflicting severe defoliation at any stage of canopy development, and rotation times for *E. globulus* are intended to be short (10-15 years, Shea and Bartle 1988).

A field trial was established to assess growth and recovery responses of *E. globulus* saplings to different amounts of manual defoliation applied over the course of the first year of growth. Treatments applied in this trial were intended to emulate the gross effects of defoliators such as spring beetles (Scarabaeidae), grasshoppers (*Phaulacridium vittatum, Chortoicetes terminifera*) and autumn gum moth (*Mnesampela privata*). We addressed three questions:

(1) Does defoliation affect height and diameter growth in young *E. globulus*?
(2) Does the season of defoliation affect growth responses to defoliation?
(3) Do growth responses to defoliation persist?

METHODS

Location of Sites

Three stands of *E. globulus* were chosen from July 1991 plantings in south-west WA. Site 1 is located 7 km north of Jarrahdale townsite (32° 15' S, 116° 04' E) with an average annual rainfall (AAR) of *c.* 1100 mm. Site 2 is located 33 km east-south-east of Collie townsite (33° 28' S, 116° 28' E) with an AAR of *c.* 650 mm, while site 3 is located 20 km north-north-west of Darkan townsite (33° 13' S, 116° 38' E) and has an AAR of *c.* 600 mm. Each site was ripped prior to planting and site 1 was mounded to 30 cm prior to planting.

Experimental Design

Treatments were factorial combinations of three levels of defoliation (0 per cent, 50 per cent, and 100 per cent) applied once to each plant at one of three times (September 1991, December 1991 or March 1992). Control plants were not defoliated (i.e. 0 per cent treatment) and 100 per cent defoliation was achieved by removing all the leaves from the plant crown. The September 1991 50 per cent defoliation treatment was achieved by removing half the number of leaves evenly distributed from the crown. The 50 per cent defoliations in December and March resulted from removing the estimated topmost 50 per cent of leaf biomass from the crown.

Plants at each site were allocated a treatment at the outset of the trial and all plants except those defoliated in September 1991 were monitored before the application of treatments. Each treatment combination was allocated to five plants at each site resulting in a maximum of five control plants per site. Plants that died before application of treatment were not re-allocated replacements.

Variables Measured

The stem length of each plant was measured during the second or third week of September 1991, December 1991, March 1992, May 1992 and September 1992. Diameter over bark at 30 cm stem height was recorded from March 1992 onwards. The presence of folivores and any damage to plants were also noted.

Growth rate was calculated as increase in height or basal area in a specified period.

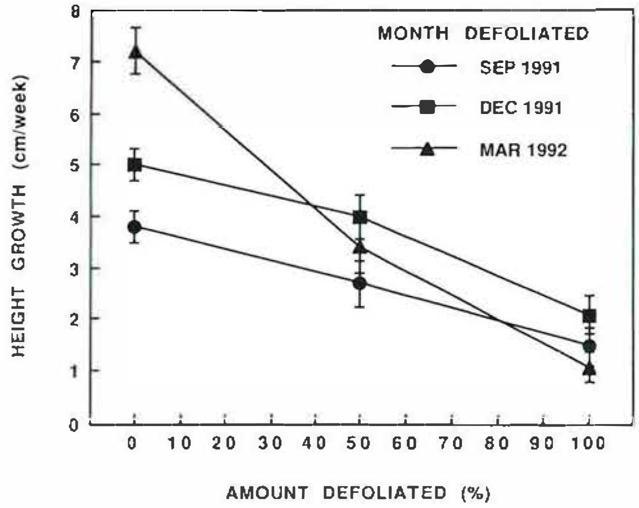

Figure 1. Effect of month and amount of defoliation on height growth rates (mean ± SE) of young Eucalyptus globulus *during the initial measurement period, approximately 3 months after defoliation.*

Although the March to May measurement period, a period of rapid growth, was one month shorter than the other two initial measurement periods, this may not have contributed greatly to the much increased growth rate for controls. A longer measurement period should have reduced the measured growth rate of control plants only slightly (see Fig. 2C).

RESULTS

Mortality of Plants

Defoliation did not increase plant mortality (Table 1). No combination of amount and month of defoliation resulted in mortality significantly different from the control treatment (Fisher's exact tests, $\alpha = 0.05$). Only 7 of 87 defoliated plants died after defoliation. Four of 45 control plants died (Table 1).

TABLE 1

Numbers of plants dead or alive after treatment at the termination of measurements for each combination of amount of defoliation and month of defoliation.

STATUS	INTENSITY AND MONTH OF DEFOLIATION						
	50%			100%			Control
	Sept	Dec	Mar	Sept	Dec	Mar	
Dead	1	0	0	3	3	0	4
Alive	14	14	14	12	12	14	41

Timing and Amount of Defoliation

The amount and timing of defoliation and their interaction had significant initial effects on growth rates (Fig. 1). Mean height growth rates for all defoliated treatments were severely retarded compared with controls, and the amount of retardation of growth increment increased as the amount of defoliation increased (Fig. 1). Defoliation in March 1992 resulted in more severe initial retardation in height growth than defoliation in September or December because intact plants had faster growth rates in the March to May period than in the September to December and December to March periods. This probably reflected the above average rainfall at all three sites in February 1992 (Jarrahdale: 127 mm [actual] *vs* 15 mm [long term average for February]; Collie: 24 *vs* 15 mm; Darkan: 31 *vs* 15 mm).

Persistence of Effects

Mean heights of completely defoliated plants remained significantly shorter than for intact plants at the termination of measurements (Fig. 2). Differences between intact and 50 per cent defoliated plants were only detected as significant for the March 1992 defoliation (Fig. 2C).

Effects on Stem Basal Area

Effects of defoliation on basal area growth were similar to the effects on height growth. Mean stem basal areas measured in September 1992 were smaller for defoliated plants than for intact plants (Fig. 3), although only September and March 100 per cent defoliated plants were significantly smaller.

Effects of Uncontrolled Background Defoliation

In September 1992 minor defoliation of a few trees by larvae of autumn gum moth (*Mnesampela privata*) was noted at site 2 and damage by parrots to stem tips was noted at site 3. Bluegum psyllids (*Ctenarytaina eucalypti*) were abundant at all three sites in September 1991 and 1992 but were unlikely to have interfered with the treatment effects.

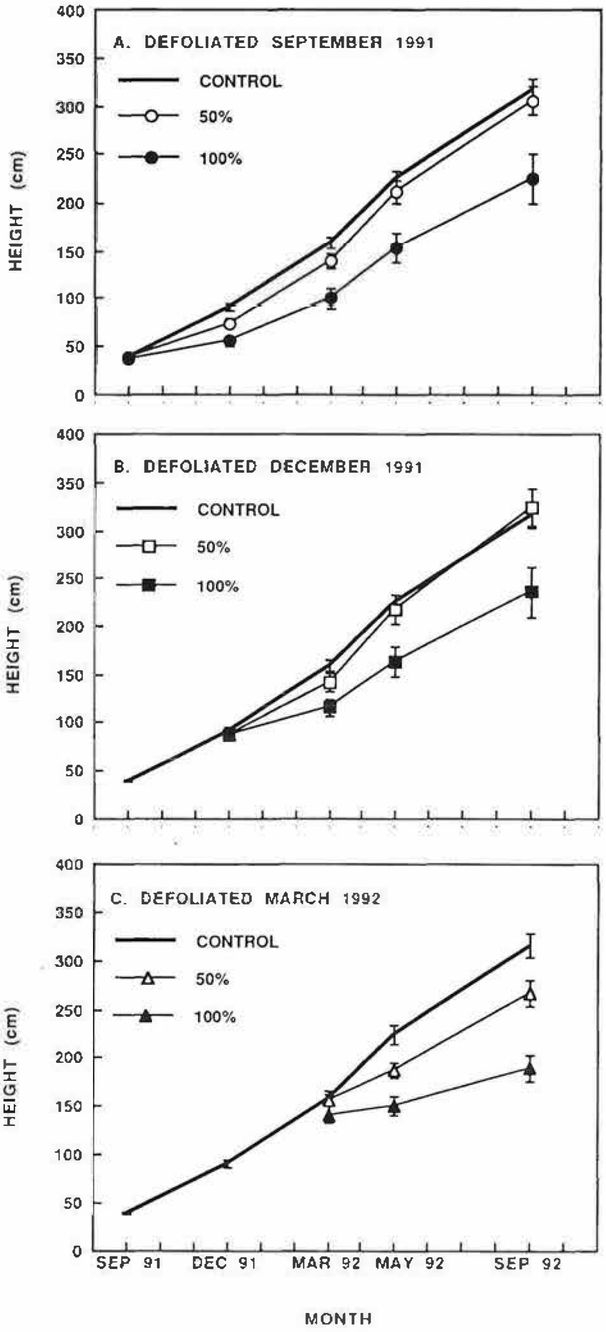

Figure 2. Height growth (mean ± SE) of Eucalyptus globulus *planted July 1991.*

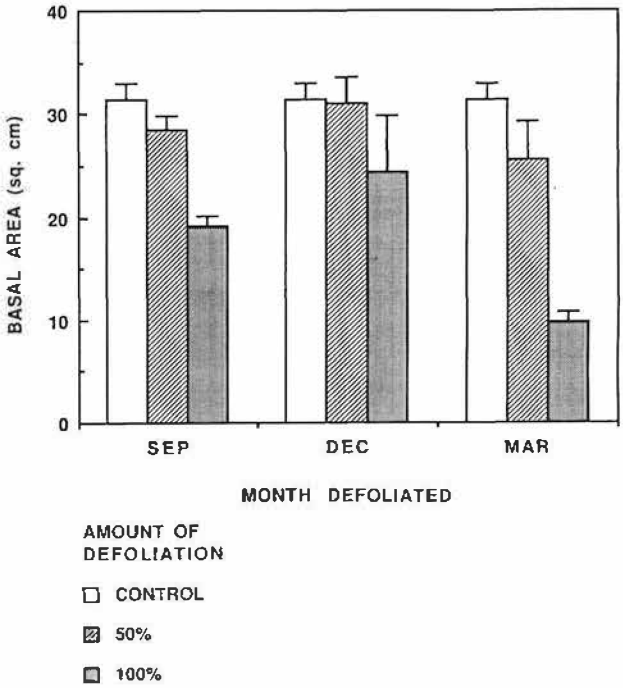

Figure 3. Basal area (mean ± SE), measured in September 1992, of Eucalyptus globulus *planted in July 1991.*

DISCUSSION

It would have been preferable to investigate effects on growth of defoliation by using defoliation caused by specific insect leaf chewers compared with controls where chewers were excluded (e.g. Elliott *et al.* 1993), rather than simulated herbivory. This is because plant growth responses often indicate sensitivity to differences between simulated and actual defoliation, even when fidelity to the mechanism of natural defoliation is rigorously attempted (Baldwin 1990). Nevertheless, each of these leaf chewer groups is capable of substantial or complete defoliation of affected plants when pest populations are great.

Eucalyptus globulus shows evidence of considerable ability to compensate for single defoliation intensities as large as 50 per cent. This robustness is shared with several other eucalypt species, namely *E. regnans* (Candy *et al.* 1992) and *E. grandis* (Carne *et al.* 1974) but not with *E. marginata* (Abbott *et al.* 1993) or *E. delegatensis* (Mazanec 1966). Defoliations >90 per cent by contrast always have large effects on growth (Mazanec 1967; Carne *et al.* 1974; Candy *et al.* 1992; Abbott *et al.* 1993).

The sensitivity of *E. globulus* to 50 per cent defoliation in autumn accords with observations made on two species of eucalypt in eastern Australia. Cremer (1973) observed that survival of *E. regnans* and *E. delegatensis* after total defoliation in late summer or autumn was lower than when defoliation was in spring. A late summer 'light' defoliation of *E. delegatensis* also had large impact on growth (Mazanec 1968). A single late summer defoliation of 66 per cent reduced height growth of *E. regnans* (relative to the control) compared with early summer defoliation of the same intensity, though the difference is not significant (Candy *et al.* 1992).

It appears that growth of eucalypts during spring and summer depletes starch reserves (Mazanec 1967; Cremer 1973). Defoliation in autumn prevents a tree from restoring its depleted starch to the level that would sustain refoliation (Bamber and Humphreys 1965), and this has a large impact on height and diameter growth.

Defoliation by insects is usually insidious, often involving partial consumption of leaves or particular plant tissue, unlike the instantaneous treatments of whole leaf removal applied here. For example, eggs of autumn gum moth (AGM) hatch in south-west WA soon after the first substantial autumn (April or May) rainfall and larvae commence skeletonizing juvenile foliage of affected *E. globulus*. By mid winter (July) larvae are large enough to remove laminae of leaves leaving only the mid-vein. Small trees up to 1-year-old may be completely defoliated by early spring (early September) if oviposition were dense and enough larvae survive. However, buds and the stem apex are not usually affected, resulting in a broomed appearance to severely affected trees as new leaves are produced. Progressive defoliation culminating in complete defoliation would have more severe and longer lasting effect on growth than a single complete defoliation, as indicated by Candy *et al.* (1992). Interpreting the results from the September defoliation (Fig. 2A) in the context of the time course of defoliation by AGM implies that even partial defoliation by AGM could have significant lasting effects on growth.

Removal of foliage from the upper crown did not appear to suppress growth more than diffuse removal of foliage (Fig. 1). However, disbudding with defoliation can severely suppress extension growth (Cremer 1972; Candy *et al.* 1992). Candy *et al.* (1992) found almost a year after treatment that disbudding and 50 per cent defoliation had a suppressive effect about three times that of just 50 per cent defoliation. Disbudding effects were not investigated in the current trial, although spring beetles and grasshoppers tend to be most active during spring and target expanding leaves and buds. The single 100 per cent December defoliation treatment is likely to underestimate the effects of severe disbudding and defoliation by spring beetles and grasshoppers.

Growth loss and death of trees from single large defoliations were surprisingly small. However, our experiment did not address the impact of frequency of defoliation on growth of *E. globulus*. If *E. globulus* behaves similarly to *E. marginata*, more frequent defoliations of low intensity should reduce growth more than less frequent defoliations of higher intensity (Abbott *et al.* 1993). The concern of plantation managers should therefore be directed at the more severe consequences of regular, small defoliations. This is why *E. globulus* plantations and timberbelts in WA require regular monitoring of pest insect densities. This will allow more informed usage of chemicals for protecting the wood resource from the effects of insect outbreaks and will direct the attention of managers to the vulnerability of partially defoliated trees to further damage.

ACKNOWLEDGEMENTS

We thank T. Burbidge and P. Van Heurck for conducting most of the field work, M. Williams for statistical advice, J. Bartle, P. Christensen, J. McGrath and S. Penfold for comments on the manuscript, and M. Gerrard, R. & M. South, and the Western Australian Water Authority for access to properties and trees.

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CALMScience 2(2): 133-140 (1996)

Prescribed burning of thinning slash in regrowth stands of karri (*Eucalyptus diversicolor*) - an operational trial using helicopter ignition

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ABSTRACT

This paper reports on an operational trial that was undertaken to evaluate the use of a helicopter-mounted incendiary machine for igniting thinning slash fuel in a regrowth stand of karri. Twenty hectares of commercially thinned 24-year-old regrowth were burnt according to a prescription developed from a prior experimental study. The burning prescription specified a moderately dry surface litter layer, a moist litter profile (>90 per cent moisture content), light winds, mild air temperatures (<25°C) and moderate relative humidity (>45 per cent). Fuel moisture contents were within the prescribed range during the burn but air temperatures were up to 7°C higher than prescribed and the Soil Dryness Index was above the recommended upper limit. Most thinning slash fuel <25 mm diameter and about half the litter load was consumed, leaving an average loading of unburnt litter residue of 11.4 t ha^{-1}. Fire-caused stem damage affected 78 stems ha^{-1} of retained crop trees while 212 stems ha^{-1} remained undamaged; the basal area of undamaged trees was 14.2 m^{2}ha^{-1}. Overall, the objectives set for fire behaviour, fuel consumption and tree damage were achieved, thereby validating the prescribed burning guidelines developed from the earlier study. The trial clearly demonstrated the effectiveness and flexibility of a helicopter for igniting prescribed fires in thinned regrowth stands.

INTRODUCTION

Thinning of even-aged regrowth stands is an important element of silvicultural practice in the tall open eucalypt forests of south-eastern and south-western Australia (Bradshaw 1985; Goodwin 1990; Kerruish and Rawlins 1991). By concentrating growth on selected trees, thinning provides a means of increasing sawlog yields from young, even-aged stands while at the same time salvaging a considerable volume of wood that would otherwise be lost to competition-induced mortality. In multiple use karri (*Eucalyptus diversicolor*) forests in south-west Western Australia (WA), commercial thinning of regenerated stands may be undertaken once stand top height exceeds 30 m (Bradshaw 1992). For most stands this represents an age of 20 to 30 years, depending on site index (Rayner 1991).

As is the case for all fire-prone forests, effective fire protection is an essential prerequisite for sustained yield management of forests in south-west WA. Strategic buffer zones within the south-west forests are subject to rotational fuel reduction burning to minimize the threat to life, property and forest values from large, uncontrolled fires. Logging and regeneration activities are directed to adjacent areas of forest from which fire is temporarily excluded, with the expectation that prescribed burning will progressively be reintroduced to regrowth stands as they develop to a fire-tolerant stage. Delay in the reintroduction of prescribed burning to regrowth stands will affect the schedule of harvesting in adjacent mature forest and therefore has the potential to disrupt sawlog supply to the timber industry. Accordingly, the development of prescribed burning techniques applicable to regrowth stands, both thinned and unthinned, is a high priority for research.

Following regeneration, fire is routinely excluded from regrowth stands for at least 15 years to allow the dominant and codominant trees to attain the height and bark thickness necessary to tolerate low intensity fire without damage to crowns or stems. Some regrowth stands are burnt prior to first thinning to reduce accumulated litter and woody fuel (McCaw 1986), but currently most stands remain unburnt until after first thinning. Thinning operations contribute additional dead fuel from the crowns and stems of felled trees and understorey shrubs, much of it remaining as elevated fuel in heaps. Consequently, dead fuel loadings in thinned stands are substantial and may amount to 76 t ha^{-1} of material <100 mm diameter (McCaw *et al.* unpublished manuscript). The more open canopy of thinned stands allows increased sunlight and wind penetration into the stand with the result that fuels may be sufficiently dry to carry fire between October and April each year. In contrast, the fire season in unthinned stands is considerably shorter and only extends from December to March in most years (McCaw, unpublished data).

In 1991 the Western Australian Department of Conservation and Land Management commenced a study to examine the feasibility of prescribed burning following thinning of even-aged karri stands. Fire characteristics, fuel consumption and tree damage were investigated by conducting small scale (<2 ha) experimental fires over a range of conditions, and the results of this study used to develop guidelines for prescribed burning (McCaw *et al.* unpublished manuscript). Changes in fuel nitrogen storage as a result of burning were examined in conjunction with the experimental fires (O'Connell and McCaw unpublished manuscript). In forest fire management, there is a need to validate the findings of detailed experimental studies at an operational scale where variation in terrain and stand conditions can influence the outcome of operations. The method and pattern of ignition can also have a profound influence on the behaviour of prescribed fires. The difficult ground conditions typical of regrowth karri stands generally preclude safe and efficient use of manual lighting crews, except along tracks and where walking lanes have been constructed. For this reason, implementation of prescribed burning on an operational scale will necessitate the use of aerial ignition techniques. Even-aged regrowth stands suitable for thinning tend to be dispersed through the forest in relatively small compartments, as logging coupes in karri forest types have seldom exceeded 100-150 ha in area. Helicopters offer great flexibility in lighting pattern and can be used more effectively on small or irregularly shaped compartments than is the case for fixed-wing aircraft. This paper reports on an operational trial that was undertaken to evaluate the use of a helicopter-mounted ignition system for prescribed burning of karri thinning slash, according to the guidelines developed from the prior experimental study.

METHODS

Study Area

Prescribed burning was undertaken in a 20 ha stand of thinned, even-aged karri regrowth in Boorara 13 compartment (34° 42' S 116° 16' E), about 15 km south-east of Northcliffe, WA. This stand was silviculturally regenerated from seed trees following harvesting and high intensity slash burning in 1969, and had subsequently been protected from fire up until the time of prescribed burning in November 1993. During early 1992 the stand was commercially thinned using a tree harvester to remove uncompetitive and poorly-formed trees; wood products removed during thinning included small sawlogs and chipwood down to a small end diameter of 75 mm. Retained trees were mostly dominants and codominants, with occasional veteran trees of large diameter (>2 m diameter at breast height over bark - d.b.h.o.b.) scattered among the regrowth. Stand top height in 1992 was 31 m, corresponding to a site index (Rayner 1991) of 46 m at age 50 years. The stand was situated on a broad ridge with average slopes of about 10° and maximum slopes of 20°. Elevation ranged between 60 m and 100 m above sea level (Fig. 1).

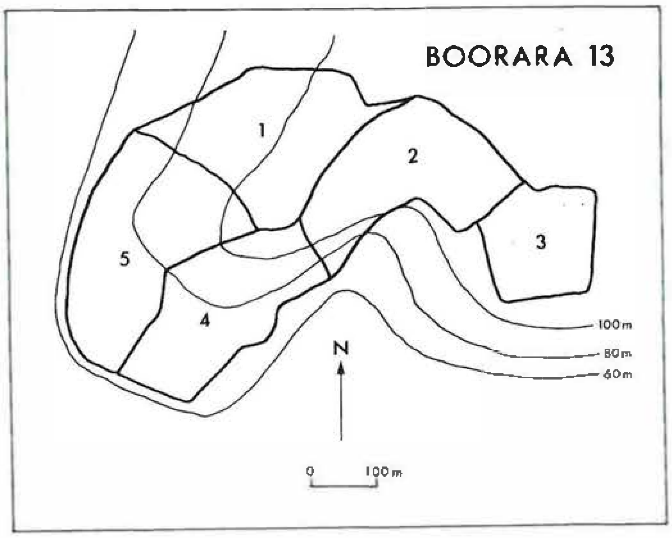

Figure 1. Map showing elevation contours and the layout of burning cells within the stand at Boorara 13.

Prescription for Burning

Weather and fuel moisture conditions prescribed for burning at Boorara 13 were based on the results of experimental fires conducted in a comparable thinned stand at Boorara 2 (Table 1), and are summarized in Table 2. The essential features of the burn prescription were: a moderately dry surface litter layer to ensure good ignition and fire spread between slash heaps; a moist litter profile and low Soil Dryness Index[1] (SDI) (Mount 1972; Burrows 1987) to limit the consumption of deep litter beds and woody fuel >25 mm diameter; light winds; and mild air temperature and relative humidity conditions to minimize the extent of crown scorch to retained trees in the stand. Burning under these conditions was expected to consume a high proportion (>80 per cent) of woody fuel <25 mm diameter and up to 60 per cent of the litter load. Results from the experimental study indicated that some fire-caused damage to retained trees was likely to occur even during low intensity fires, but not affecting more than about 80 stems per ha (stems ha^{-1}).

TABLE 1

Stand characteristics for thinned karri regrowth at Boorara 13 (this study) and at Boorara 2 where the burning prescription was developed.

CHARACTERISTIC	BOORARA 13	BOORARA 2
Site index (age 50)(m)	46	48
Year of regeneration	1969	1969
Age when burnt (years)	24	22
Stocking retained (stems ha^{-1})	328	337
Basal area retained ($m^2 ha^{-1}$)	20.8	19.5
Mean tree d.b.h.o.b. (cm)	27	26

[1] The SDI represents the amount of rainfall required to bring the soil back to a saturated condition at field capacity, which for most soils is about 200 mm of available moisture. In this paper SDI values are expressed in millimetres of moisture for consistency with SI units. For use in fire control in Western Australia the SDI is routinely expressed in millimetres x10.

TABLE 2
Prescribed and actual conditions for burning thinning slash at Boorara 13 on 23 and 24 November 1993.

VARIABLE	PRESCRIBED	ACTUAL		
		23 NOV	24 NOV	
		(1700 h)	(1200 h)	(1330 h)
Air temperature (°C)	20-25	21	29	32
Relative humidity (%)	60-45	65	43	34
In-forest wind speed (km h^{-1})	<2.8	<1	2.9	2.9
Wind direction	SE	SE	W	WNW
Fuel moisture content (%)				
-surface litter	12-18	ridge 12 l'slope 17	ridge 14 l'slope 19	(A)
-profile litter	>80	ridge 133 l'slope 97	ridge 98 l'slope 113	- -
Soil Dryness Index (mm)	<40	65	68	

(A) Fuel moisture content not sampled at 1330 hours.

Data Collection

In preparation for prescribed burning the stand was divided into five cells, each about 4 ha in area, separated by bulldozed mineral earth tracks. Stand and fuel characteristics prior to burning were assessed during August 1992 on transects established in each of the burn cells. Sample points were marked at 10 m intervals along transects and d.b.h.o.b. of trees within a 5 m radius of each point measured to the nearest centimetre. Trees were numbered to permit relocation following burning. The location and dimensions of existing stem wounds where the cambium had been damaged were recorded for 348 trees. Logs and other woody debris >20 cm diameter within 2 m of trees were noted. Fuel characteristics in thinned regrowth have previously been described in detail by McCaw *et al.* (unpublished manuscript). As the resources available for field work were limited, fuel assessment was confined to measuring the average depth of thinning slash within a 5 m radius of each sample point, to the nearest 0.2 m, using a calibrated height pole.

Ignition took place over two days (see below). During this time air temperature and relative humidity were recorded with an aspirated hygrometer at intervals of 1 to 2 hours. A sensitive cup anemometer was used to measure the average in-forest wind speed (at 1.5 m height above ground) over these same intervals. Samples of dead leaves and twigs ≤6 mm in diameter from the uppermost 10 mm of the litter layer (referred to subsequently as surface litter), and of the entire litter profile above mineral soil were collected from ridge and lower slope positions within the stand on both days. On each occasion three samples (each 30-50 g oven dry weight) were collected, sealed in air-tight tins and subsequently oven dried in the laboratory to determine moisture content. A representative SDI for the study site was calculated using rainfall and air temperature data from Northcliffe with a canopy interception function for mature open karri forest and an appropriate evapotranspiration table from Burrows (1987). Experienced observers recorded fire behaviour characteristics during the burn, including forward rates of spread and flame heights.

The helicopter used during lighting operations was a Bell Jet-Ranger which carried a crew of three (pilot, navigator, and incendiary machine operator). Incendiary capsules were of the 'ping-pong ball' type and were deployed from an incendiary machine mounted within the helicopter cabin.

Two months after prescribed burning, the extent of fuel consumption at each sample point was assessed visually according to the following rating system:

Litter fuel	- partially burnt, with litter residue remaining - completely burnt, with mineral soil exposed
Thinning slash	- thinning slash <25 mm diameter mostly unburnt (Low) - thinning slash <25 mm diameter partially consumed (Moderate) - thinning slash >25 mm diameter substantially consumed (High)

Where present, unburnt litter residue was collected from a 0.04 m^2 quadrat and later oven dried to determine loading in t ha^{-1}. During the same assessment, the height of crown scorch (m) and proportion of crown volume scorched (none, <50 per cent, >50 per cent) at each sample point were estimated visually.

Eleven months after burning, all numbered trees were re-examined and the location and dimensions of additional fire-caused wounds recorded. Where necessary, dead bark was removed with an axe to expose the full extent of dead cambium on the stem.

RESULTS

Fuel Characteristics and Burning Conditions

Fuels within the thinned stand consisted of leaf litter on the forest floor, a layer of elevated thinning slash and crushed understorey scrub, and old log debris left behind from the regeneration cut of 1969. McCaw *et al.* (unpublished manuscript) reported that the mean loading of dead fuel <50 mm diameter over bark in 22-year-old thinned karri regrowth was 62.8 t ha^{-1}, comprising 23.4 t ha^{-1} of litter, 8 t ha^{-1} of bark and wood <6 mm, 13.6 t ha^{-1} of wood 6-25 mm and 17.8 t ha^{-1} of wood 25-50 mm. Live understorey shrubs were not a significant component of the fuel loadings at Boorara 13 or at the stand described by McCaw *et al.* (unpublished manuscript).

Fuel assessment undertaken at the site indicated that about 80 per cent of the ground area was occupied by thinning slash fuel, with the remainder occupied by litter bed fuel or exposed soil on extraction tracks. The fuel bed was ≤0.2 m deep over half the site, and ≤0.6 m deep over 75 per cent of the site (Fig. 2). The maximum depth of thinning slash encountered during sampling was 1.5 m.

In the three weeks prior to burning rainfall was recorded at Northcliffe on 1 November (10.5 mm) and 16 November (3.5 mm). Prescribed burning was conducted over two days, commencing late in the afternoon of 23 November 1993 and continuing the following day. Weather and fuel moisture conditions on 23 November were within the range prescribed for each variable, except for the SDI which at 65 mm exceeded the prescribed upper limit of 40 mm (Table 2). Conditions had been suitable for lighting operations throughout the day but the helicopter was not available earlier because it was engaged in prescribed burning operations elsewhere. Following its arrival at 1700 hours (Western Standard Time) the helicopter dropped incendiary capsules in a grid pattern at an approximate spacing of 30 m x 30 m across the northern third of the stand in the area above the 100 m elevation contour (Fig. 1). Overnight, an area of about 6 ha on the ridge and upper slopes was burnt by low intensity fire with mean flame heights of 0.5 to 0.7 m, and spread rates in the range 12-20 m h^{-1}.

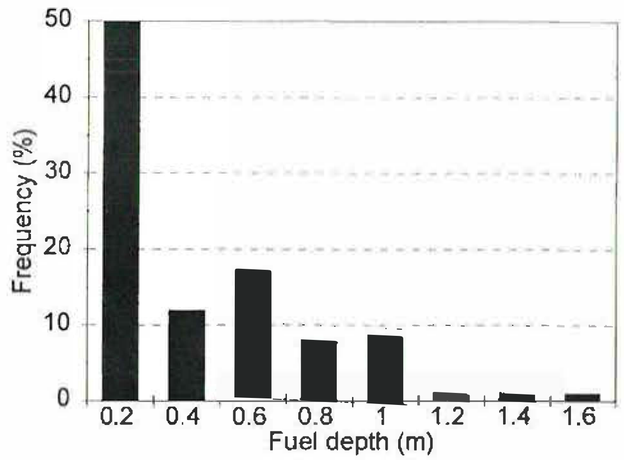

Figure 2. Frequency histogram showing depth of thinning slash fuel at 136 sample points prior to burning. Data from all five cells have been pooled.

On 24 November air temperature at the site exceeded the forecast maximum of 28°C and minimum relative humidity fell below the forecast minimum of 39 per cent, and together with the SDI were outside the prescribed range (Table 2). Conditions were hotter and drier than expected owing to the influence of a low pressure trough which directed dry northerly winds from the interior of WA over the lower south-west of the State. Wind speed and direction were as forecast, with observed wind speeds only marginally above the prescribed range. The decision to continue lighting operations took account of the fact that profile litter moisture content samples taken on the previous day were within the prescribed range and the litter profile would not have dried appreciably overnight. Test fires lit during the morning of 24 November exhibited appropriately mild fire behaviour, consistent with that prescribed. As on the previous afternoon surface litter samples collected from the ridge were substantially drier than those from the lower slope (Table 2); however, in the case of profile litter samples the difference between the moisture content of samples from the ridge and lower slope was not consistent from one day to the next, reflecting the considerable variability in the dryness of the litter profile. From 1200-1220 hours the helicopter lit along the contour about 20 m downslope from the edge of the area that had burnt-out overnight, placing incendiaries at intervals of 50-70 m. Most incendiary capsules succesfully ignited the thinning slash fuel, and the resulting fires tended to develop an elongated elliptical shape owing to the different rates of spread up and down the slope. Flames were typically 0.7-1 m high, but flared up to about 3 m in heaped slash on the edge of the central access track, probably because of the greater exposure of the fine fuels in this area to sunlight and wind. Flames were also prone to flaring in shoots from stump coppice, particularly in Cell 5 which had been thinned some months before the remainder of the area and as a result was densely stocked with coppice shoots up to 3 m tall. Further lighting was undertaken from the helicopter between 1420-1430 hours to fill in several gaps in the ignition pattern, after which it departed from the site. Fires continued to spread throughout the afternoon until the compartment was largely burnt-out by 1800 hours.

Post-fire assessment indicated that 94 per cent of the area had been burnt, with most of the unburnt area concentrated in one patch at the bottom of the easterly facing slope. Of the points that had been burnt, 85 per cent retained a layer of litter residue (Fig. 3a), with the average residue loading being 11.4 t ha^{-1}. The highest proportion of area burnt to mineral soil (28 per cent, Fig. 3a) and the lowest residue loading (8.5 t ha^{-1}) were in Cell 3 which was located on the top of the ridge. Slash consumption was rated as moderate (most slash <25 mm diameter consumed) over about 70 per cent of the area, with consumption rated as low over most of the remainder (Fig. 3b). Consumption of slash did, however, vary between cells, being greatest in Cell 3 and least in Cell 5.

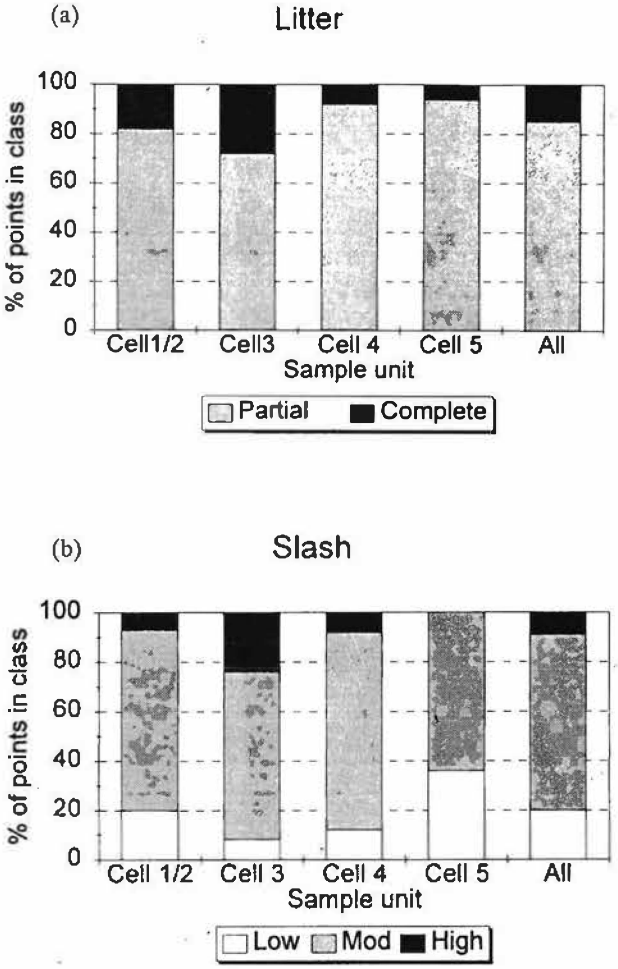

Figure 3. Histograms showing the proportion of sample points from individual cells and the whole site allocated to different fuel consumption rating classes for (a) litter fuel and (b) thinning slash fuel.

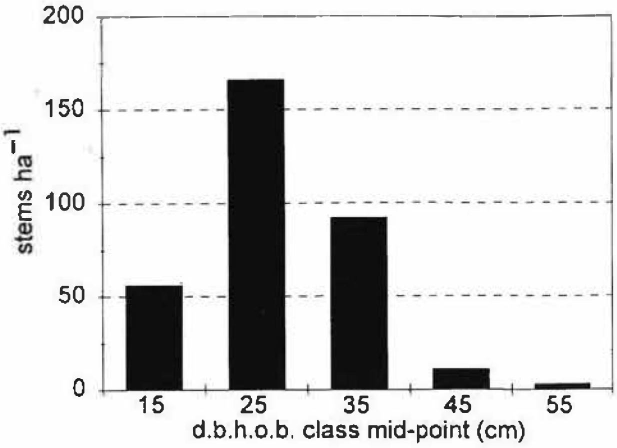

Figure 4. Stocking of trees ≥10 cm d.b.h.o.b. in 10 cm diameter classes (n = 348).

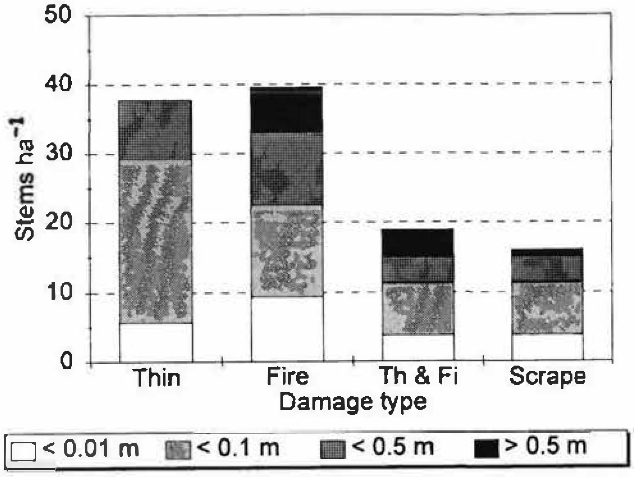

Figure 5. Stocking (stems ha^{-1}) of trees exhibiting stem damage, including only thinning-caused wounds (Thin), only fire-caused wounds (Fire), both thinning and fire-caused wounds (Th & Fi), and wounds associated with superficial bark scraping (Scrape). Data from all cells have been pooled, and columns show the frequency of damaged trees by wound-area class.

Stand Characteristics and Tree Damage

Following thinning, the stand had an average stocking of 328 stems ha^{-1} and a basal area (b.a.) of 20.8 m^{2}ha^{-1} (Table 1). Most trees were 20-40 cm d.b.h.o.b. (Fig. 4), with mean tree diameter being 27 cm. Stem damage caused by the thinning operation affected 38 stems ha^{-1} (equivalent to a b.a. of 2.4 m^{2}ha^{-1}), with most wounds between 0.01 m^2 and 0.1 m^2 in area and none exceeding 0.5 m^2 in area (Fig. 5).

Following prescribed burning, crown scorch heights were less than about 15 m over 76 per cent of the burnt area, with the result that the canopy remained unscorched. Twelve per cent of the area experienced scorch to <50 per cent of crown volume, while the remaining 12 per cent of the area was scorched to >50 per cent of crown volume with corresponding scorch heights in excess of 25 m. Crown scorch was concentrated in Cells 3 and 5, and only occasional trees in the other cells were scorched. Eleven months after burning, fire-caused stem wounds were recorded on trees that had no damage prior to burning, as well as on trees that had been damaged during the thinning operation.

About 40 stems ha^{-1} (b.a. = 2.2 m^{2}ha^{-1}) of previously unaffected trees were damaged by burning, and 19 stems ha^{-1} (b.a. = 1.1 m^{2}ha^{-1}) of trees already damaged by thinning developed additional wounds as a result of burning (Fig. 5). A further category of damage was recognized for trees that had experienced superficial scraping of the bark on the lower stem during thinning, and which subsequently developed cambial wounds directly beneath the bark scrapes; trees in this category represented a further 16 stems ha^{-1} (b.a. = 0.8 m^{2}ha^{-1}). Fire-caused wounds were most frequently 0.01-0.1 m^2 in area, but some exceeded 0.5 m^2 in area and extended for several metres up the stem. On average only 4 stems ha^{-1} (b.a. <0. 1 m^{2}ha^{-1}) of sample trees had died 11 months after burning. In burnt areas of the stand the residual stocking of trees without any stem damage from either thinning or fire was 182 stems ha', representing a basal area of 11.9 m^2ha^{-1}. In addition, a further 30 stems ha^{-1} (b.a. = 2.3 m^2ha^{-1}) remained unburnt and were therefore not subject to any fire damage. The incidence of fire-caused stem damage, including mortality and wounds associated with superficial bark scraping, was found to be significantly greater ($p < 0.01$) on trees that were within 1 m of old log debris than for trees that were 1-2 m from debris (Table 3). Thirty-eight per cent of trees that were within 1 m of log debris were damaged by fire, compared with only 22 per cent of trees that were further than 1 m but less than 2 m from logs.

TABLE 3

Incidence of fire-caused stem damage and mortality for trees >10 cm d.b.h.o.b. with old log debris ≤1 m and 1-2 m from the stem.

	No. TREES				
Log distance from stem	Undamaged	Damaged	Total	$\chi 2$	p
≤1 m	49	30	79		
1-2 m	184	53	237		
All	233	83	316	6.67	<0.01

DISCUSSION

Fuel accumulation in regrowth karri stands is principally determined by the age of the stand and the nature of the shrub understorey, and to a lesser extent by stand density (McCaw, unpublished data). Although pre-burn fuel was not assessed quantitatively at Boorara 13, the similarity of this stand to the stand at Boorara 2 where the experimental study was conducted makes it reasonable to assume that fuel loading and structure were comparable. Based on this assumption it is estimated that about half the litter loading was consumed during prescribed burning at Boorara 13. This is within the range of litter consumption reported for similar burning conditions by McCaw *et al.* (unpublished manuscript). Consumption of slash fuel during prescribed burning at Boorara 13 was not assessed quantitatively. The results of this study should therefore be regarded as providing a general indication of the extent of damage to retained trees that may be expected from prescribed burning. However, the type, amount and condition of fuels may vary from one thinned stand to another, with the result that levels of tree damage following prescribed burning may also vary.

An important factor that may have influenced the outcome of this trial was the extent to which actual burning conditions matched those that were prescribed. Actual burning conditions differed from those prescribed in two main factors: air temperature and SDI. Air temperatures on 24 November were up to 7°C higher than prescribed, but despite this the moisture content of the surface litter remained within the recommended range throughout the morning. Surface litter fuels probably dried to below 12 per cent moisture content during the latter part of the afternoon, however, most of the area had burnt out by this time. Diurnal fluctuations in air temperature are unlikely to have had a significant effect on the dryness of the litter profile and woody components of the thinning slash fuel as these are influenced more by longer-term seasonal conditions, particularly rainfall. The relatively high air temperatures on 24 November may have contributed to elevated levels of crown scorch (Cheney *et al.* 1992), but overall only a small proportion of the stand (12 per cent) was scorched to an extent that would have adversely affected tree growth.

The SDI is used in WA forests to reflect the dryness of soils, deep forest litter, logs and living vegetation. Burrows (1987) demonstrated strong correlations between the SDI and the moisture content of eucalypt logs in different situations (on-ground; elevated) and in different conditions (freshly cut; cured). The fact that the SDI at the time of the operational trial was higher than during most of the experimental fires at Boorara 2 may have contributed to increased combustion of old log debris and larger diameter components (>25 mm) of the thinning slash fuel. One consequence of increased fuel consumption could be an increased frequency of fire-caused damage to retained trees. The incidence of fire-caused damage to trees at Boorara 13 was in fact only slightly greater than at Boorara 2 (78 and 70 stems ha^{-1} respectively), and both stands retained a similar stocking and basal area of undamaged trees (212 stems ha^{-1} and 14.2 m^2ha^{-1} at Boorara 13; 214 stems ha^{-1} and 13.4 m^2ha^{-1} at Boorara 2). Damage to trees within 1 m of old log debris occurred with similar frequency in the two stands (38 per cent at Boorara 13; 43 per cent at Boorara 2). However, in view of the high value of young regrowth stands for future timber production it is recommended that the upper SDI limit for burning of thinning slash remain at 40 mm until the relationship between SDI, fuel consumption and subsequent tree damage has been more thoroughly investigated.

The thinning prescription for karri regrowth stands of 30 m top height specifies retention of 16 m^2ha^{-1} basal area of potential crop trees exhibiting desirable form and spacing. Results from both the experimental study at Boorara 2 and the operational trial at Boorara 13 indicate that if stands are burnt following thinning it is likely that less than 16 m^2ha^{-1} of crop trees will remain undamaged. Stem damage may predispose trees to decay and insect attack, resulting in loss of merchantable wood volume (McCaw 1983; Perry *et al.* 1985). Prediction of volume loss from stem wounds over the period of a rotation is complex, and depends on a number of factors including the location and extent of wounding, the rate of development and severity of degrade resulting from wounds, the length of time for which trees are retained, and the eventual utilization of the stem (McCaw 1983; White and Kile 1991). The option exists to remove damaged trees in subsequent thinnings, but a better understanding of wood degrade processes in karri is required to accurately predict the impact of damage on the volume and quality of wood products that may be produced from later thinnings, or at the time of final felling.

Variation in topography and aspect of the stand influenced fuel dryness and fire behaviour, and hence fuel consumption and crown scorch. Surface litter was consistently drier on the ridge than on lower slopes, while profile litter moisture content exhibited substantial variability in both topographic situations. The only substantial area of unburnt fuel occurrred on a lower slope with an easterly aspect; this tends to be a characteristically moist aspect in the karri forest. The extent of crown scorch in Cell 3 can probably be attributed to the greater fuel consumption on the ridge, together with the high ambient temperatures on 24 November when most of this cell was burnt. In the case of Cell 5, which was at lower elevation and on a generally southerly aspect, the extent of crown scorch was probably related to the presence of a dense stratum of stump coppice which tended to increase flame heights, rather than to the dryness of the fuel.

The contour lighting pattern employed at Boorara 13 was generally successful in achieving satisfactory fire behaviour and fuel consumption throughout most of the stand. The helicopter-mounted ignition system proved well suited to the task, providing a high level of accuracy in the placement of incendiary capsules and the manoeuvrability necessary for following the complex boundary of the compartment. Having several nearby stands available for burning on the one day would assist in reducing unit costs for helicopter ignition by maximizing the amount of lighting that could be undertaken while burning conditions were suitable.

CONCLUSION

The operational trial at Boorara 13 demonstrated that guidelines for prescribed burning of thinning slash in karri regrowth stands developed from a prior experimental study could be effectively implemented at an operational scale using a helicopter-mounted ignition system. Despite considerable variation in topography and aspect within the 20 ha study area, the crowns of retained crop trees remained unscorched over about three quarters of the burnt area, and only a few small patches remained completely unburnt. About a quarter of the retained trees in burnt areas of the stand suffered damage to the stem which may subsequently lead to wood degrade. The rate of development and ultimate extent of such degrade needs to be further investigated so that silvicultural costs and benefits of burning thinning slash can be properly evaluated. Factors critical to the success of operational prescribed burning in thinned stands include selection of appropriate conditions for burning, and careful planning and execution of lighting operations.

ACKNOWLEDGEMENTS

We would like to thank the Department of Conservation and Land Management personnel from Pemberton District who were involved in the prescribed burning operations. Neil Burrows, Rick Sneeuwjagt, Kevin Tolhurst and Chris Trevitt provided useful comments on a draft manuscript.

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CALMScience 2 (2):141-148 (1996)

Effects of fuel reduction burning on fire behaviour and suppression difficulty of an intense wildfire in jarrah (*Eucalyptus marginata*) forest - a case study

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ABSTRACT

This paper presents a case study of fire behaviour and suppression difficulty for an intense wildfire which burnt under conditions of Very High fire danger in jarrah (*Eucalyptus marginata*) forest fuels of different ages. During a two-hour period following ignition the fire travelled a distance of 1250 m, with an average forward rate of spread of 625 m h^{-1} and fireline intensity of 4400 kW m^{-1} in nine-year-old fuel. The rate of spread and intensity of the headfire declined substantially after the fire encountered an area of forest in which fuel loads had been reduced by low intensity prescribed fire one year previously, and which also contained some patches of two-year-old fuel. Fuel loading, litter depth and cover, and understorey shrub height and cover were much lower in the recently fuel-reduced forest than in the forest carrying nine-year-old fuels. Despite continued adverse fire weather conditions the fire did not spread extensively in the low fuel area and was therefore readily suppressed, having burnt only 47 ha. Had the fire continued to spread in nine-year-old fuels the area burnt is projected to have increased to 135 ha after a further 2.5 hours. Much of this additional area would probably have burnt at fire intensities sufficient to fully scorch the forest canopy. Wildfire case studies such as this can contribute to an understanding of the circumstances under which fuel reduction burning is effective in limiting the spread and intensity of wildfires.

INTRODUCTION

Fuel reduction burning has been used extensively as a fire management tool in the multiple-use State forests of south-west Western Australia for several decades. The principal objective of fuel reduction burning is to limit the intensity of unplanned fires, thus reducing the difficulty of suppression and the level of physical damage to the forest. Open forests of jarrah (*Eucalyptus marginata*) and marri (*E. calophylla*) are typically burnt on a five- to eight-year rotation to keep fine fuel loadings below about 8 t ha^{-1} (McCaw and Burrows 1989). The frequency of prescribed fire in particular areas of the forest varies according to fuel accumulation rates and management objectives.

The extent to which fuel reduction burning programs may assist in the suppression of unplanned fires depends on the interaction of a number of factors including the level of fuel reduction achieved, the rate at which fuels re-accumulate, the location and extent of fuel-reduced areas within the forest, and the suppression capability and speed of response of agencies and volunteer fire brigades responsible for fire management. In addition, the severity of fire weather conditions prevailing at the time when a wildfire encounters a fuel-reduced area is important in determining the effect on fire behaviour. Seasonal conditions, in particular the dryness of deep litter beds, logs, and living vegetation may also affect fire behaviour and difficulty of suppression. Experimental study of these factors is complex and costly, and for this reason the contribution of fuel reduction to fire suppression has generally been illustrated by means of case studies of wildfires (e.g. McArthur 1962; McArthur *et al.* 1966; Billing 1981; Geddes and Pfeiffer 1981; Rawson 1983; Underwood *et al.* 1985; McCaw *et al.* 1993). Despite their descriptive nature and lack of replication, well-documented case studies have an important role as a source of research data and as training aids (Alexander and Lanoville 1987).

On 8 January 1993 a wildfire was deliberately lit by an arsonist in open jarrah forest at Illawarra forest block, 25 km north of Jarrahdale (116°05'E 32°20'S), Western Australia. Weather conditions at the time were typical of mid-summer, with high air temperature, low relative humidity and a steady breeze. The fire completed most of its run up-slope through nine-year-old jarrah forest fuels, then subsequently crossed a road into similar forest that had been fuel-reduced by low intensity prescribed fire one year previously, and which also contained some areas of two-year-old fuel. This paper describes the weather conditions and fuel characteristics associated with the fire, and examines the contribution of these factors to the fire's behaviour. The particular circumstances of this fire provided the opportunity to compare fire behaviour in two different fuel ages and to evaluate the effectiveness of the recently fuel-reduced area in restricting further spread of the fire.

METHODS

Study Area

Illawarra forest block is located at the interface between the outer eastern limit of Perth's urban development and the extensive tracts of State forest managed for multiple use by the Western Australian Department of Conservation and Land Management (CALM). Areas of forested land adjoining the State forest are managed by the Western Australian Water Corporation. Adjacent privately-owned lands have been developed as orchards, hobby farms, recreation camps and residential subdivisions. Some of the privately-owned land is still predominantly forested.

Illawarra block extends northwards from the deeply incised valley of the Canning River onto undulating lateritic uplands with occasional granite outcrops. Local relief ranges from 100-300 m above sea level and the terrain is steep along the valley of the river and its tributary streams. The forest type in which the fire burnt was an uneven-aged stand of jarrah/marri which included saplings, poles and occasional veteran trees; height classes for each stratum were <15 m, 15-19 m, and 20-26 m respectively. The base of the forest canopy was about 10 m above ground level.

The fire started in forest which had last been burnt by a summer wildfire in 1977, and completed its main run through forest last burnt in spring 1983 during a low intensity fuel reduction burn (Fig. 1). The forest on the

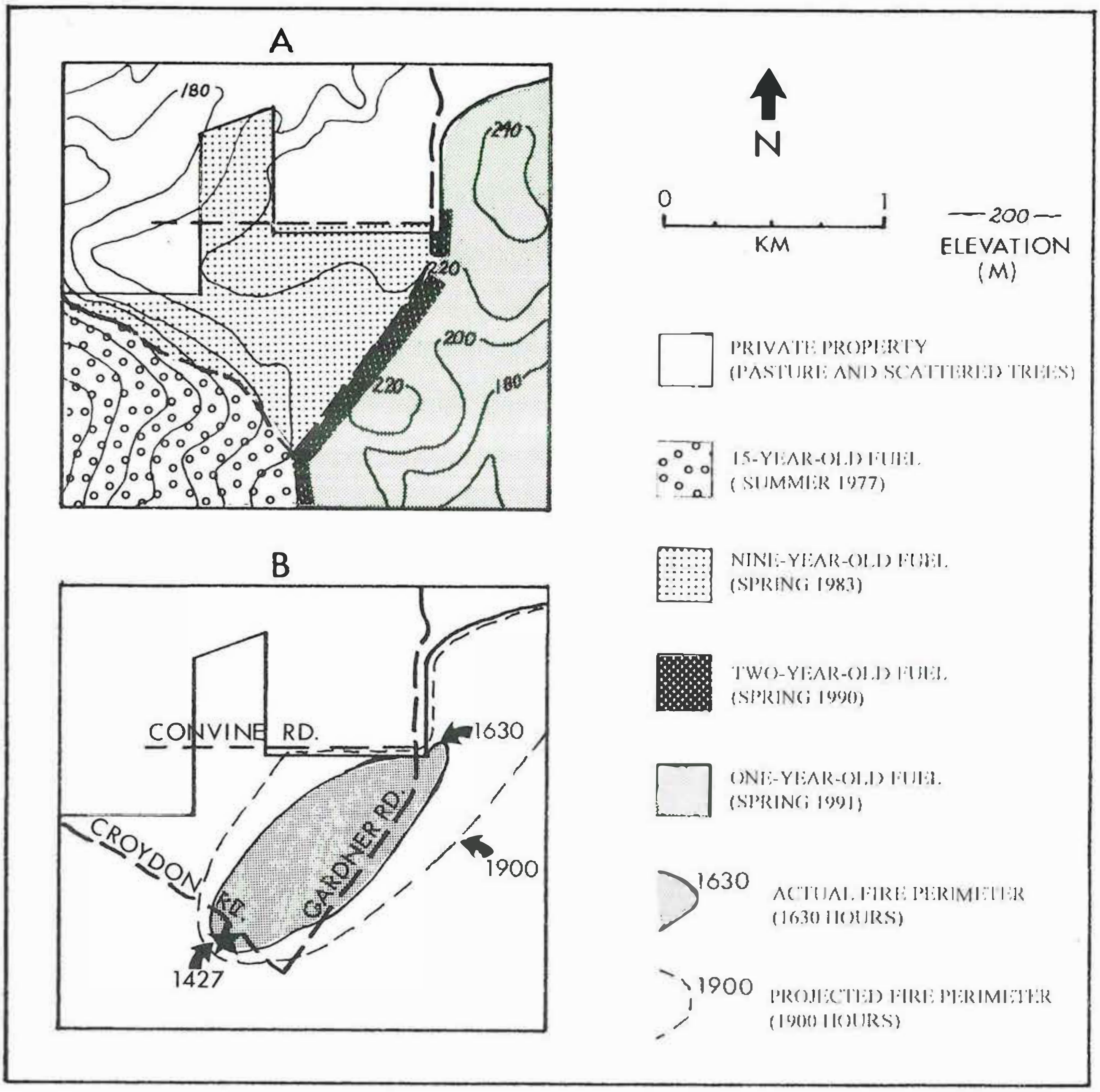

Figure 1. (A) Map showing elevation (in m), land tenure, and fuel ages within publicly-owned native forest; (B) map showing roads mentioned in the text, the ignition point of the fire at 1427 hours, the actual perimeter of the fire at 1630 hours and the projected perimeter of the fire at 1900 hours had the forest on the eastern side of Gardner Road carried nine-year-old fuel.

eastern side of Gardner Road had been burnt by low intensity fire in spring 1991 to reduce fuel loads, although a narrow zone (<100 m wide) immediately east of the road also contained patches of two-year-old fuel. The two-year-old fuel dated from edge burning operations undertaken during spring 1990 to secure the area prior to the broadscale aerially-ignited fuel reduction burn of spring 1991. For convenience, throughout the remainder of this paper fuels in the area burnt in spring 1983 are referred to as nine-year-old and those east of Gardner Road as two-year-old.

Data Collection and Analysis

Details of the development and behaviour of the fire were obtained from records held at the Jarrahdale CALM office and from interviews with personnel involved in the suppression operations.

Three weeks after the fire, fuels were sampled in an unburnt area of the nine-year-old fuel adjacent to the fire perimeter, and in an unburnt section of the fuel-reduced area on the eastern side of Gardner Road. Within each area, litter and shrubs were harvested from ten 1 m^2 quadrats located at 5 m intervals along a transect, and the depth of the litter bed, and the height and projected cover of the dominant shrub species in each quadrat were recorded. In this paper the term litter refers to the layer of fresh and partly decomposed dead leaves and fine twigs (<6 mm diameter) on the forest floor. The proportions of bare and litter-covered ground were determined from 50 point-intercept samples in each fuel age. Fuel samples were oven dried at 105°C, sorted into litter, dead shrubs <6 mm and live shrubs <4 mm, and weighed to determine loadings in t ha^{-1}. The 4 mm diameter limit was used for live shrub fuel because fires in jarrah forest rarely consume live fuel above this size (Burrows 1994).

Drought, fuel moisture and fire danger indices for 8 January 1993 were calculated using air temperature, relative humidity, wind speed and rainfall data from the CALM office at Jarrahdale, which was considered to be the recording centre most representative of the location where the fire occurred. Wind speeds at Jarrahdale were recorded in a clearing with an anemometer mounted approximately 10 m above ground. Drought conditions were described using the Soil Dryness Index (SDI) (Mount 1972; Burrows 1987) which indicates the amount of rainfall required to bring the soil back to a saturated condition at field capacity. This represents about 200 mm of available moisture for most soils. For consistency with SI units, SDI values in this paper are expressed in millimetres of moisture, but for operational use in Western Australia the SDI is routinely expressed in units of millimetres x10. The Forest Fire Behaviour Tables for Western Australia (FFBT) (Sneeuwjagt and Peet 1985) were used to predict the surface moisture content (SMC) of jarrah forest litter and the forward rate of spread (FROS) of the fire. The FROS prediction was based on the fuel load measured in the unburnt nine-year-old fuel area adjacent to the fire perimeter, and the average slope measured along the path of the headfire. Slope effect was accounted for using McArthur's (1967) correction factors. The wind speed used to calculate the FROS can be varied according to the density of the forest canopy and the topographic position of the stand for which the prediction is being made. This is accomplished within the FFBT by the use of wind ratios which represent the ratio of wind speed at 15 m above canopy to wind speed in the forest at 1.5 m above ground. A wind ratio of 5:1 is used as the standard for determining the level of fire danger in jarrah forest. To examine the sensitivity of FROS predictions for 8 January to variation in wind speed inputs, FROS values were calculated for wind ratios of 5:1, 4:1 and 3:1 with SMC, fuel load and slope held constant. Periodic values of the Forest Fire Danger Index (FFDI) were determined from the Mark 5 Forest Fire Danger Meter (FFDM) (McArthur 1967, 1973) using the equations derived by Noble *et al.* (1980) with a drought factor of 10. Forward rate of spread, flame height and the distance that spot fires may ignite ahead of the main fire front (spotting distance) were predicted for burning conditions at 1500 hours. Fire intensities (Byram 1959) were calculated for each fuel age using the observed headfire rate of spread, fine fuel load, and a low heat of combustion of 18 700 kJ kg^{-1}. Field observations indicated that almost all fine fuel had been consumed.

The pattern of crown scorch resulting from the fire was mapped from low oblique colour air photographs taken three weeks after the fire.

RESULTS

Fuel characteristics

Fine fuels were composed predominantly of leaf litter, with only minor components of dead and live shrub foliage (Table 1). Loadings of litter and total fine fuel were respectively 12 t ha^{-1} and 13.6 t ha^{-1} for the nine-year-old fuels, and 5.1 t ha^{-1} and 5.8 t ha^{-1} for the two-year-old fuels. The litter bed in the nine-year-old fuel averaged 13 mm in depth and covered 98 per cent of the ground surface while corresponding values in the two-year-old fuel were 8 mm depth and 76 per cent cover. Jarrah sheds a proportion of its leaves annually between December and March (Hatch 1955) and at the time of the fire the litter layer would have consisted of leaves recently shed from the forest canopy as well as litter that had been *in situ* for one or more winters.

Understorey shrub composition was relatively uniform across the study area with *Bossiaea ornata, Hibbertia hypericoides, Macrozamia riedlei* and *Xanthorrhoea preissii* being common dominant species. Mean shrub height and projected cover in the nine-year-old fuel were more than twice that of the younger fuel (Table 1). Dead shrub foliage comprised only a small proportion of total fuel load in either the nine-year-old fuel or the recently fuel-reduced area (two-year-old fuel). Differences in understorey structure and the cover of the litter layer in the two fuel ages are clearly illustrated in Figure 2.

In the recently fuel-reduced area the bark on most trees

TABLE 1

Characteristics of two-year-old and nine-year-old fuels at Illawarra block determined from harvesting of ten 1 m^2 quadrats in each fuel age area. Standard errors of the mean are shown in parentheses.

VARIABLE	FUEL AGE	
	TWO-YEAR-OLD	NINE-YEAR-OLD
Fuel load (t ha^{-1})		
litter	5.1 (0.6)	12.0 (1.5)
dead shrub foliage <6 mm	0.1 (0.1)	0.3 (0.1)
live shrub foliage <4 mm	0.6 (0.2)	1.3 (0.3)
total fine fuel	5.8	13.6
Litter depth (mm)	8 (1)	13 (2)
Litter cover (%)	76	98
Shrub height (m)	0.4 (0.1)	1.0 (0.3)
Shrub cover (%)	18	40

was uniformly charred for a distance of 1-2 m above ground level. Some limited bark charring was also still evident on the lower stems of trees in unburnt areas of nine-year-old fuel.

Burning Conditions

The fire occurred during the afternoon of 8 January 1993. Drought conditions were typical of early summer with an SDI of 148, which is about 80 per cent of the maximum value reached at Jarrahdale in most years. Burning conditions at Jarrahdale peaked at around 1500 hours (Western Standard Time) with an air temperature of 35°C, relative humidity of 16 per cent, and south-westerly winds at 10 km h^{-1} (Table 2). The Forest Fire Danger Index remained at 28-29 (Very High) throughout the period of the main fire run, increasing wind speeds compensating for the declining temperature and rising humidity. The rate of spread predicted by the McArthur FFDM was 590 m h^{-1}, with a corresponding mean flame height of 9 m and spotting distance of 1800 m. The FFBT predicted

(a)

(b)

Figure 2. Photographs taken in January 1993 showing (a) two-year-old and (b) nine-year-old fuels in the vicinity of the wildfire at Illawarra block.

TABLE 2
Weather conditions for the period 0900-1900 hours on 8 January 1993 recorded at Jarrahdale CALM office. McArthur Forest Fire Danger Indices are shown for three times at which wind speeds were recorded.

TIME	AIR TEMPERATURE (°C)	RELATIVE HUMIDITY (%)	WIND SPEED (km h^{-1})	WIND DIRECTION	FOREST FIRE DANGER INDEX
0900	29	39	-	-	
1000	32	35	-	-	
1100	34	27	-	-	
1200	36	22	-	-	
1300	35	17	10	S W	28 (VERY HIGH)
1400	35	16	-	-	
1500	35	16	10	S W	29 (VERY HIGH)
1600	34	17	-	-	
1700	33	19	16	S W	28 (VERY HIGH)
1800	30	24	-	-	
1900	25	36	-	-	

a minimum SMC for jarrah forest litter of 3 per cent at 1500 hours with FROS values of 367 m h^{-1} (Extreme), 259 m h^{-1} (Extreme) and 194 m h^{-1} (Very High) for wind ratios of 3:1, 4:1 and 5:1 respectively.

Fire Origin and Development

The fire (Jarrahdale Fire No. 24) was initially detected at 1427 hours by a CALM aircraft on a routine fire detection flight and appeared to have been deliberately lit at a single point about 100 m south-west of Croydon Road (Fig. 1). The fire rapidly spread upslope on a south-westerly aspect exposed to the prevailing winds and spotted across Croydon Road with only a temporary decline in intensity. Most of the forest south of the road was fully crown scorched, indicating that the fire had rapidly escalated in intensity following ignition.

The headfire spread in a north-easterly direction, arriving at a point about 50 m south of the intersection of Gardner and Convine Roads at 1630 hours; this observation is accurate to within about 5 minutes. Slope was 9° over the initial 250 m of the fire's run, but averaged 3° over the entire distance travelled from the ignition point to Gardner Road. In the two-hour period following ignition the fire travelled a distance of 1250 m with an average forward spread rate of 625 m h^{-1}. The corresponding fire intensity for the average rate of headfire spread in the nine-year-old fuels was 4400 kW m^{-1}. Aerial photographs of the burnt area revealed a pattern of concentric elliptical zones of fire-defoliated forest canopy which coincided with the path taken by the headfire, while the remainder of the area burnt by the flanks of the fire was fully crown scorched. This suggests that the fire spread as a series of pulses rather than at a uniform rate.

Firebrands were blown across Gardner Road which, including the bitumen roadway and gravel edges, is about 20 m in total width. These ignited a series of spot-fires in the recently fuel-reduced area on the eastern side of the road about 100 m north-east of the point where the headfire encountered Gardner Road (Fig. 1). Firebrands may have been blown considerably further downwind but were not effective in propagating the fire. Aerial inspection of the fire at 1800 hours revealed that the fire had declined markedly in intensity and had not extended more than about 150 m east of Gardner Road. Within the recently fuel-reduced area the rate of spread of the fire had declined to less than 100 m h^{-1} and flame heights were mostly less than 2 m, consistent with fire intensities in the range 300-500 kW m^{-1}. The forest canopy was fully scorched in a narrow zone up to 100 m wide along the eastern side of Gardner Road, owing largely to heat generated by the fire in the nine-year-old fuels on the western side of the road. Bark on most of the trees in this area was charred up to the full height of the stem and along the major branches.

Suppression Action

The general control objective for the fire was to protect life and property and to minimize the area burnt. The fire crossed Croydon Road before CALM fire tankers (3700 L capacity) were in attendance. As the intensity of the headfire in the nine-year-old fuels was too high for safe and effective direct attack, suppression forces were instead deployed along Convine Road to prevent the fire from spreading northwards into adjacent private property which contained several houses and sheds surrounded by sparse pasture fuels. The headfire and eastern flank of the fire were left to spread unchecked into the recently fuel-reduced area on the eastern side of Gardner Road with the expectation that the rate of spread and intensity of the fire would rapidly diminish in the young fuels. By about 1700 hours the fire had been stopped along Convine Road and suppression forces were diverted to contain the western edge of the fire which continued to burn in nine-year-old fuels. Operations to contain the fire on the eastern side of Gardner Road commenced at about 1800 hours and the fire was readily suppressed in the young fuels.

To provide an indication of how the fire may have developed had the fuels on the eastern side of Gardner Road been of the same age and loading as those in which the main fire run took place the FFBT was used to project the growth of the fire from its actual perimeter at 1630 hours over the subsequent 2.5 hour period to 1900 hours. This projection assumed that the fire maintained an elliptical shape, and that the SMC remained at 4 per cent and the wind speed at 12 km h^{-1}. Fuel loading was held constant at 14 t ha^{-1} and slope at 3°. A wind ratio of 3:1 was used because this ratio had provided the closest agreement between the predicted and observed rate of spread in the preceeding period (1430-1630 hours). The projection indicated that the headfire would have travelled a further 760 m between 1630 and 1900 hours, increasing the fire perimeter from 3.0 km to 5.2 km, and the burnt area from 47 ha to 135 ha.

DISCUSSION

The behaviour of this fire clearly illustrates that relatively narrow fuel breaks such as rural roads <20 m wide are insufficient to contain the spread of fires in jarrah forest when the fire danger is Very High or Extreme. Gardner Road provided sufficient break in the continuity of the fuels to temporarily halt the run of the headfire, but was not wide enough to prevent firebrands from being blown across from the main fire and igniting the fuels on the eastern side of the road. The effectiveness of roads and other fuel breaks (e.g. rock outcrops, dunes, lakes) as barriers to fire spread depends on their width, the type of fuel in which the fire is burning, and the severity of the burning conditions (Wilson 1988). Fires in eucalypt forests are renowned for their ability to propagate by means of spot-fires started ahead of the main fire front and this characteristic may negate the effect of fuel breaks even at relatively low levels of fire danger, particularly where trees carry large accumulations of fibrous stringybark or loose ribbons of smooth bark which can act as firebrands (Luke and McArthur 1978; Wilson 1992a). Rotational fuel reduction burning, in addition to limiting the accumulation of litter and understorey shrub fuels, also typically removes loose, fibrous bark from the bottom few metres of stems thereby reducing the quantity of bark fuel which may contribute to flame extension up the stem and which is available for the generation of firebrands.

Observed spotting distances were substantially less than predicted by the McArthur FFDM, and a possible explanation for this is that the amount of loose, fibrous bark on the stems of trees in the nine-year-old fuel area was still limited as a result of prescribed burning in spring 1983. Accumulation of fibrous bark on jarrah and marri stems becomes noticeably greater in stands from which fire has been excluded for 15 years or more (McCaw, unpublished data). Better understanding of the relationships between bark characteristics, firebrand generation, and spotting would allow the effect of fuel reduction burning on bark fuel hazard to be objectively assessed. This should be a priority for future fire research.

The failure of the spot-fires which ignited in the recently fuel-reduced area on the eastern side of Gardner Road to develop rapidly into a new headfire can be attributed to the lower fuel loading and the different structure of the fuel bed. Fuel load is a direct determinant of fire intensity (Byram 1959) and has also been shown to affect the forward spread rate of fires in eucalypt forests in some circumstances (McArthur 1962; Peet 1971). Other fuel characteristics that may also affect fire spread include litter depth and cover, and the height and density of understorey shrubs (Peet 1971; Cheney *et al.* 1992). All of these characteristics were substantially reduced in the two-year-old fuel. In order to properly interpret the results of fire behaviour experiments and wildfire case studies it is essential that the structure and condition of fuels be adequately described and quantified (McCaw 1991). In addition to fine fuel load, criteria such as understorey scrub flammability and bark characteristics have been employed in the assessment of bushfire hazard in some eucalypt forest types (Sneeuwjagt 1971, 1973; Wilson 1992a, 1992b).

The severity of burning conditions has a profound influence on the effectiveness of fuel-reduced areas in moderating fire behaviour. McCaw *et al.* (1993) reported that three-year-old jarrah forest fuels were capable of supporting a high intensity crown fire (estimated peak intensity 17 400 kW m^{-1}) during conditions of Extreme fire danger, but suggested that the young fuels did diminish the potential for long distance spotting and facilitate rapid containment once the weather conditions moderated. Most case studies (Billing 1981; Underwood *et al.* 1985; Grant and Wouters 1993) illustrating the contribution of fuel reduction burning to wildfire suppression in eucalypt forests relate to fuels less than three-years-old. More extensive documentation of wildfire behaviour in older fuels is desirable, as fuels 4-8 years old are widespread in multiple-use forests in Western Australia. Such investigations would help to determine the longevity of the suppression benefits of fuel reduction burning, and improve the understanding of the relationship between the age of forest fuels and the resulting level of fire damage to the forest.

The period between 1630 hours and 1900 hours was of critical importance to suppression action against the fire. Fire danger remained Very High for most of this period and the intensity of the headfire in nine-year-old fuels would have been too great to allow safe and effective direct attack on the fire front. A fire intensity of 2000 kW m^{-1} is considered the upper limit for effective direct attack with tankers and bulldozers (Loane and Gould 1985). Had the forest on the eastern side of Gardner Road not been subject to fuel reduction, and instead also carried nine-year-old fuel, the area of forest burnt at high intensity is likely to have more than doubled, necessitating deployment of additional suppression forces and delaying the eventual containment of the fire.

Accurate prediction of fire behaviour depends on site specific information on fuel, weather and terrain conditions, as well as on the existence of a robust fire spread model (McCaw *et al.* 1993). Fuel and slope data were available for the site, and temperature and relative humidity could be approximated by recordings for Jarrahdale. It is reasonable to assume that litter moisture content remained constant at 4 per cent between 1630 hours and 1900 hours in view of the relatively constant weather conditions and the characteristically slow moisture uptake of eucalypt litter during the afternoon (Luke and McArthur 1978; McCaw unpublished data). There is, however, some uncertainty as to whether the wind speeds recorded at Jarrahdale were representative of the winds experienced on the fire ground. The complex terrain associated with the Canning River valley tends to affect wind patterns, causing winds in the general vicinity of the fire occurrence to be stronger than at Jarrahdale (Ross Mead, personal communication). In view of the uncertainty over actual wind speeds at the fire, the performance of either the FFBT or the FFDM in predicting fire spread rate cannot be adequately assessed from this study.

CONCLUSION

Observations of fire behaviour from this study demonstrated that a narrow fuel break such as a rural road <20 m wide was not effective in preventing the spread of fire under conditions of Very High fire danger, when firebrands were thrown some distance ahead of the main fire front. However, spot-fires ignited by firebrands were slow to develop in two-year-old fuels, despite continued adverse fire weather conditions. Fuel loading, litter depth and cover, and the height and cover of the understorey shrub layer were substantially less in the recently fuel-reduced area than in the nine-year-old fuels where the main fire run occurred. Reduction in the amount of loose bark on the stems of trees is likely to be an important consequence of prescribed burning. The effect of bark reduction on fire behaviour, and in particular on the generation of firebrands, is a subject worthy of further investigation.

ACKNOWLEDGEMENTS

Ross Mead from the Department of Conservation and Land Management's Swan Region assisted with our investigation of fire behaviour and commented on the interpretation of events in a draft manuscript. Staff from the Jarrahdale District office kindly provided copies of the fire diary and associated weather data relating to Fire No. 24. We also thank Rick Sneeuwjagt, Chris Muller, Neil Burrows, Phil Cheney, Andrew Wilson, Tony Blanks and Jim Gould for commenting on a draft manuscript, and Joanne Healey for assisting with preparation of the manuscript.

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Abbreviations used in this paper

SDI = Soil Dryness Index

FFBT = Forest Fire Behaviour Tables

SMC = surface moisture content

FROS = forward rate of spread

FFDI = Forest Fire Danger Index

FFDM = Forest Fire Danger Meter

CALMScience 2(2):149-152 (1996)

Secondary poisoning of foxes following a routine 1080 rabbit-baiting campaign in the Western Australian wheatbelt

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ABSTRACT

There is circumstantial evidence that foxes (*Vulpes vulpes*) feeding on rabbits (*Oryctolagus cuniculus*) poisoned with sodium monofluoroacetate (1080 poison) die from secondary poisoning. A rabbit-poisoning campaign that occurred during a fox research study provided direct evidence to support the above view.

INTRODUCTION

In Western Australia (WA) 1080 was widely used by the Agriculture Protection Board (APB) to control populations of rabbits (*Oryctolagus cuniculus*) on farms. Typically, a bait trail of 'One Shot' 1080 oats (Gooding and Harrison 1964) was laid so as to intercept rabbits *en route* to their foraging areas. This method has been shown to be an efficient and effective method of control (Oliver *et al.* 1982; Robinson and Wheeler 1983).

There is circumstantial evidence that foxes feeding on poisoned rabbits die through secondary poisoning (Christensen 1980a; McIlroy 1981; King *et al.* 1981). This paper provides direct evidence to support this view.

METHODS

Study Site

Data were collected from an area of Watheroo National Park (450 km^2) approximately 200 km north of Perth in the northern wheatbelt (30° 14' S, 115° 45' E). Beard (1979) describes the vegetation as consisting mainly of undulating scrub-heath with *Banksia-Xylomelum* alliance on yellow sandplain, limited areas of *Casuarina* thicket on the lateritic ridges and *Eucalyptus* woodland in the depressions. Records from the WA Herbarium indicate the absence of 1080-producing *Gastrolobium* sp. (S. Patrick personal communication) in the area. The park is entirely bounded by farmlands and enclosed within the park is a farming property known as 'Warro Springs'.

Fox Study

Fifteen adult foxes had been captured and radio-collared in the north-western area of the park (approximately 100 km^2) during the spring of 1988. These foxes were periodically radio-tracked from fixed towers to provide information on home range and spatial organization.

While radio-tracking between 12 and 16 December 1988 it was observed that three foxes, whose home ranges were adjacent to the Warro Springs property, had not moved since the morning of 13 December. To investigate the possible reasons for lack of movement, these animals were located on 13 December, using a hand-held aerial; all three foxes were dead. Searches of the area were then conducted to locate any non-collared dead foxes.

Stomach contents were removed from all animals for laboratory examination; hair was identified as described in Brunner and Coman (1974). The foxes were not analysed for 1080 because of the difficulties of detecting small amounts of residue (D. King personal communication).

Rabbit Poisoning Campaign

On 12 December an APB officer, at the request of the owner of Warro Springs, had baited an area on the property which contained rabbit warrens and most of the farm boundary with one-shot 1080-poisoned oats. The oats were laid from a hopper into a furrow cut by a disc blade along a 6 km transect around the northern half of the farm.

RESULTS

Six non-collared, dead foxes were found on the firebreaks bordering the Warro Springs property the same day as the radio-collared foxes were located. An unusual sight was found at one site where three juvenile foxes lay dead in close proximity to each other. Nearby were the remains of a rabbit that had been almost entirely devoured, including the viscera.

All dead foxes, except for one that had died in a den, displayed signs that suggested that they had died from 1080 poisoning. All animals were lying on their side and the soil around them had been disturbed forming depressions, created by the sweeping movements of their limbs during the death throes which is typical of carnivores poisoned with 1080 (McIlroy 1981).

The three poisoned radio-collared foxes all contained rabbit hair in their stomachs as did the six non-collared foxes collected along the firebreak. Searches for other non-collared foxes were conducted in the surrounding area but the density of vegetation prevented any further animals being found. One other radio-collared fox that had occasionally been located around the farm area was located 2 km north during the rabbit-poisoning campaign.

DISCUSSION

Secondary poisoning of foxes has occurred following the 1080 rabbit-baiting campaign, causing a significant decline in their numbers. Data on carrion-eating animals found dead after rabbit poisoning campaigns in New South Wales (NSW) support the findings reported here. Foxes were the non-target species most frequently found dead after rabbit-poisoning operations in NSW State Forest areas (McIlroy 1982). McIlroy and Gifford (1991) similarly found that fox numbers were reduced by about 75 per cent after a trail-baiting campaign against rabbits with 1080-treated pellets in NSW.

In controlled secondary poisoning experiments that simulated field conditions, Marsh *et al.* (1987) fed 1080-poisoned ground squirrels (*Spermophilus beecheyi*) to 15 coyotes (*Canis latrans*). Three coyotes weighing 10.2-12.5 kg died after eating a squirrel that had consumed 3 mg of 1080 in a bait. Because One-Shot poisoned oats contains 4.5 mg of 1080 per oat, and since foxes (*ca* 4-6 kg) are considerably lighter than coyotes and have a similar tolerance to 1080 (Ward and Spencer 1947; McIlroy and King 1990), a rabbit that had eaten a single poisoned oat would be lethal to a fox. McIlroy and Gifford (1992) calculated that to receive the equivalent of an LD_{50} dose, foxes need to eat only about one-third of the muscle or half the liver of one poisoned rabbit. These amounts represent only 11 per cent or 2 per cent, respectively of their daily intake of food (McIlroy and Gifford 1992).

Direct evidence of secondary poisoning of foxes in this study further substantiates the arguments of Christensen (1980a) and King *et al.* (1981) that the fox has played a prime role in a suite of interacting factors leading to recent faunal declines and extinctions in south-west WA. These authors were the first to note the inverse relationship between fox abundance and the amount of 1080 used to control rabbits in WA. Since the completion of colonization of south-western Australia by foxes in 1931 (Long 1972), foxes increased in abundance until the mid 1950s when 1080 rabbit-baiting campaigns became widespread. By the late 1960s, the fox had declined to the point of rarity in south-western Australia (King *et al.* 1981) and in some areas, certain medium-sized marsupial species became conspicuously abundant (Sampson 1971; Christensen 1980b).

The use of broadscale 1080 rabbit-baiting campaigns declined for a considerable period (1970-78) following the introduction of the European rabbit flea, as widespread winter epizootics of myxomatosis caused a very high mortality in rabbit populations (King *et al.* 1981). Secondary poisoning was no longer of significance in controlling fox numbers and a dramatic increase in fox numbers was observed in the south-west during the 1970s (see Fig. 2 in King *et al.* 1981). Reduction in rabbit numbers and the increase in fox abundance may have resulted in increased predation on native species. As a consequence native species, even in refuge areas, declined drastically in numbers and their recovery has only followed the implementation of fox control programs. Kinnear *et al.* (1988) and Friend (1990) were able to aid the recovery of remnant populations of rock-wallabies (*Petrogale lateralis*) and numbats (*Myrmecobius fasciatus*) respectively by reducing fox numbers comparable to or in excess of secondary poisoning following rabbit control programs.

ACKNOWLEDGEMENTS

We are most grateful for the assistance provided by T.D. Leftwich and M.L. Onus. This study was part of a broader research program funded by Australian Nature Conservation Agency. This support is gratefully acknowledged.

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CALMScience 2 (2): 153-187 (1996)

A biological survey of Boonanarring Nature Reserve

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ABSTRACT

Boonanarring Nature Reserve (*ca* 9250 ha) is about 15 km north of Gingin. It extends eastward from the Gingin Scarp onto the Dandaragan Plateau, near the southern end of the plateau. It is bounded by the Swan Coastal Plain on the west. Water reserve ⩚22602 is on the southern boundary and extends into Boonanarring Nature Reserve. This reserve was included in the present survey.

The variable surface and underlying geology and topography are reflected by a mosaic of ten distinct vegetation associations. The dominant vegetation associations within the reserve are jarrah and marri woodlands typical of the south-west (Swan Coastal Plain and Darling Range) and *Banksia* woodlands with elements of the Kwongan heaths of the lower rainfall areas to the north. Boonanarring Nature Reserve contains the best and most extensive example of the poorly conserved *Banksia* woodlands on Dandaragan soils.

A total of 573 vascular plant taxa, representing 70 families and 223 genera have been recorded on the reserve. Several large populations of the previously declared rare *Grevillea saccata* occur on the reserve and are the only ones found on conservation reserves. This find was instrumental in this species being removed from the list of declared rare flora. The vegetation mosaics and ecotones support numerous rare and uncommon plant species. Seventy-five taxa (13 per cent) of the flora recorded are of particular interest, including 18 priority species and at least 47 species recorded at the ends of their known ranges. As an indication of its richness, the reserve is known to support 9 *Eucalyptus*, 11 *Banksia* and 15 *Acacia* taxa.

Amongst the animals recorded, the fossorial Black-striped Snake (*Vermicella calonotos*) is of restricted occurrence and the Carpet Python (*Morelia imbricata*) is declared 'in need of special protection'. Gould's Long-eared Bat (*Nyctophilus gouldi*) is at the northern limit of its range. Five frog species were found. The avian and reptilian faunas were reasonably diverse (74 and 20 species respectively), but the mammalian fauna was less diverse than expected (11 native species). Some species may be absent or severely reduced in number owing to the frequent burning which has occurred in recent years. Further survey work, particularly in spring, would be expected to considerably expand the fauna lists. The vertebrate fauna is representative of that of the general area. This fauna is becoming increasingly less common in the region with the development of the coastal plain and scarp.

Boonanarring Nature Reserve is a significant reserve, being rich in flora and vegetation types not present on any other conservation reserves and being large enough to provide some protection from degradation owing to edge effects.

INTRODUCTION

Boonanarring Nature Reserve (⩚41805) is an area of about 9250 ha, 15 km north of the town of Gingin (Fig. 1). The biological significance of the area was first assessed in 1971 (N. McKenzie personal communication) and on the basis of this assessment the System Six Report (Department of Conservation and Environment 1983) recommended that the then vacant Crown land be combined with several smaller reserves and an area of about 400 ha of private land along Gingin Brook, to form Boonanarring Nature Reserve. Boonanarring 'C' class Nature Reserve was finally gazetted on 9 August 1991, being vested in the National Parks and Nature Conservation Authority. Reserve ⩚22602, for water, is on the southern boundary and extends into Boonanarring Nature Reserve.

The area is situated near the southern tip of the Dandaragan Plateau. The Gingin Scarp, which forms the western boundary of the Dandaragan Plateau, runs along the western edge of the study area. The topography of the reserve is undulating, with some areas of sandplain and other areas of exposed laterite, sometimes forming small breakaways. The study area contains the upper catchment and sections of Boonanarring Brook, a predominantly dry

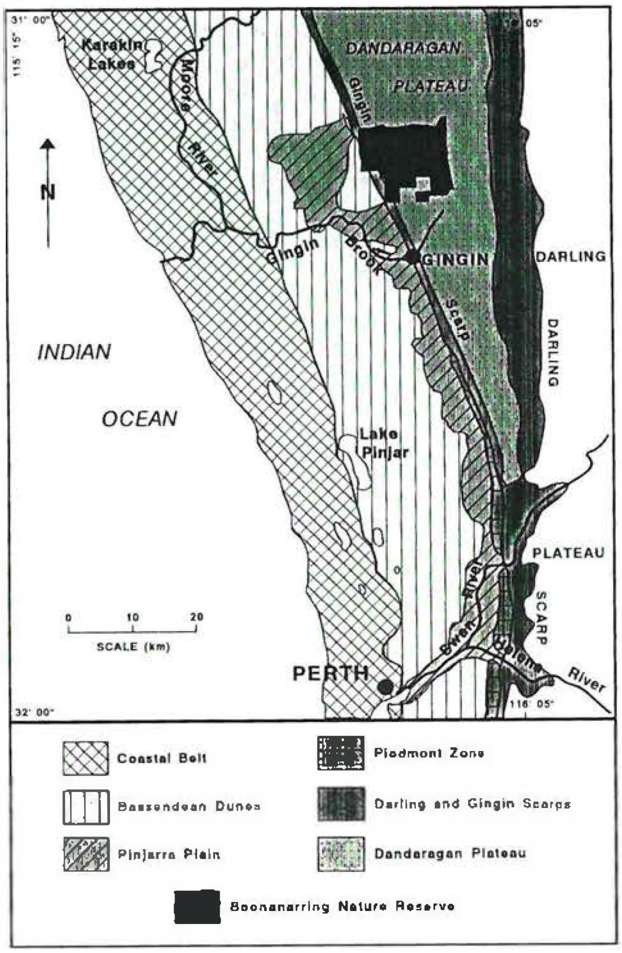

Figure 1. Location of the Boonanarring Nature Reserve in relation to significant geomorphological features of the region (after Wilde and Low 1978).

watercourse. The Brook meanders in a south-westerly direction from the southern part of the reserve (Fig. 2).

The Dandaragan Plateau consists primarily of Tertiary laterites outcropping in Pleistocene-Recent sands over flat-lying partly lateritized Cretaceous rocks. These sedimentary Cretaceous beds contrast with the hard Precambrian rocks of the Darling Plateau and the deep Pleistocene sands and alluvial soils of the eastern Swan Coastal Plain (Wilde and Low 1978).

The climate is Warm Mediterranean with 700 mm annual precipitation and 5-6 dry months per year. Mean winter temperature is about 13°C and the mean minimum temperature for the coldest month is 8°C. Mean summer temperature is about 23°C and mean maximum temperature for the hottest month is 32°C. Annual evaporation is about 1900 mm (Bureau of Meteorology 1968).

Boonanarring Nature Reserve is located within the Drummond Sub-district of the South-west Botanical Province (Beard 1980). The vegetation of this area was first mapped by Beard (1979) at a scale of 1:250 000. Physiognomy of the dominant vegetation stratum and surface geology were used to define three major vegetation components:

(1) *Banksia* low woodlands (less than 10 m),
(2) *Banksia* low woodlands with scattered jarrah (*Eucalyptus marginata*) and marri (*E. calophylla*) trees, and
(3) *E. calophylla* woodlands between 10 and 30 m.

The vegetation complexes were also mapped by Heddle *et al.* (1980), again at a scale of 1:250 000, but based on Havel's (1968, 1975a, b) site-vegetation types and the landform and soil units defined by Churchward and McArthur (1980). According to this system, the Karamal landform/soil unit is predominant within the reserve, and is described as a gently undulating landscape dominated by deep, yellow sands with lateritic gravels on the ridges. Within our study area, lateritic outcrops are common. The associated vegetation, the Karamal Complex - South, is described as being dominated by an open forest of jarrah (*Eucalyptus marginata*) and marri (*E. calophylla*) with a mid-storey of bull banksia (*Banksia grandis*). In the north-east of the study area, aeolian sandplain with some low dunes supports the Cullala complex of low open forest of *Banksia attenuata* and *B. menziesii* with some *B. ilicifolia* and *E. todtiana*. On the boundary with the Karamal complex there often occurs an intermediate vegetation type of open marri (or jarrah) forest with a second storey of *Banksia* species. The western edge of the study area consists mainly of red sandy soils on the gently sloping irregular scarp (Gingin unit) and deep red and yellow brown sands in the valleys (Moondah unit). The Gingin vegetation complex on the scarp is described as an open woodland of *E. calophylla* with a second storey of *B. grandis* and *Nuytsia floribunda*. In the valleys and slopes is an open woodland of *Eucalyptus* species, and on some of the lower slopes there is a low closed to low open forest of *Banksia* species with *E. todtiana*.

Apart from the broad scale vegetation mapping referred to above, there appear to be no published biological data on the Boonanarring Nature Reserve. Surveys from nearby areas include observations on the birds of the Moore River gorge area, 25 km to the north (Whitlock 1905; Loaring and Serventy 1952), a study of the fauna of the northern Swan Coastal Plain (How 1978), the quadrat-based vegetation survey of Moore River to Jurien Sandplain (Griffin and Keighery 1989), work on fire effects in *Banksia* woodland about 10 km to the south-east at Mooliabeenee (Bamford 1985, 1986) and a general survey of Julimar Forest Block, about 40 km to the south-east on the Darling Plateau (Forests Department unpublished).

The present survey was undertaken with two aims in mind. The first was to obtain base-line data on the assemblages of plants and animals present at selected sites in the study area. Such data can be used in quantitative comparisons between these and other sites or, with resampling, comparisons over time (monitoring) (McKenzie 1988; McKenzie *et al.* 1991). The second aim was to provide an assessment of the conservation values of the area as the basis of a management program for the reserve.

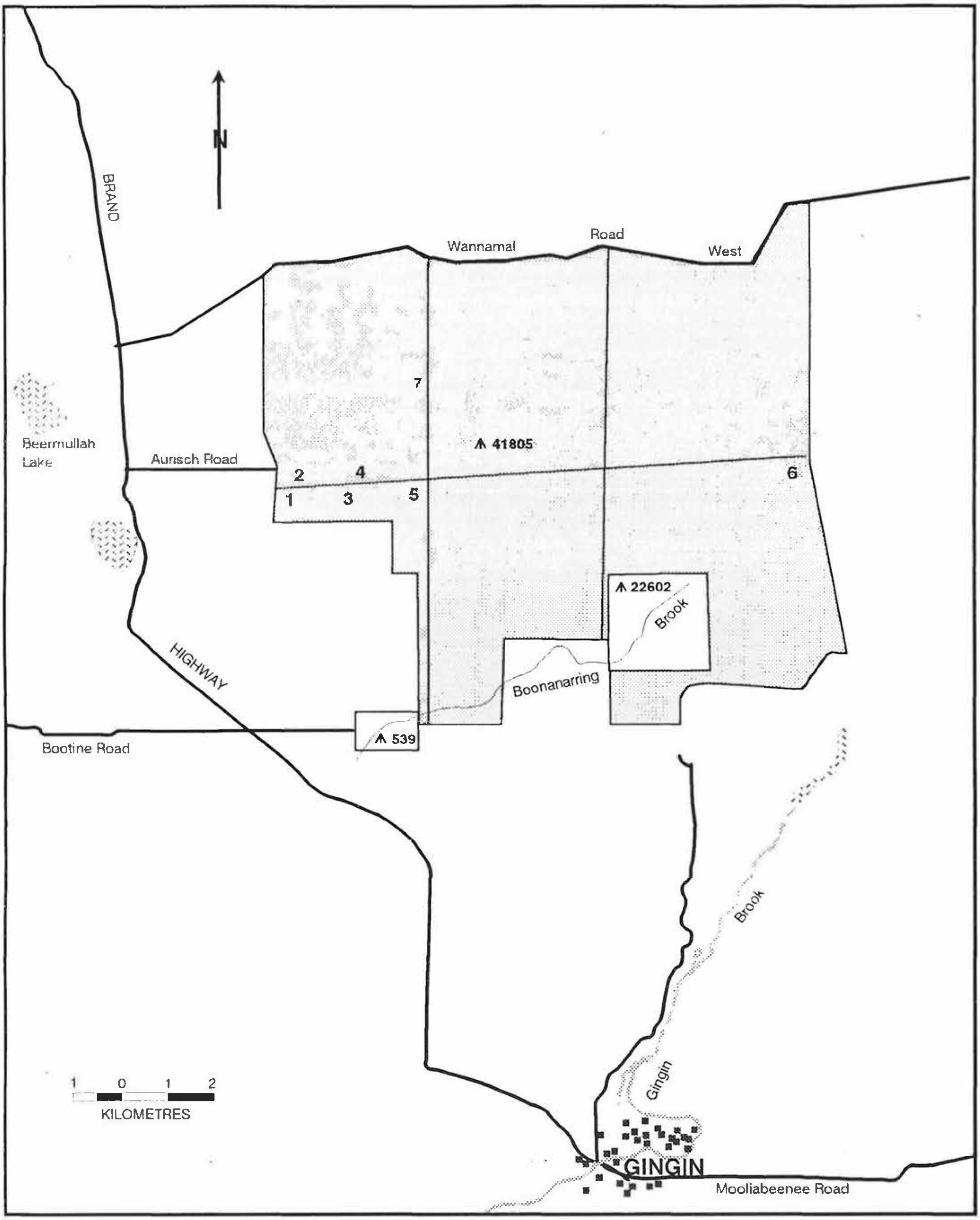

Figure 2. Locations of sample sites (quadrats) in the Boonanarring Nature Reserve

METHODS

Seven sites (quadrats) were selected for systematic sampling for assemblage data in March 1986 (Table 1 and Fig. 2). These sites were arranged to form a transect from the foot of the Gingin Scarp in the west, through the woodlands of the plateau to a dense heath on the eastern boundary, and placed so as to sample some of the major vegetation types in the study area. A detailed description of vegetation at each site is given in Appendix 1.

TABLE 1

Locations of permanent sampling sites in the Boonanarring Nature Reserve. (Elevations were estimated from the Gingin 1:100 000 map.)

SITE	LATITUDE	LONGITUDE	ELEVATION (m)
1	31°13'05"	115°50'15"	140
2	31°13'00"	115°50'30"	145
3	31°13'00"	115°51'05"	220
4	31°12'55"	115°51'15"	225
5	31°12'55"	115°52'05"	260
6	31°12'40"	115°56'55"	220
7	31°11'45"	115°52'10"	240

Sampling for assemblage data (including live-trapping for vertebrates) was carried out from 17 to 23 March 1986. Each site was sampled as exhaustively as possible for species of vascular plants, amphibians, reptiles, birds and mammals. The search area for each site was an unbounded quadrat of about 2 ha centred on the trapping lines at that site. Opportunistic observations were made at other times (mostly in February, July and August 1986) and at other places in the study area.

Vegetation at each site was described using Muir's (1977) system of vegetation classification. Voucher specimens were collected for most vascular plant species and lodged at the Western Australian Herbarium (PERTH), but a number of common, widespread species were simply recorded. Soil substrate type and topography was recorded for each site. Sites were resampled at several different times of the year to record annual or inconspicuous plant species. Opportunistic flora records for the reserve were made by several collectors. No estimates of species abundance were made.

Vegetation mapping was undertaken using monochrome 1:250 000 (1985) and colour 1:20 000 (1989) aerial photographs and the 1:50 000 Mindarra SW topographic map. Geological and soil maps were consulted to assist in vegetation interpretation. Transition zones in vegetation types were recorded along all tracks and fire breaks throughout the reserve and by extensive ground reconnaissance. Mapping from aerial photographs was made difficult by the presence of extensive fire scars of variable age.

Sampling of vertebrates was done by live-trapping and systematic searching. Bats were caught in mist nets near Site 5 and at two locations to the south of this site. Mist nets were run for 9.5 net hours (1 net x 1 hour = 1 net hour). Small ground-dwelling vertebrates were sampled by means of pitfall (Sites 1-4, 7) and Elliott traps (Sites 5 and 6). A description of traps and trap layout is provided in Appendix 2. The total trapping effort was 300 pit trap nights and 300 Elliott trap nights (1 trap x 1 night = 1 trap night).

Spotlighting from a vehicle was conducted throughout the reserve on the existing main tracks. Spotlighting effort totalled five hours.

In order to identify recaptures, small mammals were marked using alcohol-based coloured marker pens, usually on the base of the tail or under the chin. This proved to be an effective technique since, in some cases, one application persisted for the duration of the five-night trapping period.

Fishes were sampled from the headwaters of Boonanarring Brook by means of 40 x 25 x 25 cm traps with two funnel entrances giving access to a baited pouch. Traps were baited with dry cat food ('Go Cat'). Four traps were set for a total of eight hours during daylight hours on 15 July 1992.

Identifications in the field were done with reference to a range of guides including Tyler *et al.* (1984), Storr *et al.* (1981, 1986) and Strahan (1983). Voucher fish, frog, reptile and mammal specimens were collected and have been accessed by the Western Australian Museum. Accession numbers (where known) are listed in Appendix 3.

Samples of heart, liver and kidney tissues were taken from specimens of *Sminthopsis* and frozen in liquid nitrogen for electrophoretic analyses. Analyses were run by the Evolutionary Biology Unit of the South Australian Museum. Electrophoretic determinations were used in conjunction with standard taxonomic procedures to verify our identifications.

RESULTS

Vegetation

Ten discrete vegetation associations were recognized within the Boonanarring Nature Reserve (Fig. 3). As expected, these correlated with soil type, topography and drainage. Some vegetation types had distinct boundaries while others represented ecotones, particularly where *Banksia* woodland adjoined jarrah forest and heaths. Some rare or unusual species occurred within these ecotones; for example *Eucalyptus lane-poolei* populations occur only where upland jarrah forest adjoins *Banksia* woodland.

Woodlands and Forests

There are seven woodland and forest types in the study area.

The first vegetation type occurs in valleys on Moondah soil and consists of tall forests of *Eucalyptus calophylla* over open, variable scrub. This vegetation association flanks most of the slopes running down into Boonanarring Brook.

The second vegetation type, open forest or low woodland of *Melaleuca preissiana* and *Eucalyptus rudis*, is extremely limited in occurrence within the reserve, being restricted to the watercourses and areas where the water table is close to the surface (palusplains; see Semeniuk 1987).

The third vegetation type is limited to the small areas of massive, exposed laterite rock breakaways supporting *Eucalyptus wandoo* on their western facing slopes.

Banksia woodlands on deep yellow or grey sand are the second most abundant vegetation type on the reserve, occurring on the sandier components of all major soil units present. Understorey components were highly variable, reflecting substrate depth and type. Two major sub-associations were identified.

The fourth vegetation type consists of a low open woodland of *Banksia menziesii*, *B. attenuata* and *Eucalyptus todtiana* with occasional *Nuytsia floribunda* and *Banksia ilicifolia* in wetter sites. The understorey is dominated by *Adenanthos cygnorum*, often dense scrub to 2 m. This association occurs in the lower landscape on Cullala soils or as an ecotone at the junction of Cullala and Karamal soils.

The fifth vegetation type consists of *Banksia attenuata*, *B. grandis* and *Eucalyptus todtiana* with occasional *Nuytsia floribunda* and a low, variable, often species-rich understorey. Quadrats 2, 3 and 4 are representative of this vegetation type on the Moondah soil unit.

Most of the reserve consists of Karamal soils which support the predominant vegetation type of an open forest or woodland of jarrah and marri. This broadscale association is further defined based on vegetation structure and floristics, soil type and topography. The sixth vegetation type occurs on the shallow soils of the gravelly, lateritic uplands. At these sites jarrah is the dominant tree with some marri and occasional *Banksia grandis* in the mid-storey. *Dryandra sessilis* is found in large stands where soils are very shallow. The shrub layer is species-rich, denser and smaller than in the surrounding lower landscape. This represents a typical response of jarrah forest to soil depth (Havel 1975a). This vegetation type was recorded at permanent quadrat 5.

The seventh vegetation type occurs in the deep yellow sands in the swales between the laterite uplands. Here, the jarrah woodland becomes more open and marri is more abundant. Understorey species and cover vary considerably. Large patches and mosaics of *Petrophile ericifolia* and *Melaleuca scabra* occur with variations in soil depth and topography. Where fires have been intense or frequent the understorey appears depauperate and *Stirlingia latifolia* is dominant. This vegetation type was recorded at permanent Quadrat 7.

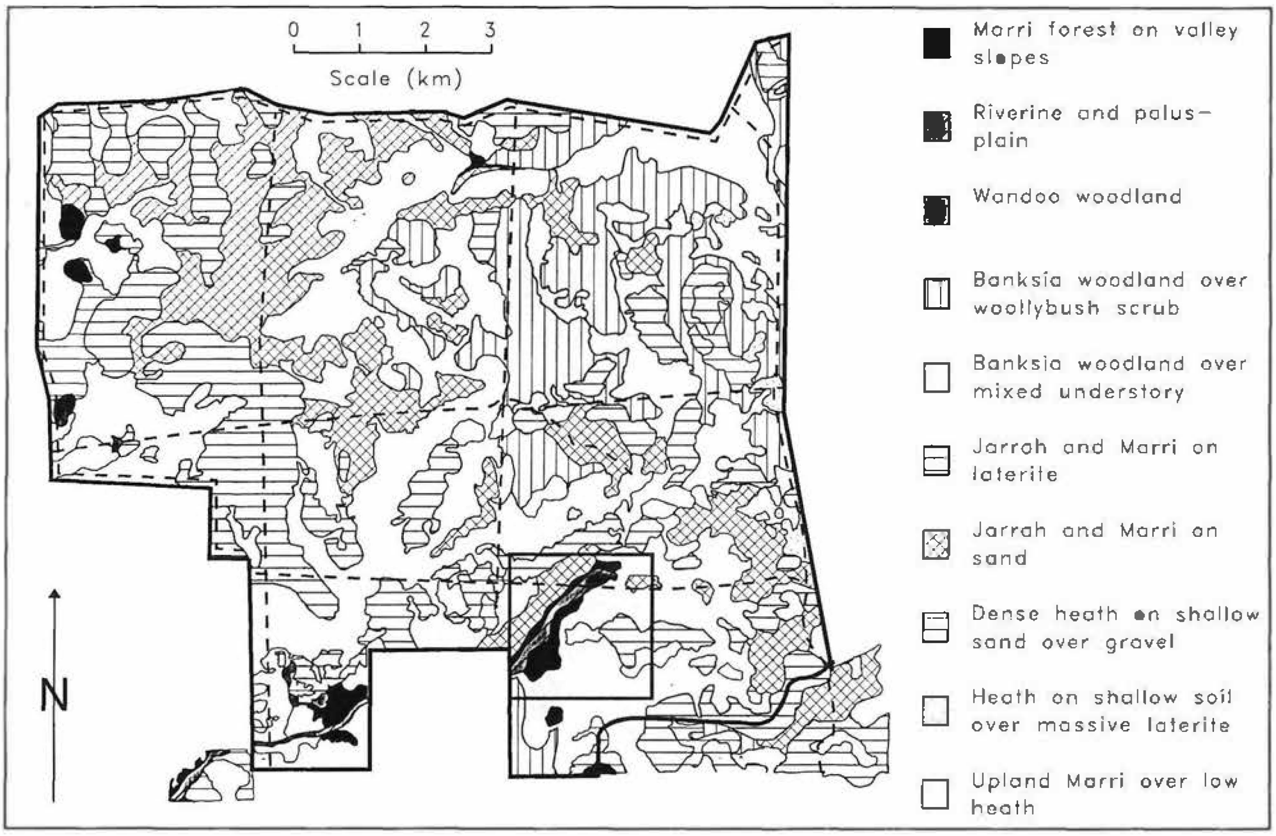

Figure 3. Vegetation unit boundaries within the Boonanarring Nature Reserve

Heaths

Three major heath associations were recognized. These occurred in patches throughout the reserve, corresponding to soil depth and aspect. The first occurs on the western scarp boundary and on breakaways where shallow, grey sand (Karamal soil) occurs over massive laterite. In this association *Dryandra sessilis* dominates with varying amounts of *Hakea ruscifolia*, *Xanthorrhoea preissii* over *Stirlingia latifolia*, *Jacksonia* spp., *Calytrix* spp., *Leucopogon* spp. and *Petrophile linearis*. The second heath consists of species-rich, dense heath to 1.5 m on shallow white to grey sandy soils over gravel, on low rises within the Cullala soil unit. The species-rich scrub heaths were highly variable in composition with *Allocasuarina humilis*, *Hakea trifurcata* and *Adenanthos cygnorum* occurring in patches, generally to 1 m with emergent *Nuytsia floribunda* and *Jacksonia* spp. Quadrat 6 provides a typical example of this vegetation type. The final vegetation type recognized occurs on rises where sands are shallow in the Karamal soil unit. This is a very sparse, low heath with open, tall *Eucalyptus calophylla*. The understorey is highly variable but usually dominated by *Dryandra echinata*, *Hakea lissocarpha*, *Petrophile serruriae*, *Macrozamia riedlei* and *Bossiaea eriocarpa*. These heaths are unusual because they are generally in the upper landscape and contain several rarely recorded plant species such as *Conospermum incurvum*.

Floristics

A total of 573 vascular plant species (from 70 families and 223 genera; see Appendix 4) have been recorded within the Boonanarring Nature Reserve. Herbs were well represented within the reserve; for example, Orchidaceae and Asteraceae were represented by 28 and 27 taxa respectively. The reserve was relatively free of introduced species, but included 27 taxa (4.7 per cent) dominated by members of the families Asteraceae (5) and Poaceae (5). Given the relatively large size of the reserve and the difficulty in traversing it on the ground, further investigations will undoubtedly result in additions to the flora list, although we believe that the majority of perennial and annual species present were recorded.

Of the total number of families recorded, the Myrtaceae (63 native species), Proteaceae (58) and Papilionaceae (44) were dominant, with Epacridaceae (31 native species) and Asteraceae (27) significant (Table 2). Important genera include *Stylidium* (19 taxa), *Acacia* (15), *Leucopogon* (15), *Hibbertia* (13), *Hakea* (13), *Banksia* (11) and *Eucalyptus* (9). A noticeable feature of the area is the low mean number of species per genus (2.1). Of the 223 genera listed, 129 (59 per cent) are represented by only one species, highlighting the level of generic richness in the reserve. Further research is needed to ascertain whether this is a general feature of species-rich reserves in south-west Western Australia.

Rare and Unusual Plant Species

Of the 573 species recorded at Boonanarring, 75 species (13 per cent) are considered to be of particular interest (Table 3). This includes 18 priority species (Atkins 1995). Based on Marchant *et al.* (1987), current herbarium records and personal knowledge, 67 species records were considered to represent range extensions or disjunct populations.

TABLE 2

Dominant plant families in Boonanarring Nature Reserve and water reserve A22602.

FAMILY	No. of TAXA native	No. of TAXA introduced	% of TOTAL (native taxa)
Myrtaceae	63	0	11.6
Proteaceae	58	0	10.6
Papilionaceae	44	4	8.1
Epacridaceae	31	0	5.7
Orchidaceae	28	1	5.1
Asteraceae	27	5	5.0
Cyperaceae	26	0	4.8
Anthericaceae	25	0	4.4
Stylidiaceae	23	0	4.2
Goodeniaceae	18	0	3.3
Haemodoraceae	18	0	3.3
Mimosaceae	15	0	2.8
Poaceae	15	5	2.8
Restionaceae	15	0	2.8

Several populations of the previously declared rare *Grevillea saccata* occur on the Moondah soil unit within the reserve. These represent the only secure populations, as all others occur on alienated lands or road verges. The location of these populations and the subsequent declaration of the nature reserve were instrumental in removing this species from the list of declared rare flora.

Several populations of *Acacia clydonophora*, *Verticordia paludosa*, *Conostephium minus*, *Calytrix sylvana*, (all Priority 4), *Acacia cummingiana*, *Acacia pulchella* var *reflexa* (acute bracteole variant), *Leucopogon oliganthus*, *Banksia micrantha*, *Dryandra echinata*, *Haemodorum loratum*, *Olax scalariformis* (all Priority 3) and *Macarthuria apetala*, *Lysinema elegans*, *Pithocarpa achilleoides* (all Priority 2) were all recorded on the reserve. Several large populations of *Dryandra echinata* occur within areas of Vegetation type 6. These are the largest known populations on a reserve.

A population of *Banksia chamaephyton* (Priority 4) on the eastern side of the reserve represents a southerly extension of the known range of this species which until recently was declared rare and endangered. The record of *Laxmannia omnifertilis* is a southerly range extension (by about 70 km, from north of Cataby) of a species which has been relatively well surveyed.

In shallow sands over laterite at Quadrat 6, *Eucalyptus decurva* was found. This is a predominantly south-coast species recently found near Northam and near New Norcia (M. Brooker, personal communication; Brooker and Kleinig 1990). The population at Boonanarring is the farthest north-west known occurrence. Also of interest is another eucalypt, *E. lane-poolei*. Within Boonanarring Nature Reserve this species forms sparse woodlands on laterite derived sands and near the Gingin Scarp which runs down the western edge of the study area. This is one of several disjunct populations which occur to the north of the bulk of the species' range, which is south of Perth (Brooker and Kleinig 1990). At the same site we found a subspecies of *Lomandra micrantha* (*L.m. teretifolia*) normally found only on the south coast.

The type specimen of *Stylidium carlquistii* (Priority 1) is from the reserve, and several previously unknown species were first collected from the reserve, including *Tetratheca* aff. *hirsuta* (JJA153) and several undescribed orchid species (S.D. Hopper personal communication).

Other flora records of interest include a hybrid population between *Eucalyptus marginata* and *E. todtiana* and the presence of blue-green leaved jarrah (*E. marginata* subsp. *thalassica*) as well as trees with dark green leaves (subsp. *marginata*). This is the most northerly record for subsp. *thalassica*. Populations of *Stylidium leptocalyx* and *S. carlquistii* are the only ones found on nature reserves, making this reserve important to the conservation of these species.

TABLE 3

Biogeographically interesting, significant or unusual plant occurrences known from Boonanarring Nature Reserve.

SPECIES	COMMENT
SCHIZAEACEAE	
Schizaea fistulosa	northern limit, previously Muchea
POACEAE	
Eriachne ovata	south-western limit; closest population Bakers Hill
CYPERACEAE	
Schoenus efoliatus	northern limit
Tetraria capillaris	northern limit, extension from Busselton
RESTIONACEAE	
Ecdeiocolea monostachya	at southern limit of range
Onchysepalum laxiflorum	at southern limit of range
DASYPOGONACEAE	
Lomandra hastilis	at southern limit of range
Lomandra aff. *micrantha*	population apparently referable to *L. micrantha* subsp. *teretifolia*, previously recorded from Albany to Cape Arid
ANTHERICACEAE	
Borya scirpoidea	only population known from north of Perth
Laxmannia omnifertilis	southernmost known population
Laxmannia sessiliflora subsp. *australis*	at or near northern limit of this subspecies
Laxmannia squarrosa	northern-most known population
HAEMODORACEAE	
Anigozanthos pulcherrimus	uncommon; southern extension of range (from Bartlett's Well)
Haemodorum loratum	Prioirity 3 species
Phlebocarya filifolia	rarely collected, Priority 2 species[1]
ORCHIDACEAE	
Caladenia 'arenicola'	north-eastern limit of range; unusual away from coastal plain
Calochilus aff. *robertsonii*	northern-most occurrence; range extension from near Perth
Corybas abditus	northern-most occurrence; range extension from Busselton-Albany region
PROTEACEAE	
Banksia burdettii	southern-most record
Banksia chamaephyton	until recently declared endangered; southern-most known population; Priority 4

Table 3 (continued)

Banksia micrantha	Priority 3 species; southern extension of known range
Dryandra echinata	Priority 3 species; extensive populations on the reserve
Grevillea saccata	Priority 4 species; southernmost known population; only known population not on a road verge
Lambertia multiflora var. *multiflora*	near southern limit of range
Isopogon adenanthoides	southern-most known population
Isopogon linearis	southern-most known population
Petrophile scabriuscula	furthest south record
AMARANTHACEAE	
Ptilotus drummondii	northern end of range
OLACACEAE	
Olax scalariformis	Priority 3 species
Olax spartea	southern-most known population
RANUNCULACEAE	
Clematis pubescens	northern-most record
DROSERACEAE	
Drosera pulchella	northern-most known population; usually Perth to Albany
MOLLUGINACEAE	
Macarthuria apetala	Priority 3 species
MIMOSACEAE	
Acacia clydonophora	Priority 4 species, at southern limit of range
Acacia cummingiana	Priority 3 species, at southern limit of range
Acacia pulchella var. *reflexa* (acuminate bracteole variant)	Priority 3 species
PAPILIONACEAE	
Aotus gracillima	northern-most known population
Bossiaea ornata	northern-most known population
Daviesia striata	northern-most known population
Gompholobium scabrum	northern-most known population
Sphaerolobium vimineum	northern-most known population
RUTACEAE	
Boronia molloyae	northern-most known population
Boronia purdieana	?eastern margin of range
TREMANDRACEAE	
Tetratheca aff. *hirsuta*	First known locality of undescribed species, proposed type locality
POLYGALACEAE	
Comesperma virgatum	northern-most known population
RHAMNACEAE	
Cryptandra scoparia	poorly collected
Stenanthemum humilis	southern-most known population
MYRTACEAE	
Agonis linearifolia	one of only nine records; northern-most population known; range extension
Calytrix sylvana	Priority 4 species
Calytrix variabilis	restricted range
Eucalyptus decurva	very unusual occurrence, only two other populations not on the South Coast.
Eucalyptus lane-poolei	patchy occurrence along and near the Darling and Gingin Scarps; uncommon
Eucalyptus marginata x *todtiana*	only known hybrid between these two taxa
Homalospermum firmum	northern-most known population
Kunzea ericifolia	northern-most known population
Pericalymma ellipticum	near northern limit (Moore River)
Verticordia paludosa	Priority 4 species
APIACEAE	
Platysace ramosissima	rarely collected; second known population and the only one known on a Nature Reserve
EPACRIDACEAE	
Astroloma macrocalyx	poorly collected
Conostephium minus	Priority 4 species

Table 3 (continued)

SPECIES	COMMENT
Leucopogon oliganthus	Priority 3 species
Leucopogon oxycedrus / nutans	northern-most known population
Leucopogon cf. verticillatus	northern-most known population
Lysinema elegans	Priority 2 species
Styphelia tenuiflora	near northern limit
LENTIBULARIACEAE	
Utricularia violacea	northern-most known population
Utricularia volubilis	northern-most known population
LOBELIACEAE	
Lobelia tenuior	northern-most known population
STYLIDIACEAE	
Stylidium albo-lilacinum	rarely collected
Stylidium aff. rhynchocarpum	either a new species or northern-most occurrence of *S. rhynchocarpum*
Stylidium carlquistii	Priority 1 species, only known occurrence
ASTERACEAE	
Asteridea pulverulenta	northern-most known population
Blennospora drummondii	restricted
Millotia tenuifolia	poorly collected
Pithocarpa achilleoides	Priority 2 species; widespread throughout the Nature Reserve

[1] CALM Flora Conservation Codes (as at 14 September 1995) (Atkins 1995)

Declared Rare Flora - Extant Taxa: Taxa which have been adequately searched for and are deemed to be in the wild either rare, in danger of extinction, or otherwise in need of special protection, and have been gazetted as such.

Priority One - Poorly Known Taxa: Taxa which are known from one or a few (generally <5) populations which are under threat, either due to small population size, or being on lands under immediate threat, e.g. road verges, urban areas, farmland, active mineral leases, etc., or the plants are under threat, e.g. from disease, grazing by feral animals, etc. May include taxa with threatened populations on protected lands. Such taxa are under consideration for declaration as 'rare flora', but are in urgent need of further survey.

Priority Two - Poorly Known Taxa: Taxa which are known from one or a few (generally <5) populations, at least some of which are not believed to be under immediate threat (i.e. not currently endangered). Such taxa are under consideration for declaration as 'rare flora', but are in urgent need of further survey.

Priority Three - Poorly Known Taxa: Taxa which are known from several populations, at least some of which are not believed to be under immediate threat (i.e. not currently endangered). Such taxa are under consideration for declaration as 'rare flora' but are in need of further survey.

Priority Four - Rare Taxa: Taxa which are considered to have been adequately surveyed and which, whilst being rare (in Australia), are not currently threatened by any identifiable factors. These taxa require monitoring every 5-10 years.

Fishes

Three individuals of the Western Pygmy Perch (*Edelia vittata*) were captured near the head of Boonanarring Brook.

Frogs and Reptiles

Three frog and 18 reptile species were detected on the reserve during the assemblage survey in March, and another two frog and two reptile species were recorded opportunistically at other times (Table 4). Six species were detected once only at a single sample site: *Heleioporus eyrei*, *Pletholax gracilis gracilis*, *Morethia obscura*, *Tiliqua rugosa*, *Vermicella calonotos* and *Pseudonaja affinis*. However, four of these, *Heleioporus eyrei*, *Morethia obscura*, *Tiliqua rugosa* and *Pseudonaja affinis*, are common and widespread species in the south-west of the State and are likely to be more common and widespread in the study area than these data suggest.

TABLE 4

Reptile and amphibian species recorded from each sample site on Boonanarring Nature Reserve.

SPECIES	SITE 1	2	3	4	5	6	7	OPPORTUNISTIC RECORD
Frogs								
Hylidae								
Litoria adelaidensis								*
Leptodactylidae								
Heleioporus eyrei	X							
Limnodynastes dorsalis			X	X			X	
Myobatrachus gouldii	*		X	X				
Ranidella glauerti								*
Reptiles								
Gekkonidae								
Crenadactylus ocellatus					X			X(scarp)
Pygopodidae								
Aprasia repens	X	X	X		X		X	
Delma fraseri				*	X			X(scarp)
Lialis burtonis								*
Pletholax gracilis gracilis		X						
Pygopus lepidopodus								X(scarp)
Scincidae								
Cryptoblepharus plagiocephalus			X		X			
Ctenotus fallens	X			X				
Lerista distinguenda	X					X		
Lerista praepedita	X	X	X	X				
Morethia obscura							X	
Tiliqua rugosa						X		
Agamidae								
Pogona minor							X	X
Tympanocryptis adelaidensis		X	X		X			
Boidae								
Morelia spilota								*
Elapidae								
Vermicella bimaculata	X	X						
Vermicella calonotos	X							
Vermicella semifasciata	X			X				
Notechis curtus	X		X					*
Pseudonaja affinis	X							
Number of species at each site:	11	5	7	6	5	2	4	

All records except * were made during the assemblage survey in March. 'Scarp' refers to lateritic breakaway surfaces of the Gingin Scarp, between Sites 2 and 3.

Table 5 shows the number of individuals of each species captured in pitfall traps and during diurnal searches. Pitfall captures equate with the total number of individuals captured since there were no recaptures. Only eight species (three frog and five reptile species) were pit-trapped. Twelve species of reptiles were detected only by active searching techniques.

TABLE 5

Total numbers of each frog and reptile species recorded from pitfall traps and diurnal searches at sample sites on Boonanarring Nature Reserve, 17-23 March 1986.

SPECIES	METHOD		SAMPLE SITE
	Pitfall traps	Diurnal searches	
Frogs			
Heleioporus eyrei	1		1
Limnodynastes dorsalis	5		3,4,7
Myobatrachus gouldii	5		3,4
Reptiles			
Crenadactylus ocellatus		1	5
Aprasia repens		8	1,2,3,5,7
Delma fraseri		3	5
Pletholax gracilis gracilis	1		2
Pygopus lepidopodus		1	
Cryptoblepharus plagiocephalus	1	1	3,5
Ctenotus fallens		2	1,4
Lerista distinguenda		2	1,6
Lerista praepedita		8	1,2,3,4
Morethia obscura		1	7
Tiliqua rugosa		1	6
Tympanocryptis adelaidensis	3	2	2,3,5
Pogona minor	2		7
Vermicella bimaculata		4	1,2
Vermicella calonotos		1	1
Vermicella semifasciata		2	1,4
Notechis curtus	1	1	1,3
Pseudonaja affinis		1	2
Number of species:	8	16	

Birds

In the March survey, 47 species of birds were recorded in the reserve (Table 6). A further 27 species were recorded on other occasions, sometimes opportunistically, providing a total of 74 species known for the study area. A chestnut-shouldered fairy-wren (possibly *Malurus lamberti*) was also seen, but not well enough to distinguish it reliably from the two other species which could occur. In any case, the occurrence is of interest, being outside the normal range of these species. The Laughing Kookaburra was the only introduced species recorded. All species were within their known ranges (Storr 1991). A total of 30 families were represented (taxonomic groupings used were those of Christidis and Boles 1994). Prominent families included Meliphagidae (honeyeaters, 11 species), Accipitridae (hawks and eagles, 6) and Pardalotidae (pardalotes, thornbills and allies, 6).

Mammals

Eleven native and four introduced mammal species were recorded on the reserve (Table 7). Seven native and one introduced species were recorded at sample sites and, opportunistically, an additional four native (all bats) and three introduced species were recorded away from the permanent sampling sites (quadrats) (Table 7). A species account is presented in Appendix 5. The list of native species comprised three small ground mammals, five bats, two macropods and the echidna. All are within their known geographic ranges.

Three native and one introduced small mammal species were trapped (Table 7). Appendix 6 lists the total number of individuals captured from individual traplines at each site. Honey Possums (*Tarsipes rostratus*) had pouch young at the time of the survey (March) and several *Mus* were in breeding condition (one female was pregnant). One male *Pseudomys albocinereus* was in breeding condition, suggesting that limited breeding may have been occurring at the time of survey. Captures of juveniles and an adult female *Sminthopsis griseoventer* indicated that the species had successfully bred on the reserve before March. Males of three bat species, *Nyctophilus gouldi*, *N. geoffroyi* and *Vespadelus regulus* showed breeding condition, although we have no reproductive information from females to confirm breeding activity in March. (See Appendix 5 for further details.)

DISCUSSION

Floristics and Vegetation

Boonanarring Nature Reserve is of considerable botanical significance as it represents the transition zone of vegetation associations of the Swan Coastal Plain, Darling Scarp and the Dandaragan Plateau. These are primarily the woodlands of the Muchea-Gingin area and the heaths (kwongan) of the Mogumber area.

This transition is reflected in the floristics of the area. Griffin (1994) utilised the quadrats established for this study, and others he established in the reserve, in his analysis of the floristics of the sandplains between Perth and Geraldton. Sites from Boonanarring fell into four woodland and heath groups (20-5, 20-6 (heaths), 20-7 and 20-9 (woodlands)). The heath groups had northern affinities with those in Boonanarring near their southern limits. The woodland group 20-7 also was a northern group, while 20-9 was essentially a group allied to the Dandaragan scarp extending from Wannamal to Bullsbrook. Gibson and Keighery (personal communication) using Griffin's sites, those from the Swan Coastal Plain survey (Gibson *et al.* 1994) and from the Department of Environmental Protection's System Six update study (1996), have also found that floristic sites from Boonanarring have affinities to heaths and woodlands north and south of the reserve, rather than the adjacent coastal plain. These data are currently being prepared for publication elsewhere.

TABLE 6

Bird species recorded at each sample site on the Boonanarring Nature Reserve.

COMMON NAME	SCIENTIFIC NAME	SITE 1	2	3	4	5	6	7	Opp.
Emu	*Dromaius novaehollandiae*			+	+		+	+	
Australian Shelduck	*Tadorna tadornoides*								+
Pacific Black Duck	*Anas superciliosa*								N
Black-shouldered Kite	*Elanus axillaris*								+
Whistling Kite	*Haliastur sphenurus*								+
Brown Goshawk	*Accipiter fasciatus*								R
Collared Sparrowhawk	*Accipiter cirrhocephalus*								+
Wedge-tailed Eagle	*Aquila audax*								+
Little Eagle	*Hieraaetus morphnoides*								+
Brown Falcon	*Falco berigora*	+	+	+					+
Australian Hobby	*Falco longipennis*								+
Australian Kestrel	*Falco cenchroides*								+
Painted Button-quail	*Turnix varia*			?					
Common Bronzewing	*Phaps chalcoptera*								+
Crested Pigeon	*Ocyphaps lophotes*								+
Short-billed Black-Cockatoo	*Calyptorhynchus latirostris*				+				+
Galah	*Cacatua roseicapilla*								+
Purple-crowned Lorikeet	*Glossopsitta porphyrocephala*							+	+
Australian Ringneck	*Barnardius zonarius*			+	+			+	+
Red-capped Parrot	*Purpureicephalus spurius*								+
Pallid Cuckoo	*Cuculus pallidus*								+
Fan-tailed Cuckoo	*Cacomantis flabelliformis*								+
Horsfield's Bronze-Cuckoo	*Chrysococcyx basalis*	+							
Shining Bronze-Cuckoo	*Chrysococcyx lucidus*								+
Southern Boobook	*Ninox novaeseelandiae*					+			+
Barn Owl	*Tyto alba*								N
Tawny Frogmouth	*Podargus strigoides*								+
Australian Owlet-nightjar	*Aegotheles cristatus*								+
Laughing Kookaburra	*Dacelo novaeguineae*					+		+	+
Sacred Kingfisher	*Todiramphus sanctus*								+
Rainbow Bee-eater	*Merops ornatus*								+
Splendid Fairy-wren	*Malurus splendens*					+		+	+
White-winged Fairy-wren	*Malurus leucopterus*	+	+				+		+
Striated Pardalote	*Pardalotus striatus*							+	+
Weebill	*Smicrornis brevirostris*							+	+
Western Gerygone	*Gerygone fusca*	+		+	+	+		+	+
Inland Thornbill	*Acanthiza apicalis*								+
Western Thornbill	*Acanthiza inornata*			+		+	+	+	+
Yellow-rumped Thornbill	*Acanthiza chrysorrhoa*			+				+	+
Red Wattlebird	*Anthochaera carunculata*			+	+	+		+	+
Little Wattlebird	*Anthochaera chrysoptera*		+	+	+	+			+
Yellow-throated Miner	*Manorina flavigula*								+
Singing Honeyeater	*Lichenostomus virescens*	+	+	+	+			+	
Yellow-plumed Honeyeater	*Lichenostomus ornatus*								N
Brown-headed Honeyeater	*Melithreptus brevirostris*					+		+	
Brown Honeyeater	*Lichmera indistincta*	+	+	+	+	+	+	+	+
New Holland Honeyeater	*Phylidonyris novaehollandiae*								+
Tawny-crowned Honeyeater	*Phylidonyris melanops*	+	+	+	+		+		+
Western Spinebill	*Acanthorhynchus superciliosus*			+	+	+	+	+	+
White-fronted Chat	*Ephthianura albifrons*						+		
Scarlet Robin	*Petroica multicolor*				+	+		+	+
Red-capped Robin	*Petroica goodenovii*								+
Hooded Robin	*Melanodryas cucullata*		+						
Varied Sittella	*Daphoenositta chrysoptera*					+		+	+
Golden Whistler	*Pachycephala pectoralis*								R
Rufous Whistler	*Pachycephala rufiventris*		+		+	+		+	+
Grey Shrike-thrush	*Colluricincla harmonica*	+				+		+	+
Magpie-lark	*Grallina cyanoleuca*								+
Grey Fantail	*Rhipidura fuliginosa*	+		+	+	+		+	+
Willie Wagtail	*Rhipidura leucophrys*								+
Black-faced Cuckoo-shrike	*Coracina novaehollandiae*			+	+	+	+	+	+
White-winged Triller	*Lalage sueurii*								N

Table 6 (continued)

COMMON NAME	SCIENTIFIC NAME	SITE 1	2	3	4	5	6	7	Opp.
Black-faced Woodswallow	*Artamus cinereus*	+				+			+
Dusky Woodswallow	*Artamus cyanopterus*							+	
Grey Butcherbird	*Cracticus torquatus*			+	+			+	+
Australian Magpie	*Gymnorhina tibicen*				+				+
Australian Raven	*Corvus coronoides*			+					+
Richard's Pipit	*Anthus novaeseelandiae*								+
Mistletoebird	*Dicaeum hirundinaceum*								+
White-backed Swallow	*Cheramoeca leucosternus*						+		+
Welcome Swallow	*Hirundo neoxena*	+							+
Tree Martin	*Cecropis nigricans*	+	+	+	+	+			+
Rufous Songlark	*Cinclorhamphus mathewsi*								+
Silvereye	*Zosterops lateralis*	+	+	+		+		+	+
Number of species		13	10	19	17	19	9	24	
Total number of species recorded = 74									

R = species recorded during an RAOU excursion in June 1989 (R. van Delft, personal communication) and N = recorded during Western Australian Naturalists Club excursions in October 1992 (H. and K. Frederiksen, personal communication) and August and October 1995 (R. Roe, personal communication), but not during earlier sampling.
Opp. = opportunistic sightings, away from detailed sampling quadrats.
Nomenclature and order follows Christidis and Boles (1994).

The topographic complexities of the area are reflected by the soil patterning and hence patterns in the species-rich vegetation. Although there are few comparable studies, the list of 573 species recorded at Boonanarring is similar to that recorded from John Forrest National Park (590+ species) (Mattiske and Associates 1991; Armstrong and Muir 1994; Foulds and Parsons 1996), although the latter is a rather smaller area (*ca* 2550 ha) but more intensively studied. The list from Boonanarring is also comparable with the 624 species recorded in and around 93 quadrats (each 10 x 10 m, across a study area of about 2400 km^2) in the Moore River to Jurien Sandplain Survey (Griffin and Keighery 1989).

The records of *Laxmannia omnifertilis, Ecdeiocolea monostachya, Banksia chamaephyton, Grevillea saccata, Isopogon adenanthoides, Isopogon linearis* and *Pileanthus filiformis* are the southern most for these taxa and are further evidence of the influence of the kwongan vegetation boundary. Conversely, the northern-most records of *Schizaea fistulosa, Eriachne ovata, Borya scirpoidea, Laxmannia squarrosa, Gompholobium scabrum, Agonis linearifolia, Eucalyptus marginata* ssp. *thalassica, Homalospermum firmum, Kunzea ericifolia* and *Pericalymma ellipticum* indicate the influence of the Darling Province flora. The number of vascular plant species recorded for Boonanarring Nature Reserve will undoubtedly increase with further sampling during other times of year and when less accessible parts of the reserve are studied.

A unique feature of the reserve is the large number of taxa of *Eucalyptus* (9, including two subspecies), *Banksia* (11), and *Acacia* (15). Reasons for this are unknown but can be attributed in part to the mosaic of soil and vegetation associations. Many of the more unusual species such as *Eucalyptus lane-poolei* were found in transitional zones or ecotones, particularly where Karamal and Moondah soils adjoin.

TABLE 7

Mammal species recorded at each sample site on Boonanarring Nature Reserve, February to August 1986.

SPECIES	SITE 1	2	3	4	5	6	7	RECORDED OPPORTUNISTICALLY
Tachyglossus aculeatus			D	D				D
Sminthopsis griseoventer	X	X						*
Tarsipes rostratus	X	X	X	X				
Macropus fuliginosus	S	S	X	X	S	S	S	X
Macropus irma	X			X				X
Nyctinomus australis								X
Nyctophilus geoffroyi								X
Nyctophilus gouldi								X
Chalinolobus gouldii								X
Vespadelus regulus					X			X
Pseudomys albocinereus	X	X	X	X	X	X		
Mus musculus	X	X	X	X	X	X		
Vulpes vulpes								X
Felis catus								X
Oryctolagus cuniculus								X
Canis familiaris								S

X = capture or sight record
S = scats, tracks
D = diggings
* = *Sminthopsis* sp.

Opportunistic records were made away from the seven sample sites. A description of the vegetation at each site is given in Appendix 1. Taxonomic order of native species follows Strahan (1995).

The reserve contains the most extensive example of the poorly conserved *Banksia* woodlands on Dandaragan soils (the Cullala complex). Nearby, on the Swan Coastal Plain, Moore River National Park also supports large areas of *Banksia* woodland, but these occur on Bassendean dunes of deep grey sand. The rest of the national park consists of subdued swales supporting primarily wet heaths. It has been estimated (Beard and Sprenger 1984) that *Banksia* woodlands in Western Australia originally covered 6229 km^2 of which 61 per cent is now alienated land where the vegetation is presumed cleared. All of an estimated 680 km^2 of *Banksia* woodland with scattered *Eucalyptus* is now on alienated land. Approximately one third of all *Banksia* woodlands were found on the Dandaragan Plateau, reaching an optimum on the Swan Coastal Plain between Muchea and Cataby and extending northward along the Dandaragan Plateau to the middle of Watheroo National Park (Beard 1989). Hopper and Burbidge (1989) estimated that only 7 per cent of the original 281 000 ha of *Banksia* woodland on the Swan Coastal Plain south of Lancelin were on conservation reserves. *Banksia* woodlands in general are under threat from rapid urban and rural development and degradation owing to weed invasions and recreational usage.

Boonanarring Nature Reserve contains extensive areas of *Banksia* woodland with *Eucalyptus todtiana* and *E. lane-poolei*. With further survey utilizing quadrat-based data, the two *Banksia* woodland associations described could be redefined based on the understorey species composition. A quantitative analysis of the vegetation using quadrats would be expected to confirm analyses elsewhere (Havel 1968; Dodd and Griffin 1989) that soil leaching and moisture availability are the major determinants of variability within the *Banksia* woodlands. The species richness of unbounded sampling sites within our study site ranged from 68 at site 2 to 108 at site 1 (mean = 92). These cannot be directly compared with bounded sites but indicate that *Banksia* woodlands within Boonanarring Nature Reserve may be more species-rich than those reported in other studies. In 83 quadrats, each 400 m^2, in *Banksia* woodland in the Perth region (Dodd and Griffin 1989) perennial species richness varied from 16 to 53 species per site. Dominant woody families found within the *Banksia* woodlands were Myrtaceae, Proteaceae, Papilionaceae and Epacridaceae, indicative of the influence of Kwongan flora species. *Allocasuarina fraseriana*, usually a co-dominant in *Banksia* woodlands south of Yanchep National Park (Beard 1989), is apparently absent from Boonanarring Nature Reserve.

Jarrah forest on Boonanarring Nature Reserve is extensive and basically similar to that on the Swan Coastal Plain and Darling Scarp in being rich in species. Jarrah forest is relatively well represented on conservation reserves, being the predominant vegetation association within John Forrest National Park, Moondyne Nature Reserve and Walyunga National Park. It is also widespread in State forest. The jarrah forest types found in the reserve correlate strongly with soil type and landform, in the manner described by Havel (1975a). The best developed, taller jarrah forest on the gravelly uplands has been heavily exploited for timber at unknown times in the past. Stands of *Banksia grandis* and *Dryandra sessilis* often occur nearby, depending on soil depth and slope. On the deep, sandy plains and swales between laterite breakaways the slower growing, straggly jarrah open mixed woodland (vegetation Type 7) appears to have been affected in some areas by severe wildfires. In burnt vegetation east of site 7 the understorey is dominated by *Stirlingia latifolia* in stark contrast to the more species rich unburnt site. The establishment of permanent monitoring quadrats within areas that are to be prescription burnt may indicate whether species diversity is affected in the long term. Although Bell and Koch (1980) suggest that richness and diversity are not reduced by fire in jarrah forest, their study was carried out in different vegetation types in higher rainfall areas to the south, and the effect of site to site variation is not clear from their data. There is still a need to follow individual sites through time.

The distribution of wandoo woodland is limited within the reserve, being restricted to areas where the Gingin Scarp adjoins the Moondah soils unit. At these junctions massive exposed consolidated laterites with heavy textured soils occur over clays which remain wet in winter and bake over summer. Although limited in size, the wandoo woodlands may prove, with further sampling, to be habitat for a number of flora and fauna species not occurring in other parts of the reserve.

Fishes

The one species collected (*Edelia vittata*) is within its known range, which is from the Phillips River on the south coast to the Moore River, a little to the north of our study area (Allen 1982). More extensive sampling, using a broader range of techniques to detect secretive and nocturnal fish, would probably reveal the presence of other species.

Frogs and Reptiles

A reasonably diverse herpetofauna, comprising five frog and 20 reptile species, was detected in the study area. Data from the Swan Coastal Plain and Darling Range near Perth (How and Dell 1994) suggest that further work at Boonanarring would reveal the presence of additional species. All species detected at Boonanarring are within their known geographic ranges. However, two records are of particular significance. Until recently, *Vermicella calonotos* was declared endangered. It still has only an extremely restricted geographic distribution in the south-west, from Lancelin to Mandurah (Storr *et al.* 1986; Bush *et al.* 1995). Within this range, the species has previously been recorded only rarely outside the coastal belt (Quindalup and Spearwood Dune Systems of McArthur and Bettenay (1960)). These records are from the coastal plain at Bullsbrook, Caversham and Riverton, and in *Banksia* woodland at Mooliabeenee on the Dandaragan Plateau (Bamford 1985, 1986; Storr *et al.* 1986). Our record from sands at the base of the Gingin Scarp is an additional inland record. The second record of particular interest is the Carpet Python, *Morelia spilota imbricata*, which is declared 'in need of special protection'.

Several other records are also of some interest. Three species of *Vermicella* (small fossorial snakes) were detected at one site (Site 1) at the base of the Gingin Scarp. No microhabitat differences were apparent, suggesting that the three are syntopic. A total of five species of *Vermicella* are known to occur sympatrically on the coastal plain from Perth to the Moore River (Storr *et al.* 1978); interestingly, all five occur in a relatively small area at Bold Park in the western suburbs of Perth (How and Dell 1994).

Our list is clearly not exhaustive since the herpetofaunal survey was brief and trapping was restricted to one season. There was also a difference in sampling effort between sandy and lateritic sites (no pit-trapping) and overall, capture rates were low; for example, seven species were represented by one specimen recorded at one sample site only. Thus apparent absence from a site may not be real. Further sampling in warmer weather would have resulted in more species being detected, and at more sites.

Nevertheless, several broad trends were indicated. Seven species were detected only on deep sands at the base of the Gingin Scarp and on the Dandaragan Plateau: *Heleioporus eyrei*, *Pletholax gracilis*, *Vermicella bimaculata*, *V. calonotos*, *V. semifasciata*, *Notechis curtus* and *Pseudonaja affinis*. The first five are burrowing species typically associated with sandy surfaces on the coastal plain between the Swan and Moore Rivers (Storr *et al.* 1978; How and Dell 1994; Tyler *et al.* 1994), while the last two are non-burrowing snakes.

Four of these species were absent from our sites on the Dandaragan Plateau: *Heleioporus eyrei*, *Pletholax gracilis*, *Vermicella calonotos* and *Pseudonaja affinis*. However, the first three have been previously recorded in *Banksia* woodland about 10 km away at Mooliabeenee (Bamford 1985). *P. affinis* has been recorded some 10 km south-east of there, near Bindoon (Western Australian Museum records).

Four species were detected only at sites on laterite or lateritic sands in gullies between lateritic ridges: *Crenadactylus ocellatus*, *Morethia obscura*, *Tiliqua rugosa* and *Pogona minor*. However, all are known from the adjacent northern Swan Coastal Plain (Swan River to Moore River), where with the exception of *C. ocellatus*, they are common (Storr *et al.* 1978). *C. ocellatus* is scarce on the Swan Coastal Plain because of the paucity of suitable rocky habitat; the species is considered to be more common on the adjacent Darling Scarp and Plateau (Storr *et al.* 1978). Dell (1983) recorded it from 'woodland' and 'granite' on the Darling Scarp near Perth.

The list of species includes four reptile species endemic to the west coastal sandplains from Geographe Bay to North West Cape: *Pletholax gracilis gracilis*, *Lerista praepedita*, *Tympanocryptis adelaidensis adelaidensis* and *Vermicella calonotos*.

A much richer herpetofauna than that detected by our survey is predicted to occur on the reserve. How and Dell (1994) have demonstrated strong patterning of reptiles across landscape gradients near Perth, and so one would expect significant differences between the lateritic upland, scarp deep sand sites within Boonanarring, resulting in a rich reptile fauna. Records from a three-year pitfall trap study near Mooliabeenee (Bamford 1985), 10 km south-east of the reserve, provide a comparison with our list (Appendix 7). From *Banksia* woodland alone, Bamford (1985) recorded an additional four frog and 16 reptile species. On current knowledge of the geographic distribution, habitat associations and status of each of these species, all could occur on the reserve. The four frogs are most easily detected after winter rains when breeding, and our failure to detect any of these species on the reserve is probably related to our survey work being restricted to autumn. Two points should be made, however. The frog *Crinia georgiana* has not been collected north of Gingin (Tyler *et al.* 1994), but the Mooliabeenee record indicates that the species occurs inland in this region. *Lerista christinae* is an uncommon species and hence, if present at Boonanarring, may be sparsely distributed. Prior to the Mooliabeenee records, it was known only from sandplains near Badgingarra and near Eneabba (Storr *et al.* 1981).

We recorded four species on the reserve that are additional to Bamford's (1985) list from near Mooliabeenee: *Crenadactylus ocellatus*, *Lerista distinguenda*, *Vermicella bimaculata* and *Pseudonaja affinis*. The presence of *C. ocellatus* in the study area appears to be related to the presence of suitable rocky habitat, and the presence of *R. glauerti* related to the availability of surface water in Boonanarring Brook.

A search of unpublished Western Australian Museum records (to August 1986) from the area within a 25 km radius of Gingin yielded records of an additional two frog and nine reptile species. These are listed in Appendix 8, and are possible additions to the list for Boonanarring. Of note is that the reserve is very close to the known northern limit of *Leiolopisma trilineatum* at Gingin Brook (Storr *et al.* 1981) which has its head-waters adjacent to the southern boundary of the study area.

Birds

We detected over 60 per cent of the 120 terrestrial species recorded in the surrounding 1° x 1° block during the RAOU Atlas of Australian birds survey (Blakers *et al.* 1984). The RAOU survey was of a much larger area than our study site, extended over five years, involved many observers in all seasons and covered a much greater range of habitat types. The number of species detected in our study site suggests that its avifauna is reasonably rich for this general area.

Most (65 per cent) of the species we recorded are of widespread occurrence, 28 per cent are Bassian (southern) species and 7 per cent are Eyrean (arid zone) species.

Few site specific data exist with which to make meaningful comparisons of community structure. However, in terms of species composition, the avian communities of the eucalypt woodland sites at Boonanarring appear more similar to those of eucalypt woodlands in the Yanchep area on the Swan Coastal Plain

(Burbidge *et al.* unpublished data) than to those of the Darling Range jarrah forests (Wykes 1985; Worsley Alumina Pty Ltd 1985). Not surprisingly, there are numerous bird species in common between each of these sites, but there are also a number of differences. For example, Golden Whistlers were common in the Darling Range sites, but they were absent from the Yanchep and Boonanarring sites (although there is one opportunistic record of this species in eucalypt woodland at Boonanarring, they were probably once at Yanchep (Storr and Johnstone 1988) and may have once been more common at Boonanarring). On the other hand, Rufous Whistlers were commonly recorded at Yanchep and Boonanarring but only rarely recorded in the Darling Range sites. Similarly, Red-capped Parrots were more common in the Darling Range sites than at Yanchep or Boonanarring, whereas the opposite was true of the Australian (Port Lincoln) Ringneck. Brown-headed Honeyeaters were absent from the Darling Range sites whereas White-naped Honeyeaters were rarely recorded at Yanchep or Boonanarring. Yellow Robins, White-browed Scrubwrens, Red-winged Fairy-wrens and Western Rosellas were recorded only at some of the Darling Range sites; on the other hand, some species preferring more open habitats (e.g. Singing Honeyeater) were not recorded in the Darling Range sites, although this species is known to occur elsewhere in the Darling Range, particularly around towns (I. Abbott personal communication).

In *Banksia* woodland about 10 km south-east at Mooliabeenee, Bamford (1985, 1986) recorded about twice as many species per site as we did in *Banksia* woodland. However, his was a detailed study carried out over all seasons over three years, and his sample areas were much larger than ours. All species recorded in *Banksia* woodland by us were also recorded at Mooliabeenee. Boonanarring *Banksia* woodland sites are, however, very similar in bird species richness and composition to those at Yanchep National Park (Burbidge *et al.* unpublished data). The most noticeable differences between these two areas are that both Splendid Fairy-wrens and New Holland Honeyeaters were absent from the *Banksia* sites at Boonanarring, presumably because of the sparser shrub layer and absence of stands of *Calothamnus*.

Heathland sites at Yanchep (Burbidge *et al.* unpublished data) are richer in bird species than are heathland sites at the Southern Beekeepers Reserve (Burbidge and Boscacci 1989) or those in the Boonanarring Nature Reserve. Most of the bird species in the Boonanarring heaths were also recorded in heaths in the other two areas.

Red-tailed Black-Cockatoos occurred in the area in the past, and as occasional visitors in recent times (Storr 1991). We did not record this species, but there seems no reason that it could not occur, unless suitable nest sites have been destroyed.

Mammals

Our record of *Nyctophilus gouldi* is of biogeographical interest. It is the first from the Dandaragan Plateau and indicates the species' presence at the northern extremity of the Darling Range. There is a single record of the species from the Wheatbelt (Jibberding, 1982 - Western Australian Museum records) and an old record (1949) from the northern Swan Coastal Plain at Muchea (Kitchener and Vicker 1981), 40 km south of Gingin. However, all other Western Australian records are from the forests and woodlands of the mesic south-western corner, from the Darling Scarp near Perth (Kalamunda, 1970) south to Pemberton (1980) (Kitchener and Vicker 1981; Western Australian Museum records). The species has been recorded as far east as Frankland (Christensen *et al.* 1985) on the edge of the south-west forest block.

An additional four native ground mammals have recently been recorded near Mooliabeenee, approximately 10 km south-east of the reserve. These are *Cercartetus concinnus*, *Sminthopsis dolichura*, *Sminthopsis granulipes* and *Isoodon obesulus* (diggings only) (Bamford 1985). All were recorded in *Banksia* woodland in the period 1983 to 1985; the first three were pit-trapped (Bamford 1985). On current knowledge of the geographical distribution and habitat associations of each species, the first three may occur on the reserve and further pit-trapping, particularly in spring, is required to clarify this. The presence of *I. obesulus* is less likely. On the Darling Scarp near Perth this species prefers dense heath understorey at the breakaway edge (Dell and How 1988) but there is little of this habitat at Boonanarring. Some further discussion is given below.

The effects on populations of small mammals of the extensive burning that has occurred on the reserve in recent years are unknown, but may be relevant to the apparent absence of at least one species, *Cercartetus concinnus*. Bamford (1985, 1986) found that small mammals in *Banksia* woodland at Mooliabeenee were more severely affected by fire than either reptiles or birds. Response to fire (susceptibility) was found to vary considerably between different species and of the five species monitored, *Cercartetus concinnus* was most adversely affected. It, along with *Pseudomys albocinereus*, was not recorded at all immediately following fire and took the longest time to reappear in samples after fire (three years). Effects of fire on a range of species near Perth are described in Harris (1995).

It should also be noted, however, that our survey was conducted in autumn when few plant species were flowering. *C. concinnus* is nectarivorous and insectivorous (Strahan 1983) and although little is known of the species' population biology, it is possible that the species is more easily detected in spring and early summer, corresponding with peaks in food sources. Kitchener and Vicker (1981) list a 1962 specimen of *C. concinnus* from Bindoon Creek. Kitchener *et al.* (1978) concluded that the species appeared to be uncommon on the northern Swan Coastal Plain. Dell (1983) listed *C. concinnus* as moderately common on the Darling Scarp, occurring mainly in the heath understorey of wandoo and jarrah woodlands.

Sminthopsis dolichura is predicted to occur on the reserve. In addition to the Mooliabeenee records (two specimens pit-trapped in 1985), there is also one specimen (1979) from *Banksia* woodland near Gingin (Kitchener *et al.* 1984; Western Australian Museum records). At Mooliabeenee, the species was recorded infrequently and was less abundant than *S. griseoventer* (Bamford 1985). However, unlike *S. griseoventer*, *S. dolichura* was also pit-trapped in jarrah forest on laterite (M.J. Bamford, personal communication 1986) and this vegetation type is extensively represented in the reserve.

Compared with *S. dolichura*, the local distribution and status of *S. granulipes* in the region of the reserve is less easily assessed. Most records of *S. granulipes* since 1920 have been from the Western Australian wheatbelt and Eastern Goldfields where characteristic habitat is low shrubland and surfaces of sand and sandy loam are preferred (Kitchener and Vicker 1981; Kitchener in Strahan 1983). However, Boonanarring Nature Reserve is close to several known capture sites for the species: *Banksia* woodland at Mooliabeenee (Bamford 1986), heathland communities in Badgingarra National Park (1979; Kitchener and Vicker 1981), heathland near Cataby (1993; M.J. Bamford personal communication) and at Eneabba (1981; Western Australian Museum records). It is noteworthy, however, that the Mooliabeenee record is of a single juvenile from a three-year program of monthly pit-trapping (M.J. Bamford personal communication) which suggests that the species is currently common locally, at least in *Banksia* woodland. The only other record from the vicinity of the reserve is an old (1934) record from nearby Gingin (Kitchener and Vicker 1981) for which habitat information is unavailable. Of interest also is that the species has previously been recorded at one locality on the coastal plain north of Perth, in low heath on sandy soils in the coastal belt at Cockleshell Gully Reserve (1973, 1974; Chapman *et al.* 1977). However, it was not recorded in more southerly (Kitchener *et al.* 1978) or more recent (Burbidge and Boscacci 1989) surveys on the coastal plain, although pit-trapping was not deployed in the former study. The most likely habitat for the species on the Boonanarring Nature Reserve would appear to be the dense heathlands on sandy soils in the eastern section, although it may also be sparsely distributed in *Banksia* woodland. If *S. granulipes* is present, the reserve would provide additional unalienated habitat in the westernmost part of the species' geographic range.

Bamford's (1985) record of *Isoodon obesulus* near Mooliabeenee, on available data, is the northernmost record of this species in the south-west, although sub-fossil records extend further north (Strahan 1995). Shortridge (1909) in Kitchener *et al.* (1978) stated that *I. obesulus* extended as far north as the Moore River, although it was scarce in that area. More recently, the species was recorded on the northern Swan Coastal Plain as far north as Wanneroo and Yanchep National Park in 1977/1978 and 1988; here, it was found to inhabit predominantly thickly vegetated damp situations, typically dense shrubland of *Melaleuca* and *Kunzea ericifolia* over low heath and sedgeland (Kitchener *et al.* 1978; Burbidge *et al.* unpublished). On the Darling Range near Perth, the species was reported to inhabit dense riparian vegetation (Dell 1971; Dell and How 1988). There appears to be very limited suitable habitat on the reservet o support *I. obesulus* and thus its occurrence seems unlikely. However, a permanently moist area supporting *Melaleuca* woodland and sedgeland in the upper reaches of Boonanarring Brook warrants further inspection.

An interesting absence from our list is *Rattus fuscipes*. Similarly, the species was not detected near Mooliabeenee by Bamford (1985, 1986) and within Yanchep National Park it is now restricted in occurrence (Burbidge *et al.* unpublished) despite its having once been common at this latter site (How 1978). Another recent survey (Ninox Wildlife Consulting 1991) failed to detect this species in John Forrest National Park on the Darling Scarp near Perth. Previously, we have found the species to be readily trappable in pit-traps near Cervantes (Burbidge and Boscacci 1989). Its absence, specifically from our sites at the base of the Gingin Scarp, suggests that immediately north of Perth the species may be restricted to the Coastal Plain and possibly declining.

Management Issues

In recent years, two major activities causing deterioration of the conservation values of the reserve have been gravel mining and wood cutting.

Gravel has been removed from several parts of the reserve on several occasions during recent years. Gravel mining and construction of roads within the reserve for the extraction of gravel has left problems of rehabilitation. Gravel has been extracted from the reserve with little apparent regard for hygiene precautions to prevent the spread of dieback (*Phytophthora*) and with little apparent regard for the conservation status of the land. Some such areas need to be rehabilitated to CALM and Main Roads Department standards.

Wood cutting for housing, fencing, etc., has occurred in the area since early this century (R. Roe, personal communication). However, wood cutting has continued into recent times, resulting in the creation of numerous tracks with no regard whatsoever to conservation values. Most recent wood cutting appears to have been for firewood and occurred in winter, when the risk of the introduction and spread of dieback is greatest.

Management will need to address the issue of rationalizing the track system which has become excessive as a result of gravel mining and wood cutting activities. It may be appropriate to mechanically rip some tracks to aid in revegetation and reduce internal fragmentation in the reserve.

A major management problem on this reserve relates to the control of fire. Given the very high conservation values of the reserve, particularly for flora, fire management must be a high priority (Harris 1995). In relatively recent times, large segments of the reserve have been burnt with little apparent regard for possible implications concerning the conservation values of the area. For the area to be managed adequately with regard to fire, planning needs to take into account the need to contain fires to a manageable area and to ensure that entire habitat types are not burnt at the one time. From studies at nearby Mooliabeenee and near Cataby, some small ground mammals (*Sminthopsis*, *Tarsipes*) have been shown to prefer long (> 10 years) unburnt vegetation (M. J. Bamford personal communication), and it is possible that populations of small mammals might not be maintained in the long term in the face of more frequent burning. Recently burnt areas can be colonized, but only if there is a population in a nearby long unburnt area.

Management needs to continue to take into account the presence of the declared endangered and priority flora and fauna species present. Much research needs to be done on the effects of fire on rare species and communities, but for a number of species, sufficient knowledge is already available to guide management. For example, *Grevillea saccata* is known to be killed by fire, and therefore areas containing this species need to be managed accordingly. Such occurrences should also be taken into account in any review of the track system (and therefore fire breaks/ access), to minimize the risk of unnecessary burning of *G. saccata* populations. Research needs to be undertaken on the appropriate fire regime for this species.

It is unknown to what extent feral animals may be a problem, but they are unlikely to be a problem for the restricted *Vermicella calonotos*, as this species is fossorial. Foxes may well be a problem for small ground mammals in particular, and fox baiting could be considered as a management option in the future, as a reserve of this size should be capable of maintaining viable populations of small mammals in the absence of foxes. While some weed species were detected during our survey, none appears to be a serious problem at present, and virtually all are confined to tracks and edges except in the Boonanarring Brook head-waters, where weeds were apparently introduced by marijuana cultivators. The situation should be monitored, and action taken if weed invasion increases.

Some areas, particularly along Boonanarring Brook, may be susceptible to invasion by *Phytophthora*, as many susceptible species are present in the area and the climate is suitable for dieback disease.

Consideration of the issues discussed above highlights the need for a management plan for this highly significant reserve.

RECOMMENDATIONS

1. Because of the very high conservation value of the reserve, particularly with regard to flora, it is strongly recommended that it be reclassified from 'C' Class to 'A' Class Nature Reserve. Water reserve A22602 and the area around the head of Gingin Brook should be included in the nature reserve.

2. Rationalization of the system of roads and tracks and rehabilitation of some tracks is required.

3. A fire management plan, which takes into account the known high conservation values of the reserve, is required. Such a plan should include some areas in which burns are not planned. Further research is needed on species such as *Grevillea saccata* which are killed by fire, to determine appropriate fire regimes.

4. Areas mined for gravel require adequate rehabilitation.

5. Permanent vegetation quadrats (10 m x 10 m) should be established within each vegetation type to assess the effects of long-term change, including the effectiveness of management practices.

6. A management plan, taking into account the high conservation values, should be prepared for the reserve.

ACKNOWLEDGEMENTS

We wish to thank the Western Australian Museum for access to unpublished locality data, A. Danks, J. Rolfe and J. Raines for assistance in the field, E.A. Griffin, S.D. Hopper, A.P. Brown, W. Muir and L. Talbot for access to unpublished data on plant species occurrences, and members of the Royal Australasian Ornithologists Union (WA Group) and members of the Western Australian Naturalists' Club (particularly Helen and Kel Frederiksen) for assistance with supplementary surveys. Fish traps and advice on catching methods were provided by R.P. Jaensch.

I. Abbott, J. Dell, W. Loneragan and N. Marchant provided numerous useful comments on a draft of this paper.

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APPENDIX 1

Descriptions of vegetation and soils at each sample site on Boonanarring Nature Reserve.

Quadrat 1

Open woodland A of *Eucalyptus calophylla* and *Nuytsia floribunda* with occasional *E. todtiana* over open scrub of *Allocasuarina humilis, Jacksonia sternbergiana, Hakea trifurcata, Xanthorrhoea preissii* and *Adenanthos cygnorum* over low heath C of mainly *Calothamnus sanguineus* and *Banksia candolleana* over low sedges and herbs.

Light grey sand over brown sand on western facing gentle slope.

Quadrat 2

Open low woodland B of *Banksia menziesii, B. attenuata, B. prionotes, Eucalyptus todtiana* and occasional *E. lane-poolei* over low heath C of *Acacia lasiocarpa, Conospermum stoechadis, Calothamnus sanguineus* and *Xanthorrhoea preissii* over low sedges and herbs with occasional emergent *Jacksonia sternbergiana* and *Allocasuarina humilis.*

Dark red-brown sand over laterite on western facing slope.

Quadrat 3

Low woodland A/B of *Banksia menziesii* and *B. attenuata* with occasional *B. grandis, Eucalyptus todtiana* and *Nuytsia floribunda* over low heath C of *Xanthorrhoea preissii, Stirlingia latifolia, Banksia candolleana, Allocasuarina humilis* with emergent *Adenanthos cygnorum* and *Jacksonia floribunda* over low sedges and herbs with patches of bare ground.

Yellow sand over dark brown coarse sand in gently undulating topography.

Quadrat 4

Open low woodland B of *Banksia menziesii* and *B. attenuata* with occasional *Eucalyptus todtiana* over low heath C of *Hibbertia hypericoides, Eriostemon spicatus, Petrophile ericifolia* and *Xanthorrhoea preissii* over low sedges and herbs.

Yellow-grey sand over laterite in gently undulating topography.

Quadrat 5

Low woodland A dominated by *Eucalyptus marginata* with occasional *E. calophylla, E. todtiana* and *Banksia grandis* over open low scrub A of *Xanthorrhoea preissii* and *Acacia* sp. over low heath C/D.

Brown sandy loam over laterite and laterite over black rich sand in very gently undulating topography.

Quadrat 6

Scrub of *Allocasuarina humilis, Adenathos cygnorum* and *Hakea trifurcata* with emergent low, *Eucalyptus decurva* and *E. todtiana* over low heath C of *Xanthorrhoea preissii, Calothamnus sanguineus, Petrophile* spp., *Hakea* spp. and *Allocasuarina humilis* over low sedges and herbs.

Grey sand over laterite on the crest of a hill.

Quadrat 7

Low woodland A of *Eucalyptus marginata* and *E. calophylla* over dwarf scrub C of *Petrophile ericifolia, Xanthorrhoea preissii* and *Acacia pulchella* over low heath D of *Hibbertia* spp., *Hakea* spp., and very open low sedges and herbs.

Deep yellow loamy sand over ? laterite on gentle easterly slope.

APPENDIX 2

Description of trap layout used in the assemblage survey at the Boonanarring Nature Reserve, March 1986.

Pitfall traps (12.5 x 60 cm PVC tubing) were arranged 10 m apart in lines. A flywire drift fence (30 cm high) was placed between all pits and across the top of every pit in the line. At each of Sites 1 to 4 a line of 6 pits and 2 lines of 3 pits were laid out. The lines of 3 pits were about 50 m apart and these lines were 100-150 m from the line of 6 pits at each site. Site 7 had 2 lines of 6 pits, 150 m apart.

Sites 5 and 6 (hard lateritic surfaces) had three lines of medium Elliott traps (32 x 10 x 8 cm, Elliott Scientific Company, Upwey, Victoria) with a space of 10 m between trap locations in a line. At each site, one line had a drift fence (identical to those used for the pits) placed on a 30 cm wide scrape that had been made through the vegetation with a 'Rakho' (a hand implement with features of a rake and a hoe). Traps were placed at each end of this fence and, at 10 m intervals along the fence, traps were placed on alternate sides of the fence, facing in opposite directions. The fenced line therefore had ten traps at six locations along the fence. The second line had ten traps placed at 10 m intervals along a scrape similar to that at the first line, but without the fence. The third line consisted simply of ten traps placed at 15 m intervals. All Elliott traps were baited with a standard mixture of peanut butter, honey and rolled oats.

APPENDIX 3

Western Australian Museum accession numbers of reptiles and mammals collected on the Boonanarring Nature Reserve.

Frogs	
Myobatrachus gouldii	R 1694647
Heleioporus eyrei	R 494651
Reptiles	
Crenadactylus ocellatus	R 594640
Aprasia repens	R 994645, 1194638
Delma fraseri	R 194634, 794635 1594641, 1494642, 1994639
Pletholax gracilis	R 894649
Pygopus lepidopodus	R 694636
Cryptoblepharus plagiocephalus	R 1294646
Ctenotus fallens	R 1894643, 2094654
Lerista distinguenda	R 394650
Lerista praepedita	R 1094655
Morethia obscura	R 1394637
Tympanocryptis adelaidensis	R 294648
Vermicella bimaculata	R 2294653
Vermicella calonotos	R 2394652
Vermicella semifasciata	R 2194644
Notechis curtus	R 1794656
Mammals	
Sminthopsis griseoventer	M 25676, M 25677, 25678, 25679
Tarsipes rostratus	M 25697, 25698
Pseudomys albocinereus	M 25699
Mus domesticus	M 25700 (5 specimens)
Nyctophilus gouldi	M 25680
Nyctophilus geoffroyi	M 25675

APPENDIX 4

List of vascular plants found on Boonanarring Nature Reserve and water reserve A22602, showing occurrence at each sample site or as opportunistic collections. Order and nomenclature follows Green (1985). Introduced/naturalized species are denoted by an asterisk (*). Initials denote collectors: AB = A.H. Burbidge, ASG = A.S.George, BM = W. Muir, EAG = E.A. Griffin floristic site records (Griffin 1994 and E.A.Griffin personal communication), GK = G.J. Keighery, JA = J.J. Alford, LR = J.L. Robson, MB = M. Brooker, RR = R. Roe and WA Naturalists Club, SH = S.D. Hopper. Records with initials only represent sight records. For descriptions of sites see Appendix 1.

NAME	COLLECTION NUMBER	SITE 1	2	3	4	5	6	7	OPP. COLL.
LYCOPODIACEAE									
Phylloglossum drummondii Kunze	GK13274							+	
SELAGINELLACEAE									
Selaginella gracillima (Kunze) Alston	GK14317								+
SCHIZAEACEAE									
Schizaea fistulosa Labill.	GK10254						+	+	+
ADIANTACEAE									
Cheilanthes austrotenuifolia H. Quirk & T.C. Chambers	JA								+
DENNSTAEDTIACEAE									
Pteridium esculentum (G. Forster) Cockayne	JA								+
ZAMIACEAE									
Macrozamia riedlei (Fischer ex Gaudich.) C. Gardner	JA	+				+			
JUNCAGINACEAE									
Triglochin calcitrapa Hook.	JA								+
Triglochin centrocarpa Hook.	JA								+
Triglochin minutissima F. Muell.	JA								+
POACEAE									
* *Aira caryophyllea* L.	JA742							+	
Amphibromus neesii Steud.	GK14318								+
Amphipogon amphipogonoides (Steud.) Vick.	GK14319								+
Amphipogon laguroides R. Br.	GK14320								+
Amphipogon turbinatus R. Br.	AB/GK				+				
* *Briza maxima* L.	JA	+							
* *Briza minor* L.	JA								+
Danthonia occidentalis Vick.	GK10266						+		
Ehrharta longiflora Smith	RR								+
Eriachne ovata Nees	GK10269								+
Microlaena stipoides (Labill.) R. Br.	GK11068						+		
Neurachne alopecuroidea R. Br.	GK11065	+	+	+		+		+	
* *Pentaschistus airoides* (Nees) Stapf	GK10278							+	
Poa drummondiana Nees	JA752								+
Polypogon tenellus R. Br.	GK10277					+			
Stipa elegantissima Labill.	JA								+
Stipa macalpinei Reader	JA720		+						+
Stipa pycnostachya Benth.	GK11097						+		
Stipa trichophylla Benth.	JA							+	
* *Vulpia myuros* (L.) C. Gmelin	JA						+		
CYPERACEAE									
Baumea articulata (R. Br.) S.T. Blake	SH								+
Caustis dioica R. Br.	JA368,382,738	+		+	+				
Chorizandra enodis Nees	JA						+		
Cyathochaeta avenacea Benth.	EAG								+
Cyperus tenellus L. f.	GK14321								+
Gahnia ?lanigera (R. Br.) Benth.	GK14322								+
Isolepis marginata (Thunb.) A. Dietr.	GK10267								+
Isolepis stellata (C.B. Clarke) K.L. Wilson	GK11094						+		
Lepidosperma angustatum R. Br.	JA177,244,499 312,362	+		+		+	+	+	
Lepidosperma longitudinale Labill.	EAG								+
Lepidosperma scabrum Nees	EAG								+
Lepidosperma ?squamatum Labill.	JA266,378			+		+	+		
Lepidosperma tenue Benth.	JA258,355,383	+				+	+	+	
Mesomelaena pseudostygia (Kuek.) K.L. Wilson	JA384,298				+	+	+		+
Mesomelaena graciliceps (C.B. Clarke) K.L. Wilson	GK10044								+
Mesomelaena tetragona (R. Br.) Benth.	JA225, 358	+	+			+	+		

Appendix 4 (continued)

NAME	COLLECTION NUMBER	SITE 1	2	3	4	5	6	7	OPP. COLL.
Schoenus caespititius W. Fitzg.	JA315,GJK	+	+	+		+	+	+	
Schoenus clandestinus S.T. Blake	AB/GK				+				+
Schoenus curvifolius (R. Br.) Benth.	JA314,315 GK10246			+					+
Schoenus efoliatus R. Br.	GK11064				+				
Schoenus pedicillatus (R. Br.) Benth.	GK14323								+
Schoenus pleiostemoneus F. Muell.	JA219,347	+		+	+				
Schoenus rigens S.T. Blake	GK		+						
Schoenus subflavus Kuek.	JA								+
Tetraria capillaris (F. Muell.) J. Black	GK11091								+
Tetraria octandra (Nees) Kuek.	GK		+		+	+			
RESTIONACEAE									
Alexgeorgea nitens (Nees) Johnson & Briggs	JA215			+	+		+	+	
Ecdeiocolea monostachya F. Muell.	GK								+
Harperia lateriflora W. Fitzg.	EAG								+
Hypolaena exsulca R. Br.	JA218,371			+	+				
Lepidobolus preissianus Nees	JA399	+			+			+	
Leptocarpus ?coangustatus Nees	AB4060			+					
Lepyrodia muirii F. Muell.	JA		+						
Loxocarya 'aspera' Johnson & Briggs	JA215,350,368	+							
Loxocarya cinerea R. Br.	JA								+
Loxocarya fasciculata (R. Br.) Benth.	GK								+
Loxocarya 'lateritica' Johnson & Briggs	EAG								+
Lyginia barbata R. Br.	JA,GK	+		+	+				
Onychosepalum laxiflorum Steud.	EAG								+
Restio 'micrococodon' Johnson & Briggs	AB			+	+				
Restio 'sinuosus' Johnson & Briggs	EAG								+
CENTROLEPIDACEAE									
Aphelia cyperoides R. Br.	JA							+	
Centrolepis aristata (R. Br.) Roemer	GK								+
Centrolepis pilosa Hieron.	GK11142								+
Centrolepis polygyna (R. Br.) Hieron.	GK11892						+		
PHILYDRACEAE									
Philydrella pygmaea (R. Br.) Caruel	EAG								+
DASYPOGONACEAE									
Acanthocarpus preissii Lehm.	JA							+	
Calectasia cyanea R. Br.	JA268			+	+		+		
Dasypogon obliquifolius Lehm. ex Nees							+		
Lomandra caespitosa (Benth.) Ewart	JA181,163				+			+	
Lomandra hastilis (R. Br.) Ewart	EAG								+
Lomandra hermaphrodita (C.R.P. Andrews) C. Gardner	GK	+		+	+		+	+	
Lomandra aff. micrantha (Endl.) Ewart	GK						+		
Lomandra preissii (Endl.) Ewart	GK10052, JA180	+			+		+	+	+
Lomandra sericea (Endl.) Ewart	JA163	+				+	+	+	+
Lomandra suaveolens (Endl.) Ewart	EAG								+
XANTHORRHOEACEAE									
Xanthorrhoea drummondii Harvey	JA,GK	+	+	+	+	+	+	+	
Xanthorrhoea preissii Endl.	JA								+
PHORMIACEAE									
Dianella revoluta R. Br.	JA							+	
Typandra imbricata R. Br.	JA332					+			
ANTHERICACEAE									
Arnocrinum preissii Lehm.	GK								+
Arthropodium capillipes Endl.	GK								+
Arthropodium preissii Endl.	GK								+
Borya constricta Churchill	AB4269	+							
Borya scirpoidea Lindl.	JA								+
Borya sphaerocephala R. Br.	AB 4040								+
Chamaescilla corymbosa (R. Br.) F. Muell. ex Benth.	JA714				+				
Caesia micrantha Lindl.	JA								+
Caesia occidentalis R. Br.	GK10030								+
Corynotheca micrantha (Lindl.) MacBride	EAG								+
Johnsonia pubescens Lindl.	JA216,310	+		+	+				
Laxmannia omnifertilis G.J. Keighery	JA395	+							+
Laxmannia ramosa Lindl.	GK8044								+
Laxmannia sessiliflora Decne. subsp. *australis* Keighery	JA285	+					+	+	
Laxmannia squarrosa Lindl.	GK, JA	+					+		

Appendix 4 (continued)

NAME	COLLECTION NUMBER	SITE 1	2	3	4	5	6	7	OPP. COLL.
Sowerbaea laxiflora Lindl.	JA								+
Thysanotus anceps Lindl.	EAG								+
Thysanotus asper Lindl.	GK11970								+
Thysanotus patersonii R. Br.	JA								+
Thysanotus rectantherus N.H. Britton	GK11971,SH5828								+
Thysanotus sparteus R. Br.	JA			+					
Thysanotus thyrsoideus Baker f.	EAG								+
Thysanotus triandrus (Labill.) R. Br.	EAG								+
Thysanotus sp. (EAG2511)	EAG								+
Tricoryne elatior R. Br.	GK10293							+	+
COLCHICACEAE									
Burchardia multiflora Lindl.	SH								+
Burchardia umbellata R. Br.	JA392,739	+		+	+	+	+	+	
Wurmbea dioica (R. Br.) F. Muell	JA767								+
HAEMODORACEAE									
Anigozanthos humilis Lindl.	JA338	+	+	+	+	+		+	
Anigozanthos manglesii D. Don	JA								+
Anigozanthus pulcherrimus Hook.	BM								+
Blancoa canescens Lindl.	JA						+		
Conostylis aculeata R. Br. subsp. *aculeata*	JA151	+							+
Conostylis aurea Lindl.	JA151,179,376			+	+			+	
Conostylis festucacea Endl.	EAG								+
Conostylis setigera R. Br.	EAG								+
Conostylis juncea Endl.	AB 4062 JA159,389					+		+	
Conostylis teretifolia J.W. Green subsp. planescens Hopper	JA 226,322 JA147,300	+	+	+	+	+	+	+	
Haemodorum laxum R. Br.	EAG								+
Haemodorum loratum T.D. Macfarl.	JA	+	+	+	+	+	+	+	
Haemodorum spicatum R. Br.	JA501			+					
Haemodorum venosum T.D. Macfarl.	EAG								+
Phlebocarya ciliata R. Br.	JA753								+
Phlebocarya filifolia (F. Muell.) Benth.	JA754,SH5823			+	+				+
Tribonanthes australis Endl.	GK								+
Tribonanthes violacea Endl.	JA								+
HYPOXIDACEAE									
Hypoxis occidentalis Benth	JA								+
IRIDACEAE									
* *Gladiolus caryophyllaceus* (Burm. f.) Poiret	JA,AB4265				+				+
Orthrosanthus laxus (Endl.) Benth.	AB4222,JA239					+			
Patersonia juncea Lindl.	AB,JA145							+	
Patersonia occidentalis R. Br.	JA149,345,	+		+			+	+	+
Patersonia cf. *occidentalis* R. Br.	SH5810								+
* *Romulea rosea* (L.) Ecklon	GK								+
ORCHIDACEAE									
Caladenia 'arenicola' Hopper & Brown	SH5496								+
Caladenia 'arenicola' Hopper & Brown x *'paludosa'* Hopper & Brown	SH5497								+
Caladenia deformis R. Br.	RR								+
Caladenia denticulata Lindl.	SH								+
Caladenia flava R. Br. subsp. *flava*	JA158,SH5486							+	+
Caladenia gemmata Lindl.	SH								+
Caladenia ixioides Lindl.	RR								+
Caladenia 'paludosa' Hopper & Brown	SH5497								+
Caladenia sericea Lindl.	JA247					+			+
Caladenia 'splendens'	SH 5494								+
Calochilus cf. *robertsonii* Benth.	SH								+
Corybas abditus D.L. Jones	SH								+
Diuris corymbosa Lindl.	SH,JA235					+			+
Drakaea glyptodon W. Fitzg.	SH5821								+
Drakaea livida J. Drumm.	RR								+
Elythranthera brunonis (Endl.) A.S. George	SH5927								+
Elythranthera emarginata (Lindl.) A.S. George	AB4065						+	+	
Eriochilus dilatatus Lindl. subsp. 'multiflorus' (Lindl.) Hopper & Brown	SH								+
Leporella fimbriata (Lindl.) A.S. George	SH,GK		+	+	+	+		+	+
Leptoceras menziesii (R. Br.) Lindl.	SH,GK								+
Lyperanthus nigricans R. Br.	JA154			+		+		+	
Microtis media R. Br.	RR								+
* *Monadenia bracteata* (SW.) T. Dur. & Schinz	GK11628						+		+

Appendix 4 (continued)

NAME	COLLECTION NUMBER	SITE 1	2	3	4	5	6	7	OPP. COLL.
Paracaleana nigrita (Lindl.) Bloxell	GK								+
Pterostylis aff. *nana* R. Br.	SH								+
Pterostylis recurva Benth.	JA321,SH								+
Pterostylis vittata Lindl.	JA318			+					
Thelymitra antennifera (Lindl.) Hook. f.	RR								+
Thelymitra benthamiana H.G. Reichenbach	SH								+
Thelymitra stellata Lindl.	R.Roe and M.Hancock							+	
CASUARINACEAE									
Allocasuarina humilis (Otto & Dietr.) L. Johnson	JA273, 503	+	+	+			+	+	
Allocasuarina microstachya (Miq.) L. Johnson	EAG								+
PROTEACEAE									
Adenanthos cygnorum Diels	JA215	+		+			+		+
Banksia attenuata R. Br.	JA		+	+	+				
Banksia burdettii Bake f.r	BM								+
Banksia chamaephyton A.S. George	JA						+		
Banksia grandis Willd.	JA			+		+		+	
Banksia ilicifolia R. Br.	JA	+							+
Banksia littoralis R. Br.	JA249,BM						+		
Banksia menziesii R. Br.	JA		+	+	+				
Banksia micrantha A.S. George	JA249,BM						+		
Banksia prionotes Lindl.	JA		+						
Banksia sphaerocarpa R. Br.	EAG								+
Conospermum acerosum Lindl.	JA718, GK10241								+
Conospermum glumaceum Lindl.	AB4039								+
Conospermum incurvum Lindl.	GK10237								+
Conospermum stoechadis Endl.	JA172, 743		+						
Dryandra bipinnatifida R. Br.	JA232						+		
Dryandra carlinoides Meisn.	EAG								+
Dryandra echinata A.S. George	JA294						+		
Dryandra kippistiana Meisn.	JA224	+							
Dryandra lindleyana Meisn. subsp. *lindleyana*	JA265,292	+	+	+		+	+	+	
Dryandra sessilis (Knight) Domin	JA								+
Dryandra shuttleworthiana Meisn.	EAG								+
Grevillea saccata Benth.	AB4069								+
Grevillea synapheae R. Br.	JA160					+	+	+	
Grevillea vestita (Endl.) Meisn.	JA299								+
Hakea conchifolia Hook.	BM,JA								+
Hakea costata Meisn.	JA169,291,346	+	+				+		
Hakea erinacea Meisn.	JA282		+						
Hakea gilbertii Kipp. ex Meisn.	JA								+
Hakea incrassata R. Br.	JA222,270	+	+				+		
Hakea lissocarpha R. Br.	JA336					+	+	+	
Hakea obliqua R. Br.	GK								+
Hakea prostrata R. Br.	JA176,271		+			+		+	
Hakea ruscifolia Labill.	JA253	+	+	+	+	+	+	+	
Hakea smilacifolia Meisn.	JA233	+				+	+		
Hakea stenocarpa R. Br.	JA325	+				+	+		
Hakea trifurcata (Smith) R. Br.	JA250, 282	+	+				+	+	
Hakea varia R. Br.	EAG								+
Isopogon adenanthoides Meisn.	GK10251								+
Isopogon divergens R. Br.	JA773								+
Isopogon linearis Meisn.	AB4227, JA446	+					+		
Lambertia multiflora Lindl. var. *multiflora*	JA226						+		+
Persoonia comata Meisn.	GK								+
Persoonia elliptica R. Br.	EAG								+
Petrophile brevifolia Lindl.	JA394, GK11627						+		
Petrophile linearis R. Br.	JA146,349	+		+	+	+	+	+	
Petrophile macrostachya R. Br.	JA342								+
Petrophile media R. Br.	JA230, 394								+
Petrophile rigida R. Br.	EAG								+
Petrophile scabriuscula Meisn.	GK/JA80, JA166,372, AB4278	+	+	+	+			+	+
Petrophile seminuda Lindl.	GK10925				+				
Petrophile serruriae R. Br.	JA262,385	+				+	+		
Petrophile striata R. Br.	JA342,387,506	+		+	+	+		+	
Petrophile trifida R. Br.	JA381								+
Stirlingia latifolia (R. Br.) Steud.	JA354	+		+	+		+	+	
Synaphea petiolaris R. Br.	JA352	+	+	+	+	+			
Synaphea spinulosa (Burm. f.) Merr.	JA178,231,280,502	+	+	+	+	+	+		

Appendix 4 (continued)

NAME	COLLECTION NUMBER	SITE 1	2	3	4	5	6	7	OPP. COLL.
SANTALACEAE									
Leptomeria empetriformis Miq.	GK								+
Leptomeria spinosa (Miq.) A. DC.	GK, JA984								+
OLACACEAE									
Olax scalariformis A.S. George	GK10926								+
LORANTHACEAE									
Amyema miquelii (Lehm.ex Miq.) Tieghem	JA							+	
Nuytsia floribunda (Labill.) R. Br.	JA	+		+					+
POLYGONACEAE									
Muehlenbeckia adpressa (Labill.) Meisn.	GK, JA								+
AMARANTHACEAE									
Ptilotus drummondii (Moq.) F. Muell.	GK								+
Ptilotus manglesii (Lindley) F. Muell.	AB,JA					+			
Ptilotus polystachyus (Gaudich.) F. Muell.	AB								+
GYROSTEMONACEAE									
Gyrostemon subnudus (Nees) Baillon	JA363		+						
MOLLUGINACEAE									
Macarthuria apetala Harvey	EAG								+
Macarthuria australis Huegel ex Endl.	GK,JA AB4125								+
PORTULACACEAE									
Calandrinia corrigioloides F. Muell.ex Benth.	GK14324								+
Calandrinia granulifera Benth.	GK14325								+
Calandrinia liniflora Fenzl	GK14326								+
CARYOPHYLLACEAE									
* *Cerastium glomeratum* Thuill.	GK,JA								+
* *Petrorhagia velutina* (Guss.) P. Ball et Heyw.	GK10294								+
* *Silene gallica* L.	AB4041								+
RANUNCULACEAE									
Clematis pubescens Huegel ex Endl.	JA758								+
LAURACEAE									
Cassytha flava Nees	GK								+
Cassytha glabella R. Br.	EAG								+
Cassytha pomiformis Nees	JA508	+		+			+		
Cassytha racemosa Nees	JA357	+							+
BRASSICACEAE									
Brassica tournefortii Gouan	GK11095								+
Stenopetalum robustum Endl.	AB4049								+
DROSERACEAE									
Drosera erythrorhiza Lindl.	JA	+	+	+	+	+	+	+	+
Drosera gigantea Lindl.	JA								+
Drosera leucoblasta Benth.	JA380,AB4047	+		+	+			+	
Drosera macrantha Endl.	JA390, AB4270	+	+	+	+	+	+	+	
Drosera menziesii R. Br. subsp. *penicillaris* (Diels) N.G. Marchant & A. Lowrie	GK14327				+				+
Drosera neesii Lehm.	GK								+
Drosera pulchella Lehm.	SH5809								+
Drosera stolonifera Endl.	GK								+
CRASSULACEAE									
Crassula colorata (Nees) Ostenf.	GK, JA								+
Crassula exserta (Reader) Ostenf.	GK								+
* *Crassula natans* Thunb.	GK/JA87								+
PITTOSPORACEAE									
Billardiera sp.	JA								+
MIMOSACEAE									
Acacia alata R.Br. var. *tetrantha* Maslin	GK								+
Acacia applanata Maslin	JA157,161					+		+	
Acacia barbinervis Benth. subsp. *borealis* Maslin	GK, JA								+
Acacia clydonophora Maslin	JA236,369			+		+			+
Acacia colletioides Benth.	GK, JA	+	+						
Acacia cummingiana Maslin	EAG								+
Acacia drummondii Lindl. subsp. *elegans* Maslin	JA246					+			
Acacia lasiocarpa Benth. var. *lasiocarpa*	JA278		+						
Acacia pulchella R. Br. var. *pulchella*	JA148,242	+				+		+	

Appendix 4 (continued)

NAME	COLLECTION NUMBER	SITE 1	2	3	4	5	6	7	OPP. COLL.
Acacia pulchella R. Br. var. *reflexa* Maslin	JA238,337					+		+	
Acacia saligna (Labill.) H.L. Wendl.	GK10263, JA								+
Acacia sphacelata Benth.	EAG								+
Acacia stenoptera Benth.	GK10037	+	+					+	
Acacia tetragonocarpa Meisn.	GK10029					+		+	
Acacia willdenowiana H.L. Wendl.	JA182,391				+			+	
PAPILIONACEAE									
Aotus gracillima Meisn.	JA784								+
Aotus procumbens Meisn.	JA769								+
Bossiaea eriocarpa Benth.	JA284 AB4226, 4229	+	+	+	+	+			
Bossiaea ornata (Lindl.) Benth.	JA,AB4273	+	+					+	
Daviesia angulata Benth.	JA255, 807						+		
Daviesia decurrens Meisn.	JA174		+			+			
Daviesia divaricata Benth.	JA183, AB4274			+	+				
Daviesia gracilis M.D. Crisp	JA257		+				+		
Daviesia incrassata Smith	JA319	+							
Daviesia inflata M.D. Crisp	JA	+	+						
Daviesia nudiflora Meisn.	JA237, 398		+	+		+		+	
Daviesia physodes A. Cunn. ex Don	JA, EAG					+			+
Daviesia ? preissii Meisn.	JA225						+		
Daviesia ? striata Turcz.	GK		+						
Daviesia triflora M.D. Crisp	JA334	+		+	+			+	
Gastrolobium spinosum Benth.	AB								+
Gompholobium aristatum Benth.	GK			+					+
Gompholobium confertum (DC.) M.D. Crisp	JA304,AB4277			+	+				
Gompholobium knightianum Lindl.	JA240,AB4225		+	+	+	+	+	+	+
Gompholobium marginatum R. Br.	JA496								+
Gompholobium polymorphum R. Br.	EAG								+
Gompholobium preissii Meisn.	GK								+
Gompholobium scabrum Smith	AB4224					+			
Gompholobium tomentosum Labill.	JA370					+			
Hovea stricta Benth.	JA328	+							
Hovea trisperma Benth.	JA309	+		+			+	+	
Isotropis cuneifolia (Smith) Benth.	AB4275					+			
Jacksonia decumbens E. Pritzel	EAG								+
Jacksonia densiflora Benth.	JA406			+					
Jacksonia sternbergiana Huegel.	JA272,344	+	+		+				
Jacksonia ulicina Meisn.	JA								+
Jacksonia restioides Meisn.	EAG								+
Jacksonia sp.	AB						+		
Kennedia prostrata R. Br.	JA152,323					+		+	
Mirbelia dilatata R. Br.	GK								+
Mirbelia aff. *microphylla* (Turcz.) Benth.	AB4223	+	+						
Mirbelia trichocalyx Domin.	JA221, 283	+							
Nemcia capitatum (Benth.) M.D. Crisp	GK, JA780	+		+	+				+
Nemcia parviflorum (Benth.) M.D. Crisp	GK								+
Nemcia reticulatum (Meisn.) M.D. Crisp	JA295,301,311	+		+	+	+			+
Sphaerolobium macranthum Meisn.	GK10511						+		
Sphaerolobium medium R. Br.	AB4272, 4276	+					+		
Sphaerolobium ? vimineum Smith	SH5807								+
Templetonia biloba (Benth.) Polh.	GK								+
* *Trifolium angustifolium* L.	GK11069								+
* *Trifolium campestre* Schreber	GK						+		
* *Trifolium cernuum* Brot.	GK10295								+
* *Trifolium dubium* Sibth.	GK11090								+
Viminaria juncea (Schrader & Wendl.) Hoffsgg.	JA								+
GERANIACEAE									
* *Erodium cicutarium* (L.) L'Her.	GK10291								+
Erodium cygnorum Nees	GK								+
Pelargonium littorale Huegel	GK11093				+				
OXALIDACEAE									
Oxalis perennans Haw.	RR								+
RUTACEAE									
Boronia molloyae J. Drumm.	JA164							+	+
Boronia purdieana Diels	BM								+
Boronia ramosa (Lindl.) Benth. subsp. *anethifolia* (Bartling) Paul G. Wilson	JA287,164	+						+	
Boronia scabra Lindl.	EAG								+
Eriostemon spicatus A. Rich.	JA305,AB4271	+		+	+	+	+	+	

Appendix 4 (continued)

NAME	COLLECTION NUMBER	SITE 1	2	3	4	5	6	7	OPP. COLL.
TREMANDRACEAE									
Tetratheca aff. *hirsuta* Lindl.	JA153							+	
POLYGALACEAE									
Comesperma acerosum Steetz.	EAG								+
Comesperma ciliatum Steetz	JA,AB4212					+			
Comesperma flavum DC.	GK								+
Comesperma virgatum Labill.	GK,SH5816								+
EUPHORBIACEAE									
Monotaxis grandiflora Endl.	GK								+
Phyllanthus calycinus Labill.	JA245					+			
STACKHOUSIACEAE									
Stackhousia pubescens A. Rich.	JA223, 708	+	+			+		+	
Tripterococcus brunonis Endl.	GK								+
SAPINDACEAE									
Diplopeltis huegelii Endl.	AB								+
RHAMNACEAE									
Cryptandra glabriflora Benth.	JA,GK10035								+
Cryptandra pungens Steud.	JA168,281		+						
Cryptandra scoparia Reissek	GK10042								+
Stenanthemum humilis Benth.	GK								+
Stenanthemum tridentatum Steud.	EAG								+
Trymalium angustifolium Reissek	GK10290		+	+			+	+	+
Trymalium ledifolium Fenzl	GK								+
STERCULIACEAE									
Guichenotia sarotes Benth.	SH								+
Thomasia foliosa Gay	JA765								+
Thomasia glutinosa Lindl.	JA,SH								+
DILLENIACEAE									
Hibbertia acerosa (R. Br. ex DC.) Benth	JA709,AB4266			+	+			+	+
Hibbertia aurea Steud.	JA331								+
Hibbertia crassifolia (Turcz.) Benth.	JA264						+		
Hibbertia desmophylla (Benth.) F. Muell.	EAG								+
Hibbertia cf. *glaberrima* F. Muell.	JA	+							
Hibbertia glomerata Benth.	EAG								+
Hibbertia aff. *helianthemoides* (Turcz.) F. Muell.	JA497							+	
Hibbertia huegelii (Endl.) F. Muell.	JA227,290,302, 316			+	+				
Hibbertia hypericoides (DC.) Benth.	JA289,263,326	+	+	+	+	+	+	+	
Hibbertia cf. *rhadinopoda* F. Muell.	AB4219	+		+	+		+	+	
Hibbertia subvaginata (Steudel) F. Muell.	JA306,317			+	+				
Hibbertia stellaris Endl.	EAG								+
Hibbertia vaginata (Benth.) F. Muell.	JA717								+
VIOLACEAE									
Hybanthus calycinus (DC. ex Ging.) F. Muell.	AB,JA								+
THYMELAEACEAE									
Pimelea angustifolia R. Br.	JA,AB4218						+		
Pimelea suaveolens Meisn.	EAG								+
Pimelea sulphurea Meisn.	GK, JA324,173		+			+		+	
MYRTACEAE									
Agonis linearifolia (DC.) Schauer	JA,SH5806								+
Astartea fascicularis (Labill.) DC.	GK,SH5822								+
Baeckea camphorosmae Endl.	JA296	+				+			+
Baeckea elegans Schau.	EAG								+
Baeckea grandiflora Benth.	EAG								+
Beaufortia squarrosa Schauer	JA748								+
Calothamnus lateralis Lindl.	GK								+
Calothamnus quadrifidus R. Br.	JA175								+
Calothamnus sanguineus Labill.	JA155,276,327	+	+	+		+	+	+	
Calytrix angulata Lindl.	JA	+							+
Calytrix flavescens A. Cunn.	JA379			+					
Calytrix fraseri A. Cunn.	JA373			+					+
Calytrix leschenaultii (Schauer) Benth.	JA719								+
Calytrix oldfieldii Benth.	EAG								+
Calytrix strigosa A. Cunn.	EAG								+
Calytrix sylvana Craven	LR101								+
Calytrix variabilis Lindl.	LR426, JA303	+		+	+	+			+
Calytrix sp.	JA171,333,241	+				+		+	

Appendix 4 (continued)

NAME	COLLECTION NUMBER	SITE 1	2	3	4	5	6	7	OPP. COLL.
Darwinia aff. *nieldiana* F. Muell.	GK								+
Eremaea asterocarpa Hnatiuk	AB4063						+		+
Eremaea pauciflora (Endl.) Druce	JA509,AB4120			+					+
Eremaea purpurea (Endl.) Benth.	GK						+		
Eucalyptus calophylla Lindl.	JA	+				+		+	+
Eucalyptus decurva F. Muell.	JA267,MB9391						+		
Eucalyptus drummondii Benth.	SH								+
Eucalyptus lane-poolei Maiden	JA269		+						+
Eucalyptus marginata Donn ex Smith subsp. *marginata*	JA					+	+		+
Eucalyptus marginata Donn ex Smith subsp. *thalassica* Brooker & Hopper								+	
Eucalyptus marginata x *todtiana*	SH								+
Eucalyptus rudis Endl.	JA,SH								+
Eucalyptus todtiana F. Muell.	JA353	+	+	+	+	+	+		+
Eucalyptus wandoo Blakely	JA								+
Homalospermum firmum Schauer	SH5805, JA751								+
Hypocalymma angustifolium Endl.	JA,SH5808								+
Hypocalymma linifolium Turcz	JA162,234						+	+	
Hypocalymma xanthopetalum F. Muell.	JA307,367	+		+	+			+	
Kunzea 'glabrescens' Toelken	JA756								+
Kunzea 'glabrescens' Toelken x *recurva* Schauer	SH5826								+
Kunzea 'litticola' Toelken	GK11092								+
Kunzea recurva Schauer	SH5825								+
Leptospermum erubescens Schauer	AB4038							+	+
Leptospermum spinescens Endl.	JA261,308	+		+	+	+	+		
Melaleuca acerosa Schauer	JA744								+
Melaleuca ciliosa Turcz.	EAG								+
Melaleuca preissiana Schauer	SH								+
Melaleuca radula Lindl.	EAG								+
Melaleuca rhaphiophylla Schauer	GK								+
Melaleuca aff. *scabra* R. Br.	SH								+
Melaleuca seriata Lindl.	GK								+
Melaleuca trichophylla Lindl.	AB/GK				+				
Melaleuca aff. *urceolaris* F. Muell. ex Benth.	JA397,AB4216	+					+	+	+
Pericalymma ellipticum (Endl.) Schauer	GK								+
Pileanthus filifolius Meisn.	GK								+
Regelia ciliata Schauer	JA757								+
Scholtzia involucrata (Endl.) Druce	JA,BM								+
Verticordia acerosa Lindl.	AB4215		+						
Verticordia blepharophylla A.S. George	EAG								+
Verticordia densiflora Lindl.	BM								+
Verticordia drummondii Schau.	EAG								+
Verticordia nitens (Lindley) Endl.	JA774						+		+
Verticordia nobilis Meisn.	GK,SH,LR500, JA745							+	+
Verticordia paludosa A.S. George	JA399						+		
Verticordia plumosa (Desf.) Druce	GK								+
Verticordia pennigera Endl.	EAG								+
HALORAGACEAE									
Glischrocaryon aureum (Lindl.) Orch.	GK								+
Gonocarpus pithyoides Nees	JA762,GK								+
APIACEAE									
Eryngium pinnatifidum Bunge	GK								+
Homalosciadium homalocarpum (F. Muell.) H. Eichler	GK							+	
Hydrocotyle callicarpa Bunge	AB4267								+
Hydrocotyle diantha DC.	GK								+
Hydrocotyle pilifera Turcz.	GK								+
Platysace ramosissima (Benth.) C. Norman	GK11143	+							
Trachymene ornata (Endl.) Druce	GK								+
Trachymene pilosa Smith	JA,AB4118	+	+					+	
Xanthosia ciliata Hook.	GK10286								+
Xanthosia huegelii (Benth.) Steud.	JA,AB4214	+	+	+	+	+	+	+	
EPACRIDACEAE									
Andersonia heterophylla Sond.	JA								+
Andersonia lehmanniana Sond.	JA217,254,275	+	+	+	+		+		
Astroloma ? ciliatum (Lindl.) Druce	JA,SH	+							+
Astroloma glaucescens Sond.	JA165,170,386 GK8041	+	+	+		+		+	
Astroloma macrocalyx Sond.	GK								+
Astroloma microdonta F. Muell. ex Benth.	EAG								+

Appendix 4 (continued)

NAME	COLLECTION NUMBER	SITE 1	2	3	4	5	6	7	OPP. COLL.
Astroloma pallidum R. Br.	JA,AB4213		+	+		+		+	
Astroloma stomarrhena Sond.	GK10050	+		+	+		+		
Astroloma xerophyllum (DC.) Sond.	GK								+
Astroloma sp. (red flower, hairy leaves)	GK						+		
Conostephium minus Lindl.	GK10256								+
Conostephium pendulum Benth.	JA377,256	+		+	+	+	+	+	
Conostephium preissii Sond.	GK8045					+		+	+
Leucopogon allittii F. Muell.	JA348	+		+					
Leucopogon australis R. Br.	SH5813, JA761 AB4119								+
Leucopogon conostephioides DC.	GK10047				+				+
Leucopogon gracillimus DC.	JA243,772					+			
Leucopogon leptanthus Benth.	EAG								+
Leucopogon nutans E. Pritzel	GK10041								+
Leucopogon oldfieldii Benth.	JA150,184 228,274,396	+	+		+	+	+	+	
Leucopogon oliganthus E. Pritzel	GK10034								+
Leucopogon oxycedrus Sond.	EAG								+
Leucopogon aff. *pendulus* R. Br.	JA								+
Leucopogon polymorphus Sond.	JA		+	+	+				
Leucopogon propinquus R. Br.	EAG								+
Leucopogon racemulosus DC	EAG								+
Leucopogon sprengelioides Sond.	GK10032,10033 JA396				+	+	+	+	+
Leucopogon sp.	JA288	+							
Lysinema ciliatum R. Br.	JA252,356	+		+	+		+		
Lysinema elegans Sond.	EAG								+
Styphelia tenuiflora Lindl.	GK10039			+		+		+	+
PRIMULACEAE									
* *Anagallis arvensis* L. var. *caerulea* Gouan	JA,AB								+
LOGANIACEAE									
Logania serpyllifolia R. Br.	GK11047						+		
Mitrasacme paradoxa R. Br.	AB			+	+				
CHLOANTHACEAE									
Pityrodia bartlingii (Lehm.) Benth.	JA							+	
LAMIACEAE									
Hemiandra pungens R. Br.	GK								+
SOLANACEAE									
* *Solanum nigrum* L.	JA,AB								+
OROBANCHACEAE									
* *Orobanche minor* Smith	JA,GK								+
LENTIBULARIACEAE									
Polypompholyx multifida (R. Br.) F. Muell.	AB4058, JA								+
Polypompholyx tenella (R. Br.) Lehm.	AB4059								+
Utricularia violacea R. Br.	GK								+
Utricularia volubilis R. Br.	GK								+
RUBIACEAE									
* *Galium divaricatum* Pourret ex. Lam.	GK11645						+		+
Opercularia vaginata Labill.	EAG								+
CAMPANULACEAE									
* *Wahlenbergia capensis* (L.) A. DC.	JA								+
Wahlenbergia preissii Vriese	GK								+
LOBELIACEAE									
Isotoma hypocrateriformis (R. Br.) Druce	GK								+
Lobelia rhombifolia Vriese	GK11046								+
Lobelia tenuior R. Br.	GK							+	+
GOODENIACEAE									
Dampiera alata Lindl.	GK10236								+
Dampiera carinata Benth.	EAG								+
Dampiera linearis R. Br.	GK								+
Dampiera oligophylla Benth.	GK11096						+		
Goodenia caerulea R. Br.	EAG								+
Goodenia convexa Carolin	GK11897								+
Goodenia micrantha Hemsley ex Carolin	GK								+
Goodenia mooreana Krause	GK							+	

Appendix 4 (continued)

NAME	COLLECTION NUMBER	SITE 1	2	3	4	5	6	7	OPP. COLL.
Goodenia pulchella Benth.	GK11575								+
Lechenaultia biloba Lindl.	JA286,779	+				+	+	+	
Lechenaultia floribunda Benth.	EAG								+
Lechenaultia stenosepala E. Pritzel	GK11967								+
Scaevola calliptera Benth.	AB		+		+	+			
Scaevola canescens Benth.	GK,JA335,364		+	+	+			+	
Scaevola glandulifera DC	GK11969								+
Scaevola repens Vriese var. *repens*	JA350	+							
Scaevola striata R. Br.	JA21								+
Verrauxia reinwardtii (Vriese) Carolin	GK								+
STYLIDIACEAE									
Levenhookia dubia Sond.	EAG								+
Levenhookia pauciflora Benth.	AB4051						+		
Levenhookia pusilla R. Br.	AB4124								+
Levenhookia sp.	AB4125								+
Stylidium adpressum Benth.	AB4046,4123			+	+				+
Stylidium albo-lilacinum (Erickson & Willis) Lowrie & Carlquist	AB4064					+	+		
Stylidium breviscapum R. Br.	JA405	+	+	+			+		
Stylidium brunonianum Benth.	AB4033,JA156	+	+	+	+		+	+	
Stylidium bulbiferum Benth.	JA								+
Stylidium calcaratum R. Br.	AB								+
Stylidium carlquistii Lowrie	AB4126,4037 JA248,279		+			+			
Stylidium ? *dichotomum* DC.	AB,JA359,366	+	+	+			+	+	+
Stylidium diuroides Lindl.	AB4045,4121								+
Stylidium cf. *diuroides* Lindl.	AB4052						+		
Stylidium junceum R. Br.	AB4029								+
Stylidium leptocalyx Sond.	AB4032								+
Stylidium leptophyllum DC.	EAG								+
Stylidium miniatum Mildbr.	AB4042,4044		+	+	+		+	+	
Stylidium piliferum R. Br.	EAG								+
Stylidium pycnostachyum Lindl.	EAG								+
Stylidium repens R. Br.	JA726	+		+	+		+		
Stylidium aff. *rhynchocarpum* Sond.	AB4228								+
Stylidium schoenoides DC.	AB4050	+							
ASTERACEAE									
* *Arctotheca calendula* (L.) Levyns	JA								+
Asteridea pulverulenta Lindl.	GK								+
Blennospora drummondii A. Gray	JA734								+
Brachycome iberidifolia Benth.	JA730,AB4048						+		+
Cotula coronopifolia L.	AB4122								+
Gnephosis pusilla (Benth.) Endl.	GK								+
Gnephosis tenuissima Cass.	JA735								+
Gnephosis trifida (Short) Short	EAG								+
Helipterum manglesii (Lindley) F. Muell ex Benth.	AB4034								+
Hyalosperma cotula (Benth.) Paul G. Wilson	AB4030,4035 JA710							+	
* *Hypochaeris glabra* L.	JA804,737								+
Lagenifera huegelii Benth.	AB4057,SH5819 JA711					+		+	+
Millotia myosotidifolia (Benth.) Steetz.	AB4043					+		+	
Millotia tenuifolia Cass.	JA733								+
Olearia elaeophila (DC.) F. Muell. ex Benth.	GK								+
Olearia paucidentata (Steetz) F. Muell.	JA								+
Olearia rudis (Benth.) F. Muell. ex Benth.	JA330,402								+
Pithocarpa achilleoides P. Lewis & Summerh.	JA343,507	+					+		+
Podolepis gracilis (Lehm.) R.A. Graham	AB4066					+			
Podotheca angustifolia (Labill.) Less.	JA722	+							
Podotheca chrysantha (Steetz) Benth.	GK11067,10454								+
Podotheca gnaphalioides R.A. Graham	JA736,AB4036	+	+		+				
Pseudognaphalium luteo-album (L.) Hilliard & B.L. Burtt	GK								+
Pterochaeta paniculata Steetz.	JA393,732,AB4061		+			+	+	+	
Quinetia urvillei Cass.	JA731,GK								+
Senecio hispidulus A. Rich.	GK								+
Siloxerus humifusus Labill.	EAG								+
* *Sonchus asper* Hill	JA760								+
* *Tolpis barbata* (L.) Gaertner	GK10268								+
* *Ursinia anthemoides* (L.) Poiret	JA713,723 AB4031								+
Waitzia citrina (Benth.) Steetz	AB4217							+	
Waitzia suaveolens (Benth.) Druce	JA721	+							

APPENDIX 5

Notes on individual mammal species recorded on Boonanarring Nature Reserve.

Small mammals, other native ground mammals, bats and introduced mammals are discussed separately. Within each grouping taxonomic ordering and nomenclature follows Strahan (1995).

Small Mammals

Three native and one introduced small mammal species were trapped. Appendix 6 lists the total numbers of individuals of each species captured from individual traplines at each sample site.

Sminthopsis griseoventer Grey-bellied Dunnart
This species was captured only at Sites 1 and 2, at the base of the Gingin Scarp.
No animals were reproductively active. One adult female (13.5 g) had a stained pouch and slightly distended teats suggesting she had reared pouch young some time prior to capture. The other female (9.5 g) appeared to be a sub-adult with an undeveloped pouch and minute teats.
Males ranged in weight from 9.5 to 11.5 g. An examination of the skulls extracted from 4 specimens (listed in Appendix 3) confirmed that these were all sub-adults.

Tarsipes rostratus Honey Possum
Honey possums were captured only on sandy substrates in the study area, at Sites 1 and 2 (Low Heath) and at Sites 3 and 4 (*Banksia* woodland) (Table 7).
Six females (with a mean body weight of 11.3 g) had pouch young. Another two (7.5 g) each had distended teats and relaxed pouches indicative of having recently carried pouch young. Eight females (ranging in weight from 6.0 to 9.7 g) showed no pouch development. We assume these to include non-parous sub-adults and possibly animals in early stages of pregnancy.
Each female carrying young had at least 2 pouch young. When a pouch was checked for the presence of young, only those young which were visible after stretching the pouch open were counted. Young were not removed from the pouch because it has been found previously that they are difficult to replace and this procedure is time-costly when trap success is high. It has also been observed from holding females for short periods after capture, that on occasions when young have been removed, counted and replaced, they were found outside the pouch again shortly afterwards. It seems likely that this would cause increased mortality of pouch young if females were released immediately in the field.
All pouch young were hairless and ranged in size from 0.4 cm to approximately 1.5 cm (crown-rump measurement).
Males ranged in weight from 5.3 to 7.0 g. Scrotal length measurements suggested at least eight were adults (sexually mature) (see Renfree *et al.* 1984; Burbidge and Boscacci 1989).

Pseudomys albocinereus Ash-grey Mouse
Pseudomys albocinereus was widespread on the reserve, with captures at all sites except Site 7 (Table 7). It was the only native species captured at Site 6 (Dense Heath on shallow sands over laterite).
The species was trapped in both Elliott and pitfall traps (Table 7) but insufficient numbers were captured to allow statistical comparisons between sites. However, pooling of pitfall captures from replicate sites 1 and 2 (9 captures) and Sites 3 and 4 (8 captures) showed there was negligible difference in trap returns from Dense Low Heath on sand and *Banksia* woodland. The species was present but apparently uncommon in jarrah (with marri) forest over Low Heath on laterite (Site 5).
The thirteen females captured (Appendix 6) ranged in weight from 15.5 to 28.0 g. A proportion (7 of the 13) were classed as sub-adults, with a weight range of 15.5 to 19.5 g. Six were in a heavier weight range (22.0 to 28.0 g). None were lactating, palpably pregnant or had enlarged teats. These were classed as non-breeding adults, although females in early stages of pregnancy may also have been present (e.g. at Cockleshell Gully Reserve, Chapman *et al.* 1977 recorded pregnant females ranging in weight from 20.0 to 44.6 g). However, we did not collect specimens and cannot confirm this.
The ten males captured (Appendix 6) ranged in weight from 16.5 to 32.0 g. Only one (32.0 g) showed breeding condition (descended testes and epididymes). The remainder were classed as sub-adults (5, ranging in weight from 16.5 to 20.0 g) and non-breeding adults (4, ranging in weight from 22.0 to 26.5 g).

Mus musculus House Mouse
This species was widespread in the study area, being detected at all sites except Site 7 (Table 7).
Only four individuals were captured at Sites 1 to 4 (deep sands) compared with 10 from Sites 5 and 6 (shallow soils on laterite, with laterite outcropping in places). However, this difference may in part reflect a different response to the two trap types used - pitfall traps (at Sites 1 to 4) and Elliott traps (at Sites 5 and 6). For example, significantly higher trap returns of *Mus musculus* from Elliott traps were recorded in a vertebrate survey of the Great Sandy Desert in which some simultaneous Elliott and pit trapping was undertaken in similar habitats (McKenzie and Youngson 1983).
Five females were captured (Appendix 6) and ranged in weight from 8.5 to 14.5 g. Internal examination of two specimens showed that one (11.7 g) was pregnant and one was non-parous. One juvenile was captured.
The nine males captured (Appendix 6) ranged in weight from 8.0 to 17.5 g. Five showed breeding condition (descended testes).

Other Ground Mammals

Tachyglossus aculeatus Short-beaked Echidna
Fresh diggings were found at Sites 3 and 4 (*Banksia* woodland) in August. Diggings were also found in a stand of *Eucalyptus lane-poolei* in the north-western corner of the reserve in July (M.J. Bamford, personal communication 1986).

Appendix 5 (continued)

Macropus fuliginosus Western Grey Kangaroo
Grey Kangaroos were widespread throughout the reserve. Sightings were made on Sites 3 and 4 (*Banksia* woodland) and fresh scats were seen at all sites. In addition, 18 sightings (comprising 31 individual kangaroos) were recorded opportunistically in February and during the assemblage survey in March. The largest group seen was three. Most sightings were of one or two individuals.
Sightings were recorded in four broad vegetation types: *Banksia* woodland over low heath on deep sands, jarrah/marri forest on lateritic sands in gullies between lateritic ridges, jarrah/marri forest on lateritic ridges, and in low heath (with scattered *Banksia* spp.) on deep sands. Sightings were made in both recently burnt (March 1985) and unburnt portions of the study area.

Macropus irma Western Brush Wallaby
Brush Wallabies were sighted on the reserve on five separate occasions during February and March. All sightings were of individual animals. Individuals were observed on Sites 1 (Low Dense Heath) and 4 (*Banksia* woodland). Opportunistic sightings were from the following vegetation types: open jarrah forest with an understorey of low open heath, open jarrah (with marri) forest with an understorey of low heath which had been burnt in March 1985, and jarrah/marri forest with a tall dense understorey of *Dryandra sessilis* on laterite.
In addition to these records, two were sighted on land adjoining the south-western boundary, in dense vegetation along Boonanarring Brook.

Bats
Nyctinomus australis White-striped Freetail-bat
The characteristic vocalizations of this species were heard near Site 5 and near the Gingin townsite in March.

Nyctophilus geoffroyi Lesser Long-eared Bat
Three males (6.0, 6.0 and 6.5 g) were mistnetted in March. One had scrotal testes. They were captured at two localities south of Site 5. One of these capture sites is described below for *N. gouldi*, where the two species were taken from the same net. The other site was in *Melaleuca preissii* and marri woodland fringing Boonanarring Brook, approximately 4.5 km south-east of Site 5.

Nyctophilus gouldi Gould's Long-eared Bat
One, a male (8.0 g) with scrotal testes, was captured in a mist-net 2 km south of Site 5. Vegetation comprised open jarrah/marri forest with a tall dense understorey of *Dryandra sessilis* on a lateritic ridge.

Chalinolobus gouldii Gould's Wattled Bat
One female was flushed from the upper trunk of a large burnt marri (8-12 m) in February, approximately 300 m north of Boonanarring Brook. The bat was recovered from where it landed on the ground. Surrounding vegetation comprised Low Heath (burnt in March 1985) with scattered marri trees.

Vespadelus regulus Southern Forest Bat
Three individuals (two males and one female) were mist-netted in March. The males weighed 5.0 g each. One had scrotal testes. The female, also 5.0 g, was not lactating. Captures came from Site 5 and from 2 km south of Site 5. Vegetation at the latter site comprised open jarrah/marri forest with a tall dense understorey of *Dryandra sessilis* on laterite.

Introduced Mammals

Vulpes vulpes Fox
One was spotlighted in a cleared paddock adjacent to the southern boundary of the reserve.

Felis catus Cat
One was spotlighted in the north-eastern section of the reserve. The vegetation comprised *Banksia* woodland with a tall dense heath understorey, dominated by *Adenanthos cygnorum*. Fresh cat tracks were also seen on the vehicle track between Sites 4 and 5.

Oryctolagus cuniculus Rabbit
Two were seen in August on the north-western corner of the reserve, approximately 200 m inside the northern boundary. Rabbits were also seen on farm paddocks on the northern side of the reserve and nearby in dense roadside vegetation.

APPENDIX 6

Total captures of small mammals at each sample site on the Boonanarring Nature Reserve, 17-23 March 1986.

SPECIES	SEX	SITE 1			2			3			4			5			6			7		TOTAL No. OF INDIV.
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	
Sminthopsis griseoventer	F	2																				7
	M	2		1	2																	
Tarsipes rostratus	F	5	2	1	1	1	1	2		2		1										30
	M	2	2		5		1	2		2												
Pseudomys albocinereus	F	3		2	1			1			1	2		1			2					23
	M		1	1		1				1	1	2					1	1	1			
Mus musculus	F				1										1	1 +?1	1					14
	M	1						1					1	1	1		3		1			
No. pit trap nights		30	15	15	30	15	15	30	15	15	30	15	15							30	30	
No. Elliott trap nights														50	50	50	50	50	50			

F = females, M = males

A, B and C refer to individual traplines

APPENDIX 7

Comparative list of frogs and reptiles recorded in *Banksia* woodland near Mooliabeenee (Bamford 1985) and on Boonanarring Nature Reserve.

* = record from unpublished WA Museum records.

FAMILY	SPECIES	MOOLIABEENEE	BOONANARRING
Hylidae			
	Litoria adelaidensis	X	X
Leptodactylidae			
	Crinia georgiana	X	
	Heleioporus eyrei	X	X
	Limnodynastes dorsalis	X	X
	Myobatrachus gouldii	X	X
	Pseudophyrne guentheri	X	
	Ranidella glauerti	X	X
	Ranidella insignifera	X	
Gekkonidae			
	Crenadactylus ocellatus	X	
	Diplodactylus polyophthalmus	X	
	Diplodactylus spinigerus	X	
Pygopodidae			
	Aprasia repens	X	X
	Delma fraseri	X	X
	Delma grayii	X	
	Lialis burtonis	X	X
	Pletholax gracilis gracilis	X	X
	Pygopus lepidopodus	X	X
Scincidae			
	Cryptoblepharus plagiocephalus	X	X
	Ctenotus fallens	X	X
	* *Ctenotus impar*	X	
	Ctenotus lesueurii	X	
	Ctenotus schomburgkii	X	
	Egernia multiscutata bos	X	
	Lerista christinae	X	
	Lerista distinguenda		X
	Lerista elegans		
	Lerista praepedita	X	X
	Menetia greyii		
	Morethia lineoocellata	X	
	Morethia obscura	X	X
	Tiliqua rugosa	X	X
Agamidae			
	Pogona minor minor	X	X
	Tympanocryptis adelaidensis	X	X
Varanidae			
	Varanus gouldii		X
	Varanus tristis		X
Typhlopidae			
	Ramphotyphlops australis	X	
Boidae			
	Morelia spilota imbricata		X
Elapidae			
	Demansia psammophis reticulata	X	
	Notechis curtus	X	X
	Pseudonaja affinis		X
	Pseudonaja nuchalis	X	
	Rhinoplocephalus gouldii	X	
	Vermicella bertholdii	X	
	Vermicella bimaculata		X
	Vermicella calonotos	X	X
	Vermicella semifasciata	X	X

APPENDIX 8

Additional frog and reptile species recorded from localities within a 25 km radius of Gingin that were not detected on Boonanarring Nature Reserve. Collecting localities were: Gingin, 7 km north of Gingin, Bindoon, Red Hill and Wannamal (unpublished WA Museum records to August 1986).

SPECIES	COLLECTION DATE	No. OF SPECIMENS
Litoria moorei	(no date)	1
Neobatrachus pelobatoides	1954	1
Diplodactylus pulcher	(no date)	1
Gehyra variegata	1963	1
Oedura reticulata	1960	1
Phyllurus millii	1955	4
Egernia kingii	(no date)	1
Leiolopisma trilineatum	1959	2
Ramphotyphlops pinguis	1970	2
Notechis scutatus	1965, 1971	2
Rhinoplocephalus nigriceps	(no date)	1

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4262-1296-300