CALM science

VOLUME TWO NUMBER THREE NOVEMBER 1997

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

AIM

To foster awareness, understanding and support for the science on which CALM's nature conservation and natural land management activities in Western Australia are based.

The Science Publications Unit links the work of two CALM divisions: Science and Information and Corporate Relations. It forms part of the latter's Programs and Publications section. Its purpose is to present the scientific work of CALM to a professional readership on a regular basis. *CALMScience* is one product of the unit.

ENQUIRIES

Enquiries regarding distribution and subscriptions should be addressed to the Marketing Manager, Corporate Relations Division, Department of Conservation and Land Management, Locked Bag 29, Bentley Delivery Centre, WA 6983
Phone: (08) 9334 0296 Fax: (08) 9334 0498

Department of Conservation and Land Management, Western Australia.

IN THIS ISSUE

CALM science

VOLUME TWO NUMBER THREE NOVEMBER 1997

CALM
science
VOLUME TWO NUMBER THREE NOVEMBER 1997

WESTERN AUSTRALIAN
JOURNAL OF CONSERVATION
AND LAND MANAGEMENT

CALMScience 2 (3): 191-198 (1997)

Dimensional changes of pine timber exposed to different environmental conditions

G.K. BRENNAN[1] AND C.E. BAGGETTA[2]

[1]Forest Resources Division, Department of Conservation and Land Management, Timber Technology, Harvey, Western Australia 6220.

[2]Department of Conservation and Land Management, Harvey, Western Australia 6220.

SUMMARY

The moisture content of timber fluctuates with changes in atmospheric conditions, and because of the hygroscopic properties of timber, some changes in dimensions may occur. The change in moisture content and dimensions (length, width, thickness) of back-sawn 90 x 35 mm maritime pine (*Pinus pinaster*) and radiata pine (*P. radiata*) timber stored at 8 per cent or 18 per cent equilibrium moisture content (EMC) conditions were monitored for 40 days. Samples with sloping grain (equal to or greater than 7°) or straight grain (less than 7°) were compared.

All timber samples had been high-temperature dried to a moisture content of 10.5 ± 2.0 per cent. Timber stored in the 8 per cent EMC chamber shrank as it lost moisture and had a small decrease in width and thickness but negligible change in length, while timber in the 18 per cent EMC chamber absorbed moisture and showed small increases in width and thickness but a negligible change in length. Slope of grain showed no significant effect on changes in dimension.

Longitudinal shrinkage was negligible in the 8 per cent conditions. The greatest mean change in length owing to longitudinal movement was for straight grained radiata pine stored in the 18 per cent EMC chamber, where the increase was 0.09 per cent or 0.9 mm in a 1000 mm long sample, over a moisture content change of 5.5 per cent. This indicates that movement in-service (where the range about EMC may be perhaps 3 to 4 per cent) should be minimal. Movement of the timber may be a factor in 'inverted peaking' in ceiling and wall sheets, but a complete assessment of all factors is required.

INTRODUCTION

As green timber dries in the desorption process, it initially loses free water from the cell cavities, and then loses bound water from the cell walls. The moisture content level at which shrinkage commences is the fibre saturation point (f.s.p.) at approximately 30 per cent moisture content, and shrinkage continues from f.s.p. to equilibrium moisture content (EMC) and below. If its moisture content is below EMC, wood has adsorptive properties which give it the ability to extract water vapour from the surrounding air until it is in moisture equilibrium with the air, i.e. it is a hygroscopic material (Haygreen and Bowyer 1982). Adsorption of water results in swelling of the timber.

As the atmospheric conditions in any one place vary from day to day and season to season, the moisture content of timber constantly changes, even in a sheltered position, but at a much slower rate than the changes in atmospheric conditions. Wood used where humidity fluctuates continually changes in moisture content, and therefore dimension (Haygreen and Bowyer 1982).

Problems can arise when timber is used in widely varying humidity and temperature conditions, if the design and application of the timber product have not anticipated changes in dimension. For satisfactory performance of timber in-service, it is essential to use timber with moisture contents close to the appropriate EMC. Shrinkage can result in checking and warping of timber, and swelling in humid conditions can result in jammed doors and windows, and in buckled table tops.

The amount of shrinkage varies with orientation of the grain, and as a general rule the ratio of tangential to radial to longitudinal shrinkage is 100:50:1. Longitudinal shrinkage in any piece of straight-grained timber cut from mature wood is negligible, e.g. 0.2 to 0.3 per cent from f.s.p. to EMC, a difference in moisture content of about 15 per cent. Compression wood, which can be found in pine trees, is undesirable in timber owing to the high longitudinal shrinkage which is commonly 1.0 to 2.0 per cent and may be as great as 6.0 or 7.0 per cent (Haygreen and Bowyer 1982). Cown and McConchie (1980) quoted a mean longitudinal shrinkage of 0.02 per cent from green to 12 per cent moisture content for 52-year-old radiata pine (*Pinus radiata* D.Don). Any greater increase in length of a piece of timber may be owing to the occurrence of sloping grain, spiral grain in juvenile wood or compression wood.

A study of the shrinkage of 90 x 35 mm pine timber (*P. pinaster* Ait. and *P. radiata*), with straight or sloping grain having an initial moisture content of 10.5 ± 2.0 per cent and stored under 8 or 18 per cent EMC conditions was undertaken by the Timber Utilisation Centre (TUC) (now CALM Timber Technology) following a request from the Timber Advisory Centre. The topic is also relevant to the Association of Wall and Ceiling Contractors of Western Australia. There have been occasional problems with 'inverted peaking' in ceiling and wall fixings when radiata pine studs and rafters are used, with movement of the sheeting and perhaps nail popping. Changes in the moisture content of the pine which, because of timber's hygroscopic properties, can result in swelling or shrinking with increases or decreases in moisture content, may be a factor causing 'inverted peaking'.

The trial was designed to assess lengths of maritime or radiata pine with either straight or sloping grain to quantify the variations in length occurring when timber is stored at either 8 per cent or 18 per cent EMC.

MATERIALS AND METHODS

Sixty-two pieces of back-sawn 90 x 35 mm pine timber were randomly selected from production at Wespine's sawmill at Dardanup. The timber was a mixture of maritime pine and radiata pine. Maritime pine samples were high-temperature dried at 140°C and radiata pine at 150°C, with drying times of 14 h or 10 h respectively. Samples were reconditioned by steaming at 100°C for 3 to 4 h. Ninety per cent of the timber produced at Wespine's factory is radiata pine, however, at the time of selection a considerable volume of maritime pine had been dressed and was available for sampling. Similar shrinkage figures have been reported for both species (Kingston and Risdon 1961).

The timber was delivered to the TUC in Harvey where species, initial moisture contents, weight, slope of grain, air-dry density, and the dimensions of width, thickness and length were measured. Slope of grain was determined at two positions on the board by scribing the individual pieces of timber, and calculating slope using the method described in AS 1080.2.1 - 1981 (Standards Association of Australia 1981). The samples with a slope of grain of less than 7 degrees were classified as straight-grained, and those with a slope of grain equal to or greater than 7 degrees as sloping grained.

Fifteen samples with straight grain and fifteen with sloping grain were stored in the 8 per cent EMC chamber, and sixteen straight grain samples and sixteen sloping grain samples in the 18 per cent EMC chamber. The actual conditions in the 8 per cent EMC chamber were: 35°C dry bulb temperature (DBT) and 45 per cent relative humidity (RH) and; in the 18 per cent EMC chamber: 30°C DBT and 85 per cent RH. Twice weekly for the next six weeks, the samples were assessed for change in weight (moisture content variation) and dimensions. Thirty-nine samples were maritime pine (22 with straight grain and 17 with sloping grain) and 23 radiata pine (9 straight grain and 14 sloping grain), and these were randomly distributed between the 18 and 8 per cent EMC chambers. The samples that contained pith or 'heart-in' samples were noted and their shrinkages compared with the samples without pith. Ninety per cent of the 'heart-in' samples were radiata pine, of which two-thirds were stored in the 18 per cent EMC chamber and one-third in the 8 per cent chamber.

RESULTS AND DISCUSSION

The air-dried densities and the slope of grain were assessed before placing the samples into the EMC chambers. The results are given in Table 1.

Air-dry densities measured in this trial for maritime pine were similar to the mean density of 596 $kg.m^{-3}$ (after reconditioning) determined by Kingston and Risdon (1961), but the range was slightly greater. The air-dry densities for radiata pine were similar to the mean of 485 $kg.m^{-3}$ and range for 10- to 20-year-old trees determined by Kingston and Risdon (1961), but smaller than the mean figure of 593 $kg.m^{-3}$ for 30- to 40-year-old trees. There is a highly significant positive correlation between shrinkage and basic density (Kininmonth and Whitehouse 1991). The densities assessed in this trial were similar to density figures quoted by Kingston and Risdon (1961) suggesting that shrinkages should be representative for pine timber grown in Western Australia.

Analysis of variance was used to determine any significant differences in density between maritime pine and radiata pine, and within each species between samples with straight or sloping grain. Maritime pine was significantly higher in density than radiata pine, but no significant differences in density were found between

TABLE 1

Air-dried density and slope of grain of maritime pine and radiata pine.

SPECIES	GRAIN ORIENTATION	AIR-DRIED DENSITY ($kg.m^{-3}$) MEAN	S.D.	RANGE	SLOPE OF GRAIN (°) MEAN	S.D.	RANGE
Maritime pine	Sloping grain	605	70	490-735	7.6	1.8	8-12
Maritime pine	Straight grain	595	40	510-665	4.9	1.9	1-7
Radiata pine	Sloping grain	490	60	400-595	8.4	2.1	8-14
Radiata pine	Straight grain	485	55	420-580	5.4	1.7	2-7

Note: Air-dried density was assessed at a moisture content of 10.5 ± 2.0 per cent.

maritime pine with straight grain or sloping grain and radiata pine with straight grain or sloping grain. For grain orientation, grain angle was significantly greater in sloping grain than straight grained samples, for both species.

After determining the initial dimensions, moisture contents and weights, the timber was stored in either the 8 per cent or 18 per cent EMC chamber. The initial and final measurements of each parameter in sloping grain and straight grain timber over the 40 day assessment period are listed in Tables 2 and 3.

Figures 1 to 4 show the trends in moisture content, length, width and thickness changes for maritime pine or radiata pine with either sloping or straight grain. Samples were back-sawn, any change in width would indicate a tangential movement and any change in thickness a radial movement. Figure 1 shows moisture content variations, and that the samples stabilized at about 17 per cent in the 18 per cent chamber, or 10 per cent in the 8 per cent chamber after 40 days exposure. Figure 2 shows negligible change in length, with the straight grained radiata pine stored in the 18 per cent EMC chamber having the largest mean change of 0.09 per cent, more than the samples with sloping grain. Samples are approximately 1000 mm long, therefore a 0.01 per cent change in length is equivalent to 0.1 mm.

Other examples of overall changes in length are given in Tables 2 and 3. For example, sloping grained maritime pine stored in the 8 per cent EMC chamber actually showed a mean increase in length of 0.01 per cent and a mean moisture content decrease of 2 per cent over the 40 days exposure (Table 2). The radiata pine in this chamber decreased in length by 0.01 per cent. In the 18 per cent EMC chamber, maritime pine had a mean increase of 0.06 per cent while the mean moisture content increased 5.7 per cent, and radiata pine had a 0.08 per cent increase for a 7.5 per cent moisture content increase over the 40 days exposure.

Straight grained timber stored in the 8 per cent chamber showed a mean decrease in length of 0.01 per cent with radiata pine, but a similar increase for maritime pine over the 40 days, a fact that is difficult to explain. The respective mean moisture content decreases were 1.6 per cent for the radiata pine and 1.7 per cent for maritime pine over the 40 days exposure (Table 3). This represents a mean decrease in board length of 0.06 mm for each 1 per cent change in moisture content. Timber in the 18 per cent chamber showed increases in length of 0.06 per cent for maritime pine and 0.09 per cent for radiata pine, and moisture contents had mean increases of 6.5 per cent and 5.5 per cent respectively. This represents mean increases of 0.09 mm per 1 per cent change in moisture content for maritime pine or 0.16 mm per 1 per cent change in moisture content for radiata pine.

Figure 3 shows that the mean width of the samples in the 18 per cent EMC chamber increased from 90 mm to between 90.5 mm and 91.25 mm, a mean increase of 0.5 mm to 1.25 mm or 0.5 to 1.4 per cent. Samples in the 8 per cent EMC chamber also had a mean width of 90 mm and after 40 days exposure they had a mean shrinkage of between 0.25 mm and 1 mm, or 0.28 and 1.1 per cent. Within species, the grain orientation showed little effect on swelling or shrinkage and differences between maritime pine and radiata pine were insignificant. This result could possibly be explained by the considerable variation in grain in each piece of timber, e.g. sloping grain is also found around knots, and the samples in this trial were selected based on sloping grain in the clear wood sections between the knots.

Figure 4 gives the change in thickness of the samples stored in both EMC chambers. The samples stored in the 18 per cent chamber had a mean thickness of 35.2 mm and increased in size after 40 days exposure by 0.2 mm to 0.4 mm, or 0.6 to 1.2 per cent. Samples in the 8 per cent chamber had an original mean thickness of 35.2 mm, except for the maritime pine with sloping grain, which had a mean thickness of 35.0 mm. The results indicated shrinkages of less than 0.2 mm, or 0.6 per cent. Species and grain orientation had no effect on the change in thickness.

Samples that contained pith ('heart-in') did not have excessive changes in dimension and were similar to the samples without pith.

There are various anatomical characteristics which may affect longitudinal shrinkage. Compression wood has a different cell structure from that of normal wood because of the much greater angle of fibrils to the cell axis and discontinuities between the microfibrils of the S2 layer, giving it a greater longitudinal shrinkage (Kininmonth and Whitehouse 1991). Longitudinal shrinkage is commonly 1 to 2 per cent and may be as great as 6 to 7 per cent (Haygreen and Bowyer 1982). Juvenile wood (which occurs in the first 10 to 12 growth rings) has a greater tendency for spiral grain, which can also give a higher degree of longitudinal shrinkage than normal wood. Haygreen and Bowyer (1982) quote longitudinal shrinkage figures from green to 12 per cent moisture content for loblolly pine (*P. taeda* L.) as 0.57 per cent for juvenile wood and less than 0.1 per cent for mature wood. The longitudinal shrinkages measured in this trial were between 0.01 per cent and 0.02 per cent, while the highest amount of swelling was 0.09 per cent for straight grained radiata pine stored in the 18 per cent EMC chamber.

Mean shrinkage values may be used to predict average dimensional changes in batches of material, but there is considerable variability within and between trees and also between plantation sites. Variation in the shrinkage of different samples of the same species exposed to the same treatments and conditions results primarily from three factors :

(1) *size and shape* - this affects the grain orientation in the timber and the uniformity of moisture through the thickness;
(2) *wood density* - the higher the density of the specimen, the more it will tend to shrink;
(3) *rate of drying* - under rapid drying conditions, internal stresses are set up because of differential shrinkage: this often results in less final shrinkage than would otherwise occur. By contrast, some species shrink more than normal when dried rapidly under high-temperature conditions (Haygreen and Bowyer 1982).

TABLE 2

Dimensions and moisture contents of 90 x 35 mm sloping grain maritime pine and radiata pine timber stored at 8 or 18 per cent EMC conditions.

SPECIES/EMC	TIME (days)	WIDTH (mm) MEAN	WIDTH (mm) S.D.	WIDTH (mm) RANGE	THICKNESS (mm) MEAN	THICKNESS (mm) S.D.	THICKNESS (mm) RANGE	LENGTH (mm) MEAN	LENGTH (mm) S.D.	LENGTH (mm) RANGE	MOISTURE CONTENT (%) MEAN	MOISTURE CONTENT (%) S.D.	MOISTURE CONTENT (%) RANGE
Maritime Pine 8% EMC	0	89.7	0.3	89.4-90.1	35.0	0.5	34.2-35.5	995.5	0.6	994.7-996.3	10.9	2.8	7.6-13.5
	40	89.0	1.0	88.0-90.2	34.7	0.2	34.3-35.0	995.6	0.6	994.7-996.1	9.0	1.6	6.3-10.1
Radiata Pine 8% EMC	0	90.0	0.2	89.8-90.5	35.2	0.1	34.9-35.4	997.3	1.0	995.8-998.7	12.2	4.3	7.7-21.9
	40	89.7	0.5	88.9-90.4	35.0	0.2	34.8-35.3	997.2	1.1	995.3-998.7	10.2	2.2	7.5-15.2
Maritime Pine 18% EMC	0	90.1	0.1	89.9-90.3	35.3	0.2	34.8-35.7	997.7	1.4	995.3-1000.4	10.9	2.8	8.2-17.9
	40	91.3	0.5	90.4-92.0	35.6	0.3	35.1-36.1	998.3	1.4	995.9-1001.5	16.6	2.4	12.4-21.2
Radiata Pine 18% EMC	0	90.0	0.1	89.9-90.1	35.2	0.3	34.9-35.5	997.6	1.3	995.8-998.7	9.6	1.8	7.6-11.9
	40	91.1	0.4	90.5-91.5	35.5	0.2	35.2-35.8	998.4	1.4	996.7-1000.1	17.1	0.5	16.5-17.8

TABLE 3

Dimensions and moisture contents of 90 x 35 mm straight grained maritime pine and radiata pine timber stored at 8 or 18 per cent EMC conditions.

SPECIES/EMC	TIME (days)	WIDTH (mm) MEAN	WIDTH (mm) S.D	WIDTH (mm) RANGE	THICKNESS (mm) MEAN	THICKNESS (mm) S.D.	THICKNESS (mm) RANGE	LENGTH (mm) MEAN	LENGTH (mm) S.D.	LENGTH (mm) RANGE	MOISTURE CONTENT (%) MEAN	MOISTURE CONTENT (%) S.D.	MOISTURE CONTENT (%) RANGE
Maritime Pine 8% EMC	0	90.0	0.2	89.5-90.3	35.3	0.2	335-35.7	996.4	1.6	995.0-999.02	10.8	2.4	7.4-16.0
	40	89.6	0.5.	88.6-90.2	35.2	0.2	34.8-35.5	996.5	1.6	995.1-999.1	9.1	1.6	7.4-13.4
Radiata Pine 8% EMC	0	90.0	0.2	89.7-90.3	35.2	0.3	34.8-35.7	995.6	1.1	994.6-996.9	10.0	2.2	7.6-12.7
	40	89.6	0.4	89.1-89.9	35.1	0.2	35.0-35.3	995.5	1.2	994.2-996.9	8.4	1.8	6.1-10.5
Maritime Pine 18% EMC	0	89.9	0.3	89.3-90.1	35.2	0.3	34.6-35.9	996.5	1.4	993.5-999.3	11.7	3.2	7.0-18.3
	40	91.4	0.7	90.3-92.1	35.8	0.3	35.2-36.2	997.1	1.5	994.0-1000.1	18.2	1.2	16.6-20.5
Radiata Pine 18% EMC	0	90.0	0.1	89.9-90.1	35.2	0.2	35.1-35.4	996.3	0.7	995.3-997.3	10.5	2.6	8.2-14.5
	40	90.7	0.3	90.3-91.2	35.6	0.2	35.3-35.7	997.2	0.8	996.2-998.4	16.0	1.7	13.9-18.2

Cown and McConchie (1980) stated that:

(1) volumetric, tangential and radial shrinkages increase outwards from the pith in a pattern similar to density;
(2) values tend to decrease with increasing height in the tree, again in proportion to changes in density;
(3) longitudinal shrinkage is extremely variable - at 12 per cent moisture content most pieces show some shrinkage, but some expand. After oven drying, a greater proportion of pieces shrink, with the highest shrinkages in samples from near the pith. These changes are small although statistically significant.

CONCLUSION

In this trial, the small movements of timber measured under the extreme EMC conditions of 8 per cent to 18 per cent would indicate that movement in-service, where the range around EMC conditions would be perhaps 3 to 4 per cent, would be minimal. Movement of the timber should therefore be a minor factor in 'inverted peaking' in ceiling and wall sheets, and a complete assessment of all factors is required.

Data on the percentage change in moisture content, length, width (tangential movement) and thickness (radial movement) for samples with straight or sloping grain indicated that the different grain orientation has no effect on the moisture content variations or changes in dimensions.

ACKNOWLEDGEMENTS

Wespine Industies are thanked for supplying the timber for this trial.

REFERENCES

Cown, D.J. and McConchie, D.L. (1980). Wood properties variations in an old-crop stand of radiata pine. *New Zealand Journal of Forestry Science* **10**(3), 508-520. Cited by Kininmonth, J.A. and Whitehouse, L.J. (1991).

Haygreen, J.G. and Bowyer, J.T. (1982). *Forest products and wood science - An introduction*. The Iowa State University Press, Ames, Iowa, USA.

Kingston, R.S.T. and Risdon, C. June E. (1961). Shrinkage and density of Australian and other South-west Pacific woods. CSIRO Division of Forest Products, *Technological Paper* No.13.

Kininmonth, J.A. and Whitehouse, L.J. (1991). *Properties and uses of New Zealand radiata pine*, Volume 1 - *Wood properties*. New Zealand Ministry of Forestry, Forest Research Institute, Rotorua, New Zealand.

Standards Association of Australia (1981). Determination of slope of grain by scribe. AS 1080.2.1. Standards Australia, Homebush, NSW.

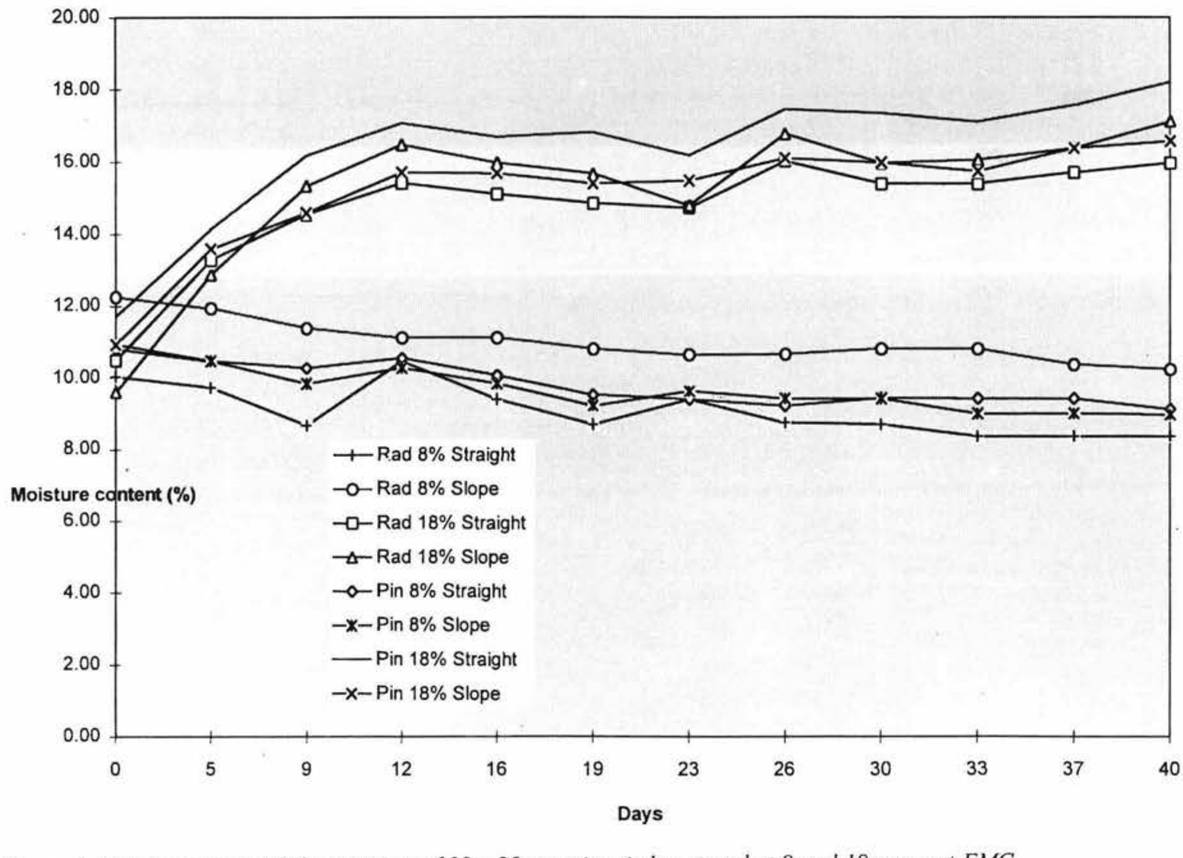


Figure 1. Moisture content (%) variations of 90 x 35 mm pine timber stored at 8 and 18 per cent EMC. Rad = radiata pine, Pin = maritime pine.

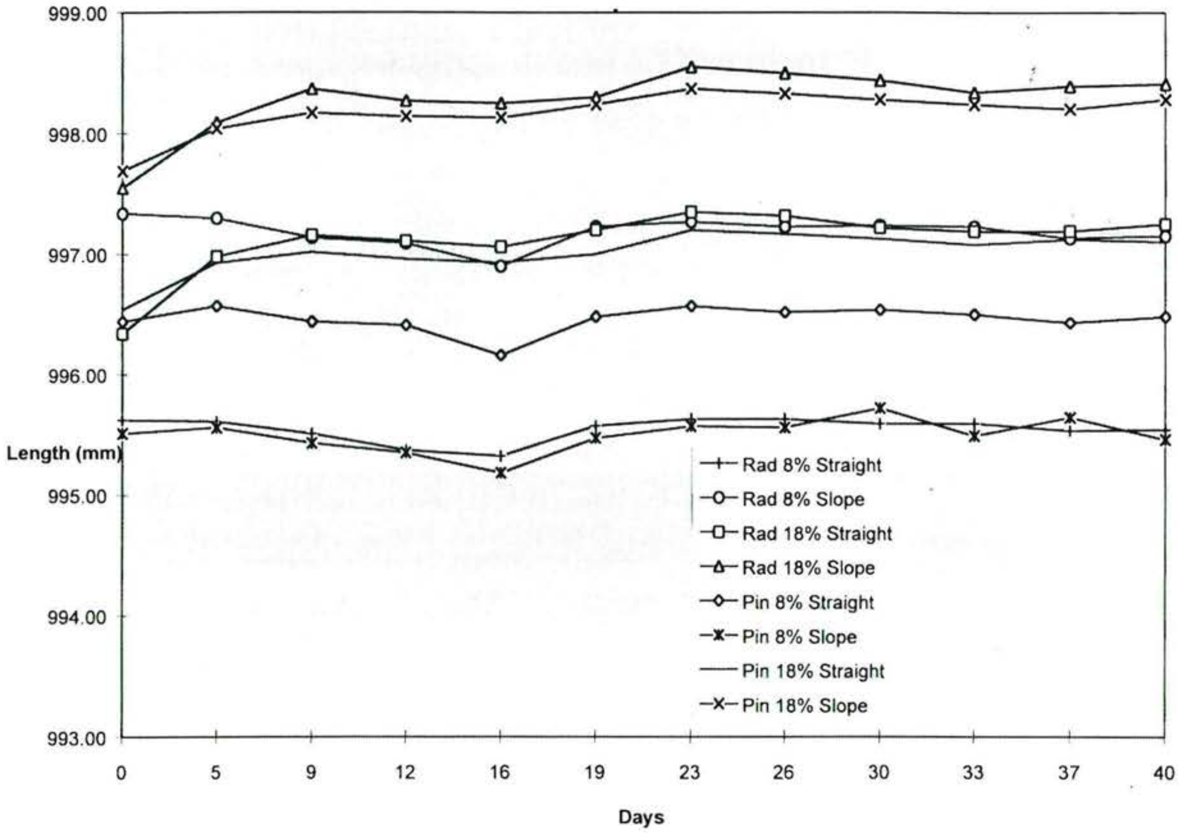


Figure 2. Change in length (mm) of 90 x 35 mm pine timber stored at 8 and 18 per cent EMC. Rad = radiata pine, Pin = maritime pine.

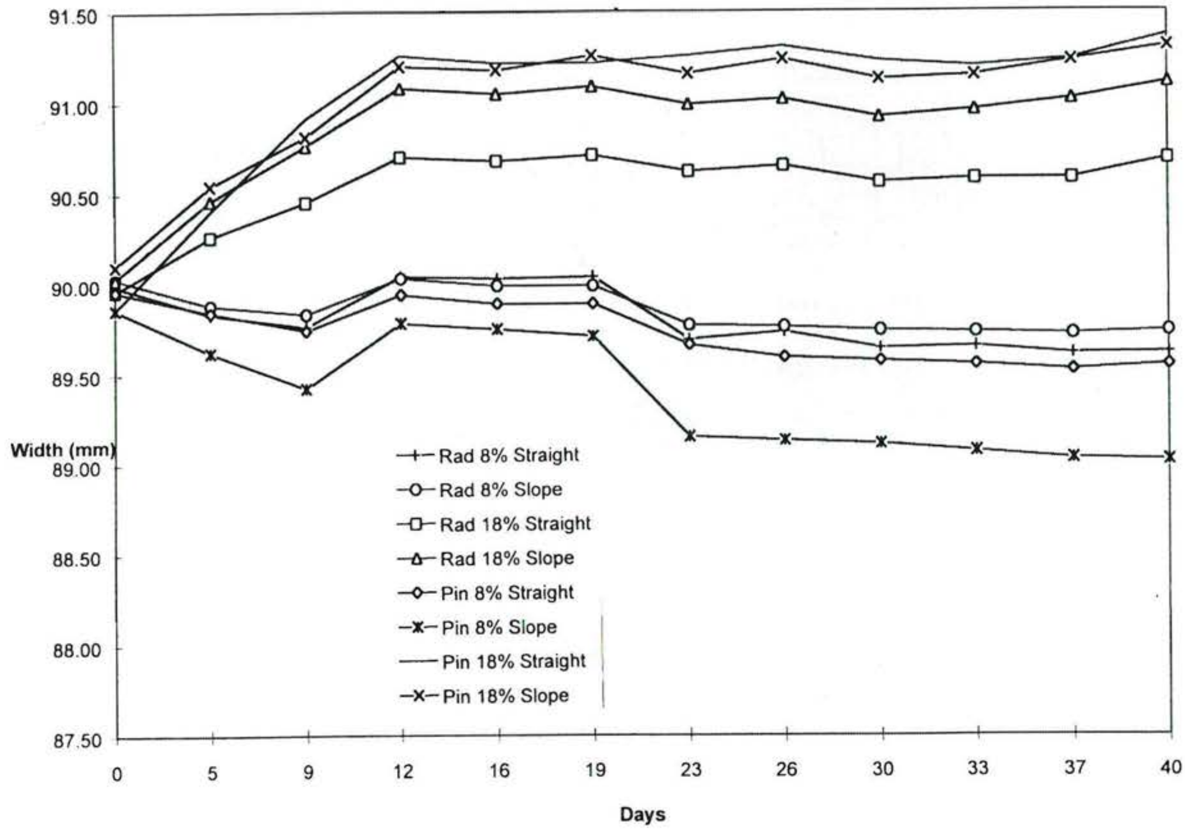


Figure 3. Change in width of 90 x 35 mm pine timber stored at 8 and 18 per cent EMC. Rad = radiata pine, Pin = maritime pine.

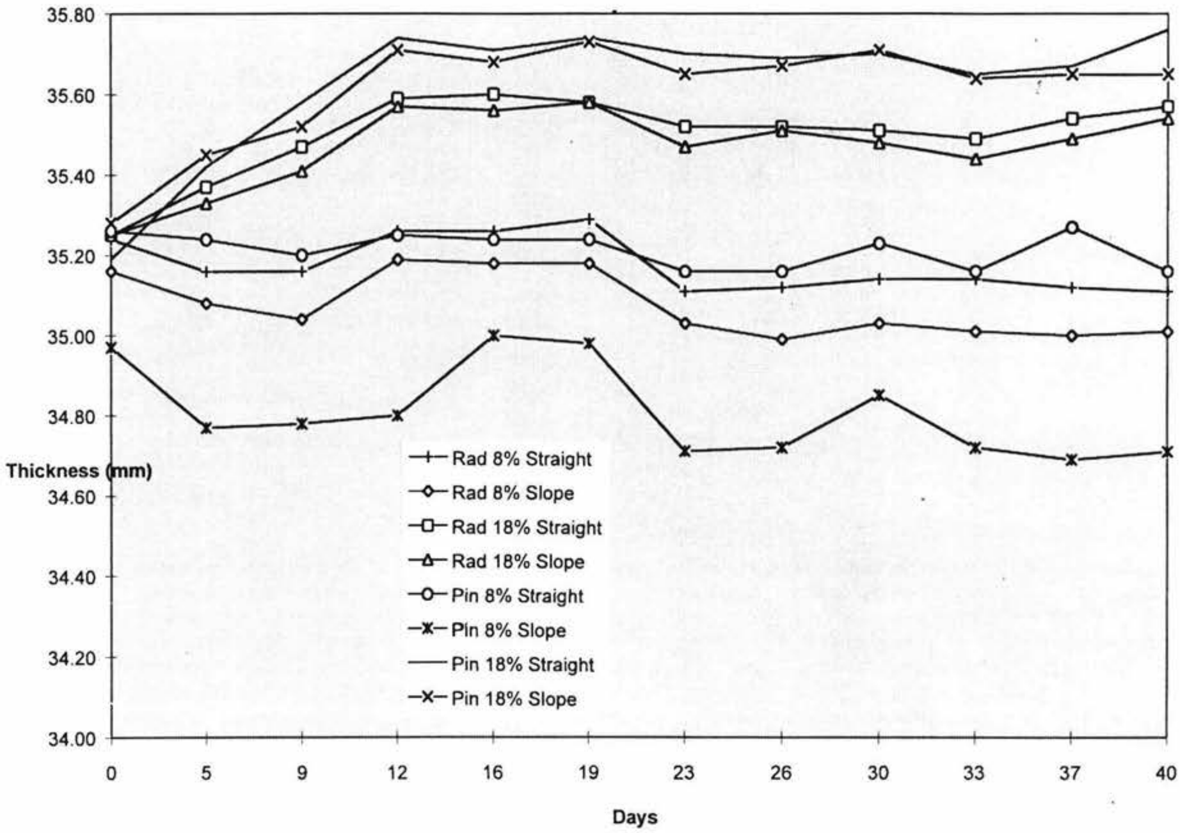


Figure 4. Change in thickness of 90 x 35 mm pine timber stored at 8 and 18 per cent EMC.
Rad = radiata pine, Pin = maritime pine.

CALMScience 2 (3): 199-202 (1997)

Sex determination in the Bulls Eye Borer *Phoracantha acanthocera* (Macleay) (Coleoptera: Cerambycidae)

J.D. FARR AND I.B. WHEELER

Science and Information Division, Department of Conservation and Land Management, Manjimup, Western Australia 6258.

ABSTRACT

Phoracantha acanthocera (= *Tryphocaria acanthocera*) was studied using behaviour and external morphology to establish characters which could be reliably used to determine sex in live beetles. Elytral width was found to be the most reliable character with females having wider elytra than males.

INTRODUCTION

Phoracantha acanthocera (Macleay) (= *Tryphocaria acanthocera* (Macleay)) is recognized as a serious pest of living eucalypts throughout southern Australia (Wang 1995). In Western Australia (WA) this insect was first mentioned as attacking marri (*Corymbia calophylla* (Lindl.) K.D. Hill & L.A.S. Johnson = *Eucalyptus calophylla* Lindl.) in relation to investigations of kino production (Forests Department 1921-22). Similarly, Clark (1925) and Duffey (1963) refer to *P. acanthocera* as causing 'damage of considerable economic importance' despite not listing as hosts WA's two main timber species, jarrah (*E. marginata* Donn ex Smith) and karri (*E. diversicolor* Muell.). Currently in WA this insect is perceived as a problem in both karri (Newman and Marks 1976; Abbott *et al.* 1991) and jarrah (McKenzie and Donnelly 1993). A study on *P. acanthocera* in regrowth karri (Abbott *et al.* 1991) concluded that infestation rates were related to drought, proximity of coupes to old growth forest, tree age, and sites where karri was a minor component before felling. Recommendations from this work included the need for further investigations into the insect's ecology and oviposition preferences.

With this and the objective of future oviposition and sex recognition behavioural studies in mind it became apparent that there was a need to readily differentiate between the sexes of live beetles. Clarke (1925) reported males as smaller than females and with longer antennae, but otherwise having few differences. Antennal length extending beyond the abdomen and overall body size is appropriate to determine dead specimens, however, this is difficult to apply to live individuals, particularly when minimal handling and disruption are desirable. This study therefore aims to examine morphological features which facilitate the ready identification of live male and female beetles.

MATERIALS AND METHODS

Live adult beetles were captured using light traps located in karri inventory plots Crowea 728 (Lat 34°32'08" S, Long 166°03'46"E) and Warren 1 (Lat 34°31'50" S, Long 115°57'30"E). To ensure that insects were captured alive no killing agent was used in the traps. The traps used 8 watt 16 x 300 mm black light fluorescent tubes which were powered by 12V deep cycle truck batteries. Traps were visited daily from December 1994 to February 1995. Captured beetles were placed separately in ventilated glass containers and transported to the laboratory. Here they were maintained in individual rearing containers and fed a 15 per cent (by weight) honey solution prior to the behavioural study. Beetles were marked with white correction fluid so that individuals could be readily identified.

The behavioural study involved placing nine adult beetles together in a 17.5 cm diameter by 18 cm enclosed arena and noting behaviour against individual identification marks. The base of the arena was lined with paper towelling and two small diameter twigs (approximately 1 cm) were placed diagonally across to provide sites for beetle interactions. Behaviour was attributed as male when the beetle exhibited mounting behaviour, downward curvature of the abdomen and 'licking' as described by Kim *et al.* (1992) and Iwabuchi (1982). Gender was then attributed to individual beetles according to behaviour. The beetles were then examined for morphological features which could be used to easily distinguish the sex of live individuals. Following this gender was ascribed to all the beetles used in the behavioural study using the morphological features formerly deemed most appropriate. The adult beetles were then dissected from the dorsal position to verify the accuracy of sex determination. To verify the reliability of these characters in determining beetle sex, pinned beetle specimens were examined, sexed and the morphological characters of antennal length, elytra length and elytra width were measured. Elytral width was determined by individually measuring right and left elytra at the widest part between shoulder and apex and calculating the sum.

RESULTS AND DISCUSSION

Results of the behaviour, morphology and dissection tests are outlined in Table 1. The test demonstrated that the morphological features discussed below are reliable characters in determining the sex of individual beetles. Beetle number one's exhibition of female behaviour was recorded during a behavioural event with beetle five. Male cerambycid beetles behaving as females in male-male encounters has been recorded by Kim *et al.* (1992).

TABLE 1

Gender determination of *Phoracantha acanthocera* using behavioural, morphological observations and dissection for male (M) and female (F) beetles.

BEETLE	BEHAVIOURAL OBSERVATIONS	MORPHOLOGICAL OBSERVATIONS	DISSECTION
1	M, F	M	M
2	F	F	F
3	F	F	F
4	M, M	M	M
5	M	M	M
6	M	M	M
7	F, F	F	F
8	F	F	F
9	M	M	M

Morphological observations showed that the posterior elytral margins of females (Fig. 1) were more obtuse than those of males (Fig. 2). Elytral spines at apex initially appeared longer for females compared with those of males, however, on closer inspection no difference was found. In live beetles the female abdomen (Fig. 3) does not closely follow the elytral margins and apices compared with those of the male whose abdomen is closely aligned with its elytral margins (Fig. 4). The outer elytral margins of males were more parallel as the insect visually appeared more streamlined. In many instances the terminal abdominal segment of the male may protrude from the base of the elytra, but this was not consistent between specimens. Comparison of the fifth visible sternites showed no easily recognizable differences between sexes.

Beetle dissection verified that elytra shape was the most reliable character to distinguish gender. Sex determination using this character was consistent with dissection results (Table 1).

Measurement of the pinned specimens (Table 2) demonstrated that although males had significantly longer

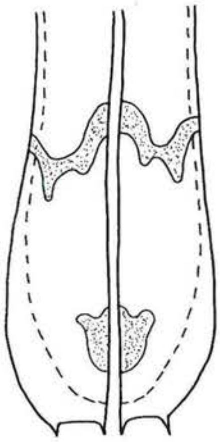


Figure 1. Dorsal view of female elytra. Broken line indicates position of abdominal wall.

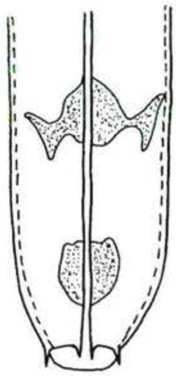


Figure 2. Dorsal view of male elytra. Broken line indicates position of abdominal wall.

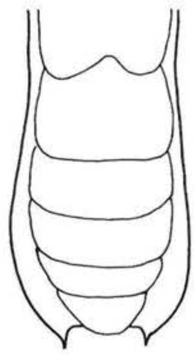


Figure 3. Ventral view of female abdomen and elytral margin.

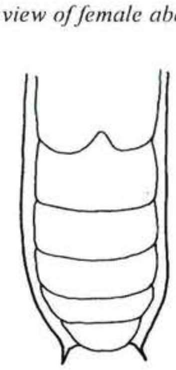


Figure 4. Ventral view of male abdomen and elytral margin.

antennae and shorter elytra, some overlap in these characters between the sexes did exist, particularly for antennal length. The greatest difference between males and females was in elytral width, with a t value of 8.04. Clear differentiation between the sexes was achieved using simple relationships between elytral length, width and antennal length (Table 3). However, these relationships are more applicable to preserved rather than to live beetles, particularly in respect to antennal length.

ACKNOWLEDGEMENTS

The authors wish to thank Dr I. Abbott, L. McCaw and T. Macfarlane for useful comments on the manuscript.

REFERENCES

Abbott, I., Smith, R., Williams, M. and Voutier, R. (1991). Infestation of regenerated stands of karri (*Eucalyptus diversicolor*) by bulls eye borer (*Tryphocaria acanthocera*, Cerambycidae) in Western Australia. *Australian Forestry* **54**, 66-74.

Clark, J. (1925). Forest Insects: The marri borer (*Tryphocaria hamata*). *Journal of Agriculture Western Australia* **2**, 513-517.

Duffey, E.A.J. (1963). *A monograph of the immature stages of Australasian timber beetles* (Cerambycidae). British Museum (Natural History), London.

Forests Department (1921-1922). *Annual Report.* Forests Department of Western Australia.

Iwabuchi, K. (1982). Mating behaviour of *Xylotrechus pyrhoderus* Bates (Coleoptera: Cerambycidae), I: Behavioural sequences and existence of the male pheromone. *Applied Entomology and Zoology* **17**, 494-500.

Kim, G-H, Takabayashi, J., Takahashi, S., Tabata, K. (1992). Function of pheromones in mating behaviour of the Japanese Pine Sawyer Beetle, *Monochamus alternatus* Hope. *Applied Entomology and Zoology* **27**, 489-497.

McKenzie, J.W. and Donnelly, D.J. (1993). *Tryphocaria* attack in regrowth jarrah. Pilot study. W.U.R.C. Internal report, Department of Conservation and Land Management, Perth, WA.

Neuman, F.G. and Marks, G.C. (1976). A synopsis of important pests and diseases in Australian forests and forest nurseries. *Australian Forestry* **39**, 83-102.

Wang, Q. (1995). A taxonomic revision of the Australian genus *Phoracantha* Newman (Coleoptera: Cerambycidae). *Invertebrate Taxonomy* **9**, 865-958.

TABLE 2

Comparison of means for Antennal length, Elytral length and Elytral width using t tests for independent samples.

	MEAN	RANGE	N	SE	DF	t^a	P
Antennal length (mm)							
Male	40.05	36.32 - 43.83	7	1.24	16	-2.98	0.009
Female	35.69	31.90 - 40.00	11	0.87			
Elytral length (mm)							
Male	19.96	18.47 - 21.91	7	0.52	16	5.988	0
Female	25.36	21.54 - 29.00	11	0.64			
Elytral width (mm)							
Male	8.58	8.01 - 9.33	7	0.16	16	8.043	0
Female	11.58	10.12 - 13.14	11	0.28			

^{a} statistic for pooled variances

Critical $t_{0.05\,[16]} = 2.120$

TABLE 3

Differentiation between male and female beetles using relationships between Antennal length (Ant len), Elytral length (Ely len) and Elytral width (Ely wid), expressed as a range.

	Ely len x Ely wid	Ant len/Ely wid	Ant len/(Ely len x Ely wid)
Male	158.12 - 203.86	4.30 - 4.94	0.21 - 0.26
Female	217.98 - 367.66	2.93 - 3.25	0.11 - 0.15

CALMScience 2 (3): 203-224 (1997)

Timber harvesting of Crown land in the south-west of Western Australia: an historical review with maps

GREG HEBERLE

Department of Conservation and Land Management, 50 Hayman Road, Como, Western Australia 6152.

SUMMARY

The forests in the south-west of Western Australia have been harvested and their timber utilized since the beginning of European settlement in 1829. The earliest methods of timber production were pit-sawing, which was common until about 1900, and hewing, which was significant until about 1945. Hauling of logs and sawn timber was done exclusively by horse or bullock team until the introduction of timber tramways in the 1870s. Since about 1970, all log hauling has been by log truck. The first sawmill in the State operated in Perth in 1833, but the first of the large sawmills was established at Quindalup in 1858.

Reliable timber harvesting records in the form of maps are held by the Department of Conservation and Land Management (CALM) for the period since 1920. Incomplete or less detailed records are available for the period 1829 to 1920. The author considers that some additional areas not shown as harvested in the CALM records were harvested before 1920. Other areas are recorded as harvested before 1920 but date unknown. Likely dates (decades) of cutting are postulated for these areas.

Maps are presented showing likely dates of first, second, third, and fourth logging (harvesting) on Crown lands in the south-west of Western Australia. Based on these maps, about half of the jarrah and wandoo forest on Crown land in the northern and central forest areas (CALM's Swan and Central Forest Regions) has been logged twice and some areas five times to 31 December 1989. By contrast, there was little logging in the southern forest area (CALM's Southern Forest Region) until about 1900 and most of the karri forest has only been logged once.

INTRODUCTION

Reliable timber harvesting records for Crown lands in Western Australia (WA) are available in the form of maps held by the Department of Conservation and Land Management (CALM) for the period since 1920; i.e. since the Forests Department was created. Much less reliable records are available for the period before 1920. This paper has been written to synthesize a considerable volume of scattered information on timber harvesting in south-west Western Australia into a unified account intended to be useful for forest biologists, forest managers and others.

BACKGROUND

In this paper, jarrah and karri forest is defined as described in Department of CALM (1992), to include associated species such as marri.

Logging

Logging (harvesting) is the felling of trees, preparation of logs (the utilizable part of a tree stem), extracting (snigging) logs from the site of felling at the tree stump to a landing or loading point, loading and carting the logs to the sawmill or other timber processing plant.

Felling Methods

Felling and snigging methods have been described by Hewett (1979). In the early days of European settlement, trees were felled using an axe or an axe and cross-cut saw.

The development of portable engines paved the way for mobile power saws in the mid-1940s. The first of these was mounted on two (occasionally one) wheels and fitted with either circular or cross-cut saw blades.

In the late 1940s the first chain-saws became available in WA. The first models were two-person saws about 2 m long and were very heavy. These saws were in use for about seven years until the first one-person chain-saws arrived in Australia in about 1955. These were still very heavy by modern standards but had better chain than the earlier chain-saws. Since then chain-saws have been greatly improved by reducing their weight, noise and vibration levels.

Hewing and Pit-sawing

The earliest methods of timber production in Western Australian hardwood forests were hewing and pit-sawing.

Hewing was a three-part process of felling, splitting and squaring large pieces of timber for railway sleepers, bridge and jetty decking and large beams. The work occurred beside the stump at the site of felling and only the finished product was carried or dragged to a loading site. Sleeper hewing involved enormous waste (Mills 1989). Between about 1900 and 1935 most sleepers produced in the State were hewn. Teams of hewers operated in many areas, notably Sawyers Valley (east of Midland), Mungalup (Lucknow, near Collie), Noggerup and Mullalyup (both near Kirup), Hester (near Bridgetown) and Palgarup (near Manjimup). By 1945 sleeper hewing had been virtually replaced by sawmilling.

Much the same process occurred with pit-sawing, except that a log was rolled with bars and levers onto a sawpit and sawn by cross-cut saw (Underwood 1977). Pit-sawing was the most common method of log sawing between 1829 and the 1880s. By 1900 it had given way to sawmilling.

Snigging

In WA's south-west forests, teams of horses or bullocks were used for snigging (dragging logs) until the 1920s. The logs were often supported by a whim or logging arch consisting of a pair of large wheels joined by a cranked axle allowing the machine to straddle logs. Chains were used to lift the front of the log off the ground for easier snigging.

The first advance from animal power for snigging occurred in the 1920s, with the introduction of steam powered hauling machines for winching logs to landings on the timber tramway. (Timber tramways were light, often temporary 'railways', usually with wooden rails, whereas train railways are always steel.) These hauling machines comprised a steel cable on a drum a metre or so in diameter and were extremely heavy so remained stationary at the landing while a small team of horses or bullocks extended the cable to the logs which were then winched on to the landing.

During the late 1930s, crawler tractors were first used for snigging small logs. As heavier and more powerful tractors were developed during and after the Second World War, they gradually displaced all other snigging methods. Since the 1960s rubber tyred articulated tractors have replaced crawler tractors except under the most difficult conditions (e.g. for very large logs or working on a steep terrain).

For photographs of snigging operations, see Forests Department (1969) and Hewett (1979).

Log and Timber Hauling

Hauling (transporting) of logs and sawn timber was carried out exclusively by horse or bullock teams until the introduction of timber tramways in the 1870s. The first steam powered locomotives used for timber hauling were the 'Ballarat' used by WA Timber Company on the Lockeville concession near Busselton from 1871 and the 'Governor Weld' used on the Jarrahdale Concession from 1872 (Southcombe 1986). Some of the smaller sawmills used horses rather than locomotives on their tramways. The first locomotives ran on wooden rails, but the wear was so great that it was not long before they were replaced with steel rails.

Provision of a reliable and economic transport system was essential for development of the timber industry. Timber company railways were among the first railways in the State. Government railways did not operate until 1879 near Geraldton and 1881 near Perth. The Government eastern railway reached Chidlow in 1884 and York by 1886. The railway network was extended into the south-west as follows: to Bunbury in 1893, Busselton in 1895 and to Collie and Bridgetown in 1898. Lines were extended to Nannup in 1909, Dwellingup in 1910, Manjimup in 1911, and Pemberton in 1913. With the advent of the Government railway system the timber company railways were only needed to transport logs to the sawmills and sawn timber from these mills to the nearest Government rail siding.

Normally the first timber tramway to be built in an area was the one to convey the sawn timber from the mill to the nearest shipping point. Then lines were constructed leading to the bush to enable logs to be hauled to the mill. Initially all the formations for the line were constructed by hand and many men were employed laying, and then pulling up line after the timber had been cut in the area.

Bush locomotives remained in general usage in the jarrah forest until around 1950 when the huge cost of pulling up and re-laying lines made their operations uneconomic and motor transport started to take their place. Some locomotives continued to be used by timber companies, especially in the karri forest, until about 1965. Since then, all log hauling has been by log truck.

Early Logging and Forest Administration

Nunn (1957) reviewed the history of timber production in WA. Reports of the valuable hardwood forests existing in WA influenced the decision of the British Government to establish a settlement at the Swan River in 1829. Timber was one of the State's first exports. Sawn timber was exported as early as 1831. This timber was pit-sawn, as no sawmill existed at that time.

The first sawmill in the State was operating in Perth, at the foot of Mt Eliza in Kings Park, by 1833. Mr J Monger was associated with this mill and also the first steam sawmill in the State, which began operations at Guildford near Midland in 1844. The latter mill was operated by Monger and Cowan. Also in 1844 J & G Handcock established a mill at Belmont near Perth. Pit-sawyers were active on the coastal plain near Perth and in the hills just east of Perth from about this time. By the 1860s pit-sawing was also taking place near Walpole, Augusta, Busselton and Bunbury.

In 1858 the first of the larger, longer lasting sawmills in the State was operating at Quindalup, west of Busselton: the earlier sawmills were typically very small, producing less than 500 m^3 of sawn timber per year. H. Yelverton operated the Quindalup mill on a concession granted to him by the Government. In the early 1870s further concessions were granted at Lockeville, Jarrahdale (near Serpentine Dam) and Canning (near Canning Reservoir). Concessionaires were granted sole rights for a number of years, at a nominal rent per annum, to remove, sell or export timber from their concessions.

In 1875 special timber licences were introduced. From 1889 until 1898 special timber licences were issued under Clause 96 of the Lands Act Regulations. Between 1899 and 1904 timber leases were issued under Section 113 of the same Act. In the Land Act amendment of 1904, sawmilling permits were issued for the first time, under Section 11.

Until 1896, timber harvesting on Crown lands was administered by the Lands Department. In 1896 a new Department, the Department of Woods and Forests, was created with a trained forester, J Ednie-Brown, as Conservator acting under the Minister for Lands. Ednie-Brown died in 1899. From then until 1916, the Department was headed by its Chief Clerk, Mr C Richardson. During these years there was no trained forester in the Department, which functioned as little more than a revenue collecting organization (Mills 1989).

In 1916 a trained forester, C.E. Lane-Poole, was appointed Conservator of Forests. Lane-Poole was a graduate of a French forestry school and was primarily responsible for drafting the Forests Act, 1918. This Act was passed by Parliament in December 1918 and the Forests Department of Western Australia came into being in January 1919. From that time, sawmilling and other timber permits were issued under the Forests Act and Regulations, until the Forests Department was absorbed into the Department of Conservation and Land Management in 1985.

Silvicultural History

Jarrah

Stoneman, Bradshaw and Christensen (1989) have described the typical silvicultural practices followed in the jarrah forest.

Prior to the 1920s there was effectively no forestry control over logging operations within timber concessions, licences, leases or permit areas. Sawmillers selected the trees they wished to cut, leaving behind the poorer trees. This meant that some areas of high quality forest were heavily cut and others had a very light selective cut. Sleeper hewers also operated over large areas of forest, selecting only the best trees. In high quality forest, the gaps created by logging generally quickly filled with saplings which developed from ground coppice, but there was no systematic attempt at reforestation, or at fire protection of new regrowth stands.

Between the early 1920s and 1940 a group selection system was employed. Areas for felling were treemarked by Forests Department foresters to create gaps for regeneration, leaving groups of immature trees intact. After logging the areas designated for gaps the remaining unwanted trees were ringbarked and small malformed trees cut off (to the extent that funds permitted this). During the Depression (in 1929 and early to mid-1930s) extensive areas of jarrah regrowth stands were thinned and unwanted overstorey trees were ringbarked (Forests Department 1969).

From the 1940s to mid-1960s a lighter selection cut was applied. Unwanted jarrah and marri trees were retained for possible future markets. There was no ringbarking of unwanted trees or cutting off of small malformed trees. The system was primarily a single tree selection system.

From the mid-1960s until 1985 the cutting intensity increased, particularly after 1970 when a more intense cut in a smaller area was introduced to reduce the area harvested each year. An individual tree selection system was employed with little or no attempt at producing gaps. In addition, all saleable produce was removed (salvaged) from areas infected by *Phytophthora cinnamomi*. Some areas were non-commercially thinned (excess trees poisoned) during this period.

In 1985, a group selection system was reintroduced, with renewed emphasis on thinning.

Karri

Bradshaw and Lush (1981) have described the development of forest policy and practice in the karri forest in the southern part of south-west WA. The earliest logging in the karri forest was carried out under a clear-felling system (all marketable trees harvested). Most of the areas logged were converted to agriculture, although harvested forests at Karridale (north of Augusta) and Denmark exhibited prolific regeneration following clear-felling. In 1925 the first karri forest was dedicated as State forest, an area of 2900 ha at Big Brook, near Pemberton. A working plan was prepared for this area and the silvicultural system employed was the clear-felling method. As most of the trees had been removed by the local sawmill, regeneration preparation was carried out and areas burnt in the next few years, to be regenerated by seed-fall from the remaining unwanted trees. Once seed-fall had taken place these trees were then ringbarked.

The clear-felling system of harvesting and regeneration was maintained in karri State forest until about 1938 when, for a variety of reasons, it gave way to the selection system. The clear-felled areas, apparently devastated and finished with, were under continuous pressure for release for agriculture: selection cut stands did not attract as much pressure for alienation to agriculture. Clear-felling and regeneration burning involved some wastage of small and defective trees, and substantial areas of old growth karri forest were deteriorating owing to fire damage and old age. A lighter selection cut enabled faster salvage of this wasting resource and expedited the provision of access to remote areas of forest to facilitate fire protection. All of these factors contributed to the change from clear-felling to selection cutting in the 1940s.

By the mid-1960s, a number of problems with selection cutting and regeneration of the karri forest had become obvious. There were difficulties of burning for regeneration in small gaps in the forest: a hot fire is needed to produce good seed bed conditions, but this often damaged the remaining trees. Retained trees often declined in health. Also, growth of regenerated forest was depressed by nearby mature trees. Another problem was the difficulty of carrying out subsequent harvesting and regeneration burning among groups of regenerated trees without destroying them. For these reasons the selection system was discontinued in favour of clear-felling in 1967.

The next major change in karri forest management practice occurred in 1975 with the establishment of the woodchip industry. To ensure optimal regeneration after harvesting, it is desirable to remove all trees from an area, including those unsuitable for sawmilling, so that there will be no competition for the new regrowth. Provision of a market for woodchips to utilize those trees unsuitable for sawmilling greatly reduced the need for ringbarking, poisoning or bulldozing unwanted trees to make way for new regeneration.

METHODS

CALM timber harvesting records were consulted to establish Crown land areas recorded as cutover (harvested) before 1920 and since 1920 (by decades), and the number of times they had been cutover, as at 31 December 1989. Some areas shown in the CALM cutting records as not cutover as at 1920, were inside sawmilling tenements, and adjoined mills or timber tramways/railways and so were almost certainly cutover before 1920 despite the evidence in the records. Other areas are recorded as cutover before 1920 but year unknown. From historical data it is possible to postulate the decade of the initial cutting for these areas. This can be done by using records of early sawmill operations and dates of operation, and records of timber licences, leases, permits, timber tramways and railways.

Maps held by CALM Information Management Branch and CALM Library and the Battye Library in Perth were searched for the locations and years of operation of sawmills and the associated roads, timber tramways and railways. Old files for timber tenements, held by the Battye Library, were also perused for similar information.

Useful historical information, such as the location of early sawmills, timber tenements and tramways was found in early reports on the forests of WA by Fraser (1882) and Ednie-Brown (1896, 1899). Further information on the dates of operation of early sawmills (opened before 1930) was obtained from the *Annual Reports* of the Woods and Forests Department and Forests Department from 1896/97 to 1929/30.

Local histories for towns and shires in and near the forest areas show how important the timber industry was in the early development of the south-west of the State and many provided data useful in establishing early logging history. These include Eliot (1983) covering Mundaring Shire; Slee (1979) Kalamunda area; Popham (1980) Armadale area; Coy (1984) Serpentine-Jarrahdale Shire; Fall (1979) Jarrahdale area; Richards (1978) Murray Shire; Snell (1980) Waroona Shire; Staples (1979) Harvey Shire; Frost (1976) Donnybrook area; Frost (1979) Balingup area; Gaines (1970) Bridgetown area; Gilbert (n.d.) Nannup area; Fall (1974) Augusta area and Berry (1987) Manjimup district.

A number of publications covering the history of the timber industry as a whole or the operations of one timber company also provided useful data, notably Thomas (1937-38), Robertson (1956), Gilchrist (1962), Calder (1980), Mack (1985), Abbott and Loneragan (1986), Southcombe (1986), Mills (1986, 1989) and Moore (1987). Some WA Heritage trail booklets provide valuable historical data, notably 'Cala Munnda', 'Geegelup', 'Kattamorda' and 'Mason and Bird'.

Records of timber exports and estimated total timber production in the early years, from Rotheram (1985), were used to derive estimates of volumes and areas logged in those years at each sawmilling centre. These data provided further evidence that some areas were harvested before 1920, before accurate records were kept. This highlighted the need to update CALM's records for pre-1920, using other available information.

DISCUSSION

Early sawmills were concentrated in the forest north of Manjimup (Appendix 1). These resulted in an extensive network of tramways and railways through the forest (Appendix 2). Activities of these mills resulted in much of the northern forest (now in CALM's Swan and Central Forest Regions - see Appendices 3a-3d) being harvested several times, especially those close to the Darling Scarp (Appendices 3a-3d). These maps are based on the best available records at the time this study was done. In addition, two areas near Jarrahdale are considered to have been harvested for sawlogs five times. It is possible that more comprehensive records of early logging may emerge in the future and revisions can be made. For example, further searches of old files in the Battye Library and access to timber company records may locate additional data.

It should be noted that the cutting records depicted in Appendices 3a-3d refer only to areas harvested for sawlogs. Many areas harvested for sawlogs had previously been worked by hewers cutting railway sleepers, or settlers cutting fencing timbers. Near Collie coal fields and adjoining areas some areas have also been harvested for mining timber on one or more occasions since 1898. Similarly, mining timber has been removed from the Greenbushes area. Some areas (mainly regrowth areas) have been harvested once or twice for poles and/or piles, in addition to the sawlog harvesting. Other areas were harvested for firewood, including a large area around Helena Reservoir which was ringbarked and then cut for firewood for the pumping stations.

In recent years, cutting for different products has been fully integrated, with sawlogs and other forest products taken in one operation. Previously, most minor forest produce such as domestic firewood and fence posts, was removed as an independent operation.

Sawmilling began on present day State forest (jarrah forest) in the Kalamunda area (near Kelmscott) in the 1860s, and in the 1870s near Serpentine Dam and near Bunbury and Busselton. Sawmilling began in the karri forest at Karridale (near Augusta) in the 1880s, Denmark in the 1890s and near Manjimup and Pemberton in the period 1912-1914. At least 260 sawmills operated throughout the south-west forests before 1930 (Appendices 4-13). Their dates of operation have been established as near as possible from the incomplete records now available. The data provided are the sawmill owner or owners (and dates ownership changed), date the mill commenced and ended operations (if known) and location. Some mills, particularly large, long-life mills, had more than one owner. Some mills had a name which, if known, is listed. In general, very small sawmills, e.g. under 500 m^3 per year of sawn timber output, have not been listed. The dates listed are the best guess, based on the available data. Some mills closed for periods. The classification of some mills (big, medium, small) changed over time.

Logging intensity varies from a thinning or light cut removing only a small proportion of the marketable trees, to a heavy cut removing a large proportion of the marketable trees. In a clear-cut, all the marketable trees are removed. The number of trees (or proportion of original number) remaining after logging is greatly affected by what products are marketable at the time and by the silvicultural system being practised. Many small trees are not marketable. If only sawlog is sold, then trees too small to contain a sawlog will be retained plus large trees not suitable for sawlogs (e.g. deformed trees) and any other trees retained as crop trees (seed trees) or for other purposes. In addition, within the harvested area there are usually pockets of trees not harvested because they occur along watercourses, or areas too steep to log. Since the late 1980s, habitat trees for fauna, often containing merchantable timber, have been retained at rates of 3-5 trees per hectare in the jarrah forest. Tree-less areas (wetlands, rocks, open areas) are obviously not harvested but have sometimes in the past been affected by logging activity such as snig tracks and haul roads.

The nominal cutting cycle for jarrah forest has typically been 30 to 50 years between cuts, in the higher rainfall areas and where a selection cutting system has been used. That is, in the first harvest (cut) in the selection cutting system only those trees of high commercial value are harvested, leaving less developed trees to develop to maturity so that they will then be harvested in a subsequent cutting cycle in 30-50 years. In less productive forest, such as occurs in the eastern low rainfall sector, the cutting cycle has been longer and many areas have been harvested only once or twice since 1829. In recent years many areas have been harvested earlier than initially planned because of the need to salvage timber on areas to be cleared for public utilities, mining or pine plantations, or to salvage windblown or diseased trees.

Rotation lengths for karri forest are described in Department of CALM (1994). Most multiple use karri forest is intended to be managed on a rotation length of at least 100 years.

A recent paper by Abbott and Christensen (1994) shows that, based on a synopsis of indicators, the jarrah and karri forests are in ecologically good condition after up to 120 years of timber harvesting.

In CALM's latest management plan covering the south-west forests (Department of CALM 1994), some 384 000 ha of jarrah forest and 53 000 ha of karri forest is in existing or proposed conservation reserves, including 135 000 ha of unlogged jarrah forest and 40 000 ha of unlogged karri forest. Additional areas are set aside to be managed as riparian and faunal travel route zones. These areas combined represent some 33 per cent of the jarrah forest and some 46 per cent of the karri forest on Crown land managed primarily for nature conservation where logging operations cannot occur.

CONCLUSIONS

Logging of forests on Crown land in areas now defined as CALM's Swan and Central Forest Regions (see Appendices 3a-3d) commenced in many areas in the 1870s or 1880s, and many easily accessible areas have been harvested for sawlogs three or more times since then. About half of the jarrah forest on Crown land in CALM's Swan and Central Forest Regions has been harvested twice. Access to the forests of the Southern Forest Region was much more difficult and logging did not commence until after 1900, apart from some pit-sawing near Walpole in the 1860s and logging by Millars in the Denmark area in the late 1890s. Of the karri forest that has been logged, most has only been logged once.

ACKNOWLEDGEMENTS

The author acknowledges the use of CALM Forest Management Branch forest harvesting records and, in particular, Pat Collins for the provision of Forest Management Information System overlays showing harvesting history. I wish to thank Mark Laming for preparing the maps and Jasmine Moylett for typing the earlier drafts. I also wish to thank Dr Ian Abbott, Dr Paul Biggs, Jack Bradshaw and Roger Underwood for comments on drafts of this paper.

REFERENCES

Abbott, I. and Christensen, P. (1994). Application of ecological and evolutionary principles to forest management in Western Australia. *Australian Forestry* 57(3), 109-122.

Abbott, I. and Loneragan, O. (1986). Ecology of jarrah (*Eucalyptus marginata*) in the northern jarrah forest of Western Australia. Department of Conservation and Land Management (Perth) *Bulletin* No.1.

Berry, C. (1987). *The history, landscape and heritage of the Warren District*. Shire of Manjimup, Manjimup, Western Australia.

Bradshaw, F.J. and Lush, A.R. (1981). *Conservation of the karri forest*. Forests Department of Western Australia, Perth.

Calder, M. (1980). *Big timber country*. Rigby, Adelaide, South Australia.

Coy, N.J. (1984). *The Serpentine: a history of the Shire of Serpentine-Jarrahdale*. Shire of Serpentine-Jarrahdale, Mundijong, Western Australia.

Department of CALM (1992). Management strategies for the south-west forests of Western Australia: a review - draft for public comment. Department of Conservation and Land Management, Como, Western Australia.

Department of CALM (1994). Forest management plan 1994-2003 (prepared for the Lands and Forests Commission). Department of Conservation and Land Management, Como, Western Australia.

Ednie-Brown, J. (1896). *Report on the forests of Western Australia, their description, utilisation and proposed future management*. Government Printer, Perth.

Ednie-Brown, J. (1899). *The forests of Western Australia and their development*. Perth Printing Works, Perth.

Eliot, I. (1983). *Mundaring: a history of the shire*. Shire of Mundaring, Mundaring, Western Australia.

Fall, V.G. (1974). Giants in the south - a history of Western Australia: Land of the Leeuwin. Typescript in the Battye Library, Perth.

Fall, V.G. (1979). *The mills of Jarrahdale: a century of achievement 1872-1972*. Perth, Western Australia.

Forests Department of WA (1919-1930). *Annual reports*. Government Printer, Perth.

Forests Department of WA (1969). *50 years of forestry in Western Australia*. Government Printer, Perth.

Fraser, M. (1882). *General information, respecting the present condition of the forests and timber trade of the southern part of the colony*, etc. Government Printer, Perth.

Frost, A.C. (1976). *Green gold: a history of Donnybrook WA*. Donnybrook-Balingup Shire Council, Donnybrook, Western Australia.

Frost, A.C. (1979). *Baylya Balinga: a history of Balingup WA*. Donnybrook-Balingup Shire Council, Donnybrook, Western Australia.

Gaines, C. (1970). Bridgetown - one hundred years of history. Typescript in Battye Library, Perth.

Gilbert, C. (n. d.). *History of Nannup*. Nannup Shire Council, Nannup, Western Australia.

Gilchrist, W.E. (1962). The history of Millars Timber and Trading Company and its influence on the timber industry of WA. Typescript in Battye Library, Perth.

Government of Western Australia (1992). Conservation and Land Management Act 1984 Reprinted under the Reprints Act 1984 as at 16 January 1992. Government Printer, Perth.

Hewett, P.N. (1979a). Logging series No. 1 - felling methods. Forests Department of WA *Information Sheet* No. 40

Hewett, P.N. (1979b). Logging series No. 2 - snigging methods. Forests Department of WA *Information Sheet* No. 41.

Mack, D. (1985). *Timber milling in Australia 1849-1984*. Adelaide Timber Company, Perth, Western Australia.

Mills, J. (1986). *The timber people: a history of Bunnings Limited*. Bunnings Limited, Perth, Western Australia.

Mills, J. (1989). The impact of man on the northern jarrah forest from settlement in 1829 to the Forests Act 1918. In *The jarrah forest: a complex mediterranean ecosystem*, eds B.Dell, J.J. Havel and N. Malajczuk, pp. 229-279. Kluwer Academic Publishers, Dordrecht, Netherlands.

Moore, B. (1987). *From the ground up: Bristile, Whittakers and Metro Brick in Western Australian history*. University of Western Australia Press, Perth.

Nunn, G.W.M. (1957). Forest management in the eucalypt forests of the south-west of Western Australia. Paper to Seventh British Commonwealth Forestry Conference Australia and New Zealand, in Adelaide 1957.

Popham, D. (1980). *First stage south: a history of the Armadale-Kelmscott District, Western Australia*. Town of Armadale, Armadale.

Richards, R. (1978). *The Murray District of Western Australia: a history*. Shire of Murray, Mandurah.

Robertson, J.R. (1956). A history of the timber industry of Western Australia. BA (Hons) thesis, University of Western Australia, Perth.

Rotheram, I.D. (1985). The use of WA's tall forests for timber production: past experience and present problems. MSc thesis, University of Western Australia, Perth.

Slee, J. (1979). *Cala Munnda: a home in the forest*. Shire of Kalamunda, Kalamunda, Western Australia.

Snell, L.J. (1980). *Drakesbrook days and Waroona years*. Shire of Waroona, Waroona, Western Australia.

Southcombe, M.R.H. (1986). *Steam in the forests*. Hesperian Press, Victoria Park, Western Australia.

Staples, A.C. (1979). *They made their destiny: history of settlement in the Shire of Harvey 1829-1979*. Shire of Harvey, Harvey, Western Australia.

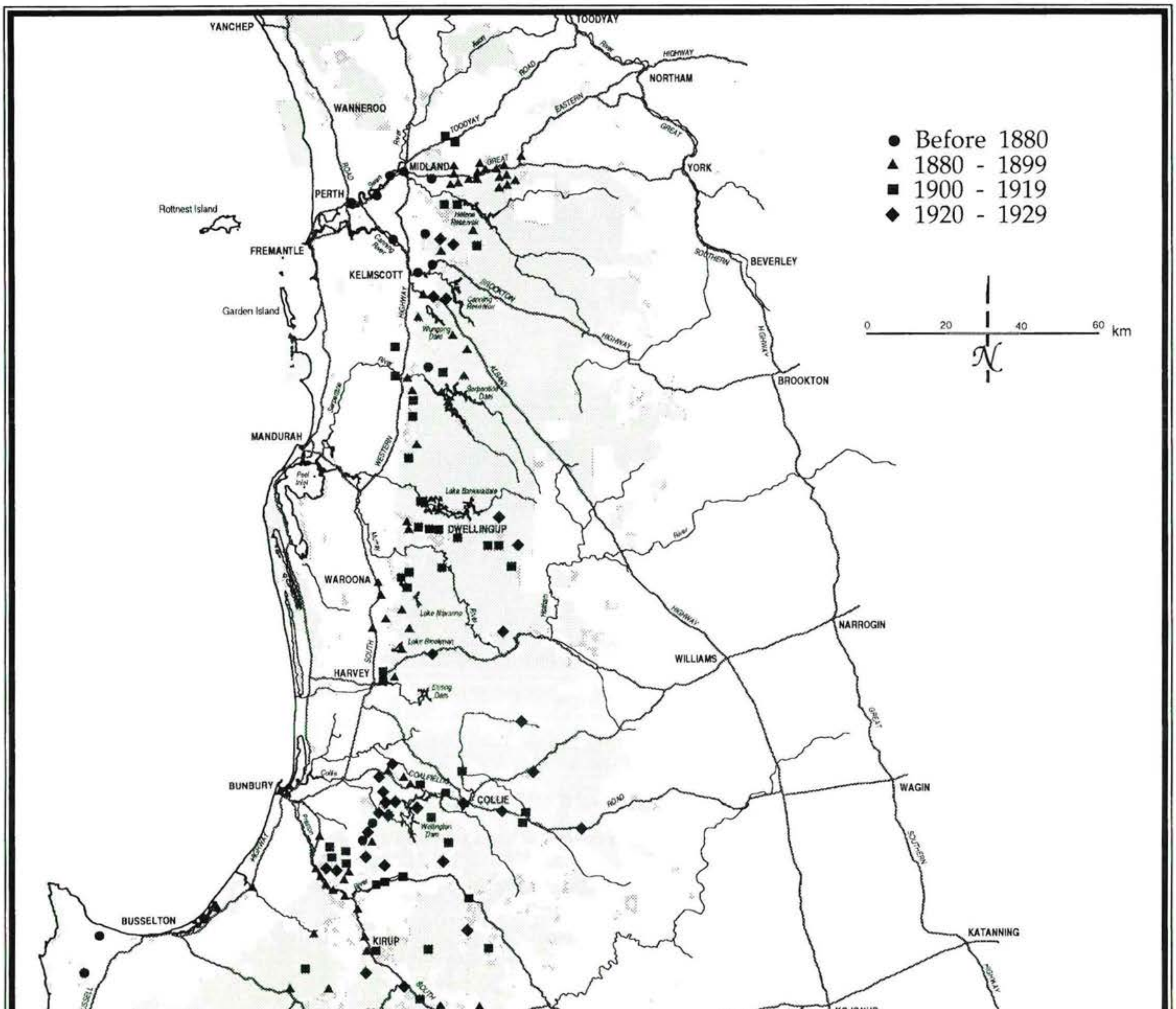
Stoneman, G.L., Bradshaw, F.J. and Christensen, P. (1989). Silviculture. In *The jarrah forest: a complex mediterranean ecosystem*, eds B.Dell, J.J. Havel and N. Malajczuk, pp. 335-355. Kluwer Academic Publishers, Dordrecht, Netherlands.

Thomas, W.C. (1937-38). Mills and men in WA - sawmilling in Western Australia: story of its development. Series of articles from *The Western Mail* and *Australian Timber Journal*. Available as a set in the Battye Library, Perth.

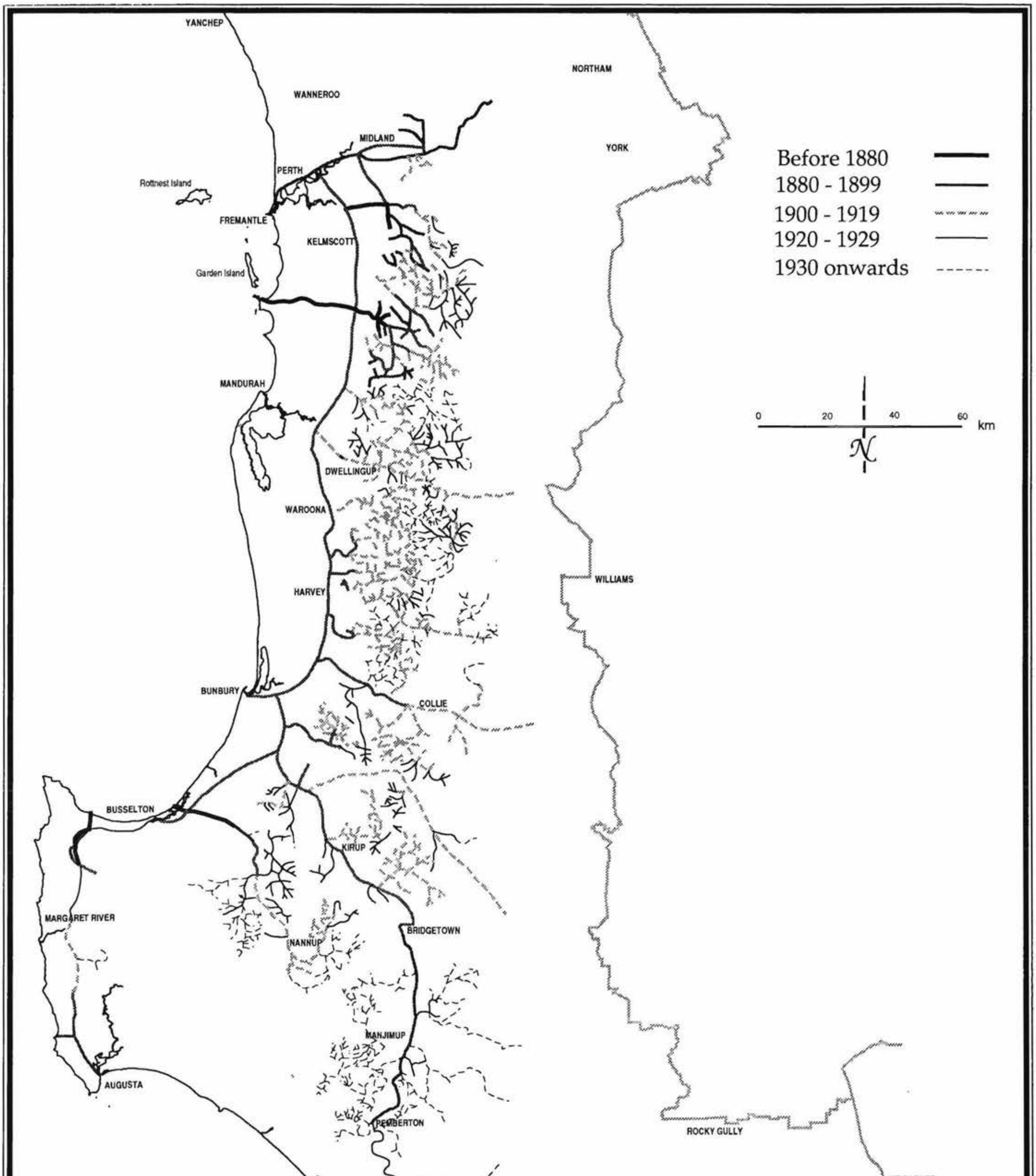
Underwood, R.J. (1977). Pit-sawing in Western Australia. Forests Department of Western Australia *Information Sheet* No. 9.

WA Heritage Committee (1988). Booklets for the heritage trails *Cala Munnda, Geegelup, Kattamorda, Mason and Bird*. Western Australian Heritage Committee, Perth.

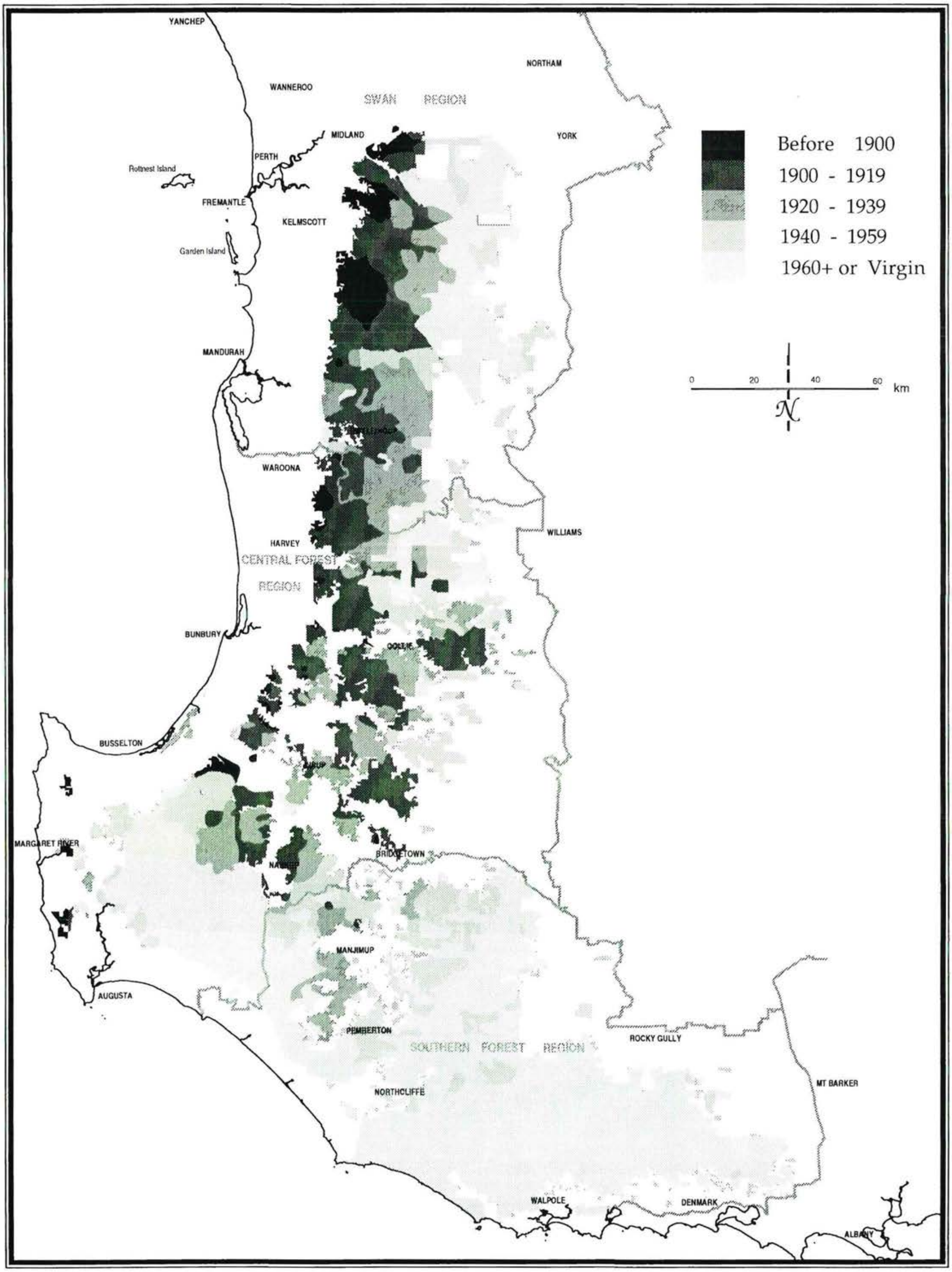
Woods and Forests Department (1897-1918). *Annual reports*. Government Printer, Perth, Western Australia.



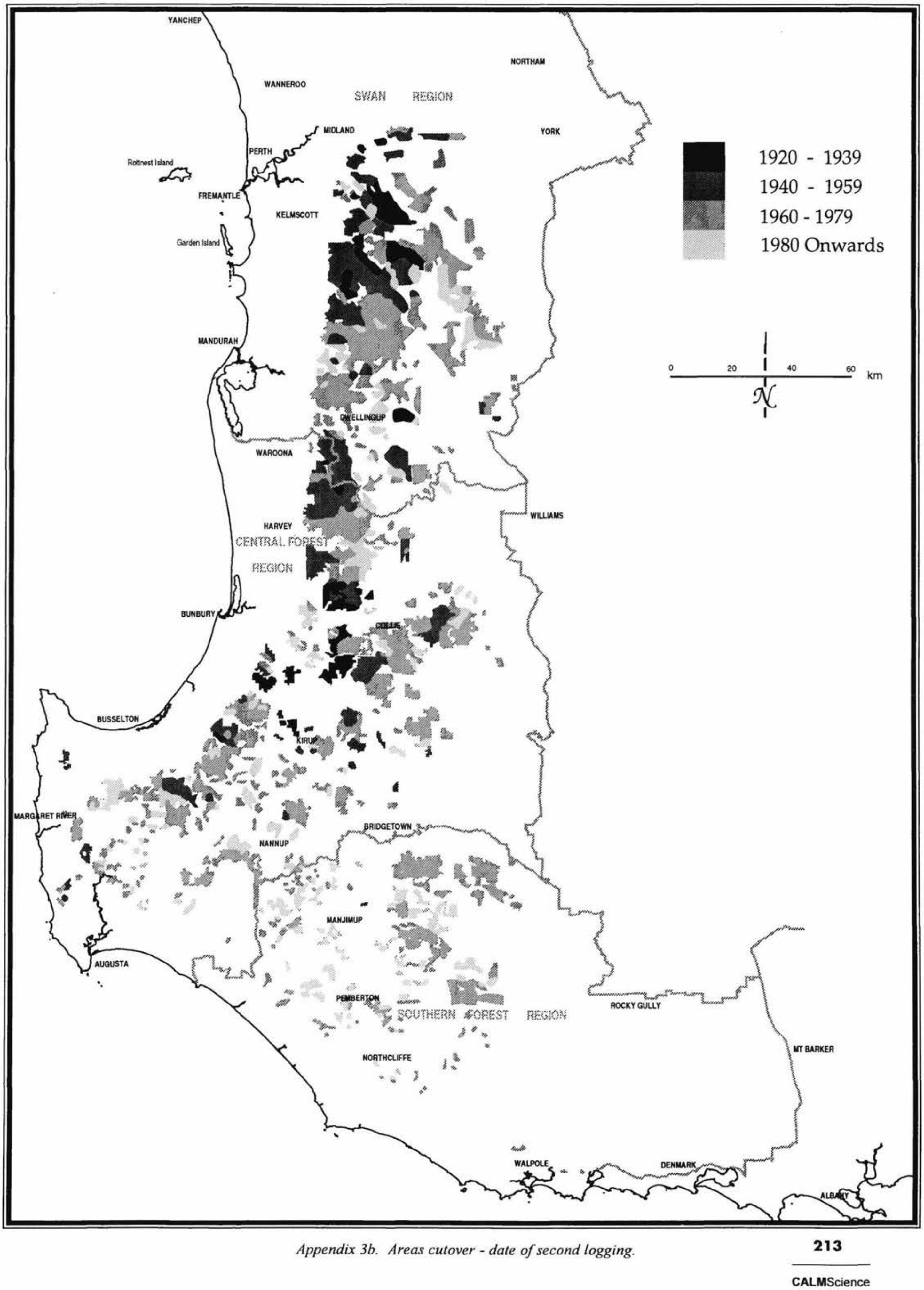
Appendix 1. Locations of early sawmills and dates first operational.



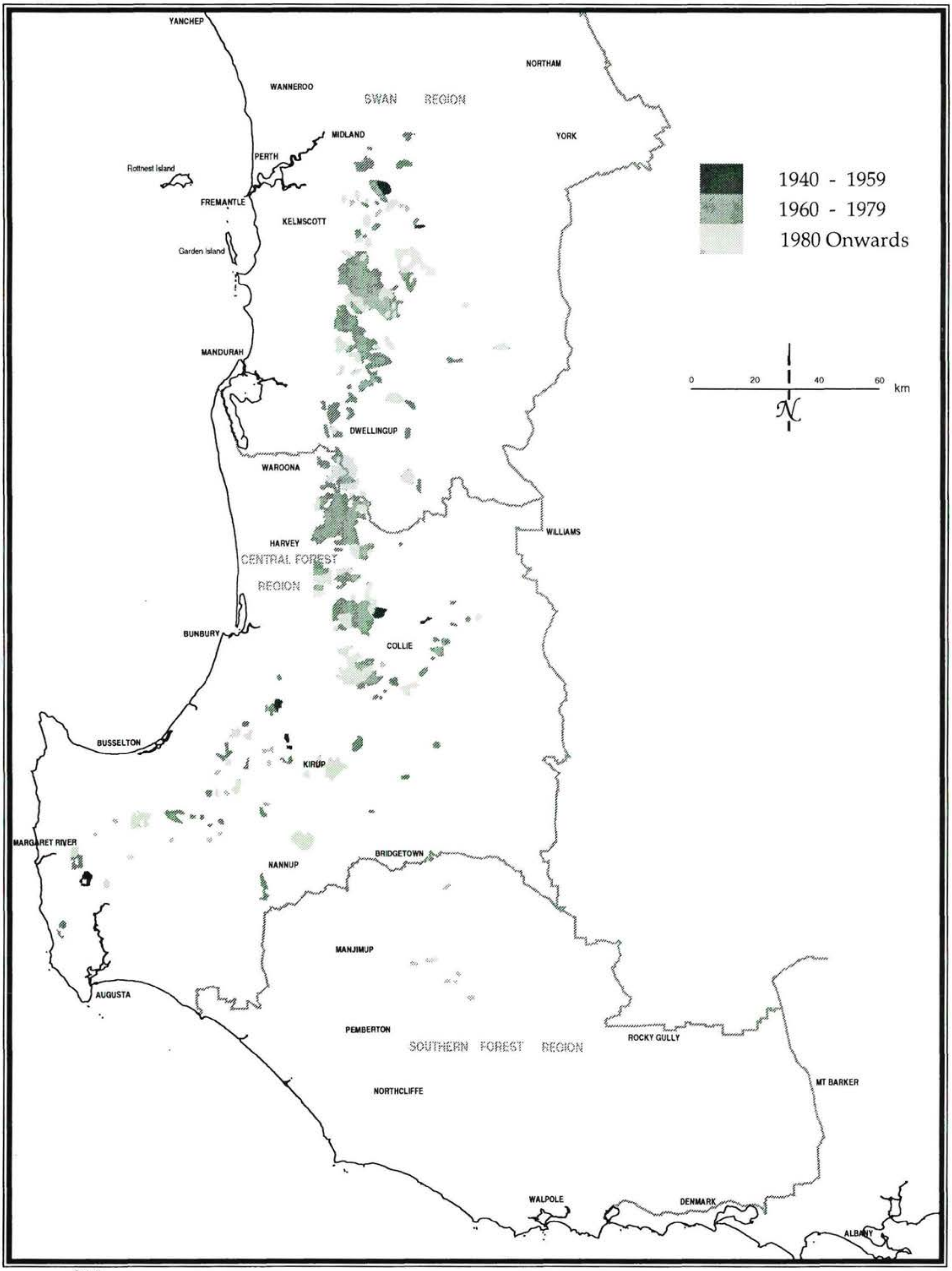
Appendix 2. Railways and tramways first used.



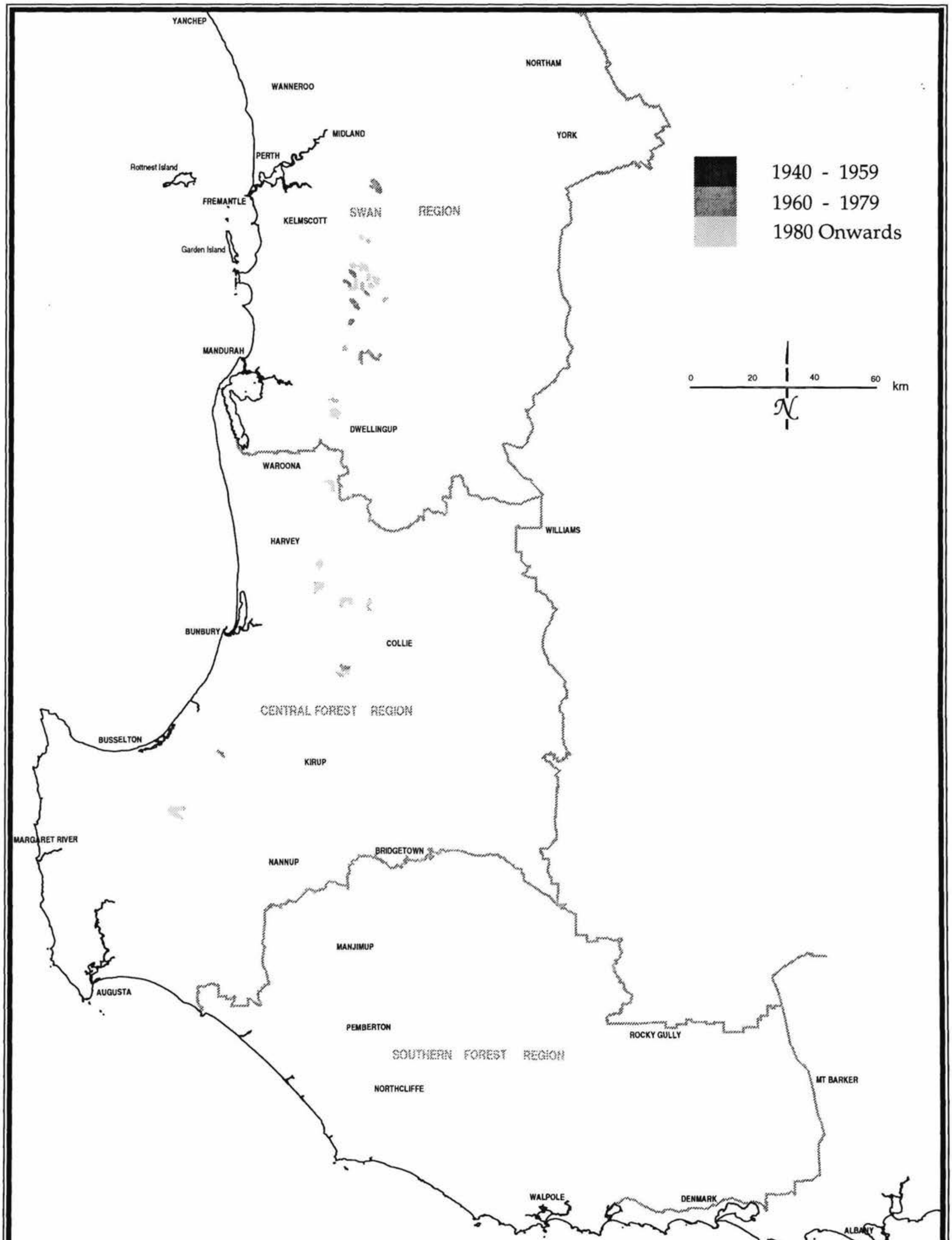
Appendix 3a. Areas cutover - date of first logging.



Appendix 3b. Areas cutover - date of second logging.



Appendix 3c. Areas cutover - date of third logging.



Appendix 3d. Areas cutover - date of fourth logging.

APPENDIX 4

Early sawmills in Perth District.

SAWMILL OWNER(S)	OPENED	CLOSED	LOCATION
Small mills (<3500 m³/year output)			
Monger	1833	?	Mt Eliza, Perth
Monger & Cowan	1844	?	Guildford
Hancock	1844	?	Belmont
Graves	1881	?	Murray Street, Perth
Honey & Co.	1883	?	Fremantle
Railway Dept	1916	1929+	Midland
Dennis	1925	1930	Wanneroo

APPENDIX 5

Early sawmills in Mundaring District.

SAWMILL OWNER(S)	OPENED	CLOSED	LOCATION
Big mills (>7000 m³/year output)			
Rockingham Jarrah Co. (Wanliss 1870); Rockingham Jarrah Timber Co. (1874); Neil McNeil (1889); Rockingham Railways and Jarrahdale Forests (1892); Jarrahdale Jarrah Forests and Railways (1897); Millars (1902); Bunnings (1983) 'Jarrahdale Mill'	1870	Still open	Jarrahdale
Medium sized mills (3500 m³ - 7000 m³/year output)			
B Mason	1884	1870	Masons Landing, Canning River
Mason, Bird & Co.	1870	1882	Masons Mill, Carmel
White, later Wright & Co. (Keane) 'White's Mill'	1882	1888	Mt Helena
R Honey & Co (1889); Forsyth & Hummerston (1893) 'Lion Mill'	1889	1898	Mt Helena
Canning Jarrah Timber Co.(1890); Millars (1902)	1890	1916	Canning Mills, Karragullen
" " 'No. 1 Sleeper mill'	1893	?	Karragullen area
" " 'Yankee Mill'	1893	?	Karragullen area
" " 'No. 3 Mill'	1893	?	Karragullen area
" " 'Death Adder Creek Mill' (No. 4)	1890	1901	Death Adder Creek
Millars (first) 'Bartons Mill'	1903	1908	Carilla
" 'Bartons Mill No. 2'	1908	1925	Bartons Mill
" 'Bartons Mill No. 3'	1925	1939	N of Bartons Mill
Rockingham Jarrah Co. (Wanliss 1885); Neil McNeil (1889); Rockingham Railways and Jarrahdale Forests (1892); Jarrahdale Jarrah Forests and Railways (1897); Millars (1902)	1885	1900	Wungong Brook
" " " 'Jarrahdale No. 2'			
" " " 'Jarrahdale No. 3'	1890	1901	39 Brook
" " " 'Jarrahdale No. 4'	1895	1901	Serpentine River
" " " 'Jarrahdale No. 5'	1895	1899	Chandlers
" " " 'Jarrahdale No. 5'	1899	1910	Big Brook
" " " 'Jarrahdale No. 6'	1899	1913	Big Brook
" " " 'Board Mill'	1903	1915 ?	Balmoral Road
" " " 'Mundijong Board Mill'	1918	1928	Mundijong
Perth Jarrah Sawmills (Bunnings) 'Lion Mill'	1905	1926	Mt Helena
Small mills (<3500 m³/year output)			
Buckingham	1866	1899	Stocker Road, Kelmscott
Buckingham 'Poplar Mill'	1872	1899	Brookton Highway, Roleystone
A.Smith & Co.	1877	1897	Nyaania Creek, Smiths Mill
Lacey "Enterprise Sawmill"	1881	1883	Zamia, Mahogany Creek

Appendix 5 (continued)

Gill & Co. (Alex Forrest & Lacey 1888) 'Enterprise Sawmill'	1882	1896	Sawyers Valley
M Smith & Sons	1882	?	Sawyers Valley
Buckingham	1882	1900	East Byford
Sexton	1885	1886	Forsyth
Sexton	1886	1896	Gorrie
Dunton & Forsyth	1890	?	Chidlow
West Australian Jarrah Timber Co.	1890	1897	Chidlow
Byfield	1891	1901+	Wooroloo
Sexton (1893); Shepperdson (1894)	1893	1898	Mundaring
Firns	1893	1918	Serpentine, Karnet
Atkins & Law	1894	1896	Roleystone
McDowell, Byfield	1894	1895	Wooroloo
McDowell	1895	1898	Parkerville
Dunton & Co. (1896); Forsyth (1899)	1896	1903	Forsyth
Gill & Co. (Alex Forrest & Lacey)	1896	1897	Mahogany Creek
McDowell (1896); Gill McDowell (1897)	1896	1898	Sawyers Valley
Dunton & Co. (Adams & Conaughton)	1896	1900	Chauncy Gully
Forsyth & Dunton 'Helena Sawmill'	1896	1903	Gorrie Road
Sexton	1896	1897	Gorrie
Isbister, Wiseman & Co. 'Federation Sawmill'	1896	1900	Sawyers Valley
Tomlinson	1896	?	Sawyers Valley
Patterson	1897	?	Smiths Mill
Sexton	1897	1902	Parkerville
McCoy & Oudaille	1897	1898	SE of Chidlow
Connaughton & Crossman 'Gem Sawmill'	1897	1900	Sawyers Valley
Brown	c1897	?	Chidlow
Silberthorpe & Adair	c1897	?	Serpentine
Johnston, Blakeney & Co	c1897	?	Armadale
Armadale Timber Co.	c1897	?	Armadale
Higgs 'Armadale Sawmill'	1897	1904	Byford
Guppy	1898	?	Gooseberry Hill
WA Timber Co. (1898); Brown (1899) "Excelsior Mill"	1898	1900+	Chidlow
Hummerston	1899	1904	Mt Helena
Port & Honey	1900	1913	The Dell
Sexton	1901	?	Sawyers Valley
Forsyth 'Avonholme Mill'	1903	1906	Chidlow
Franklin & Finlay	1903	?	Keysbrook
Frawley	1904	?	Myara
Sampson (1904) 'Dalgarup Mill'; Bunnings (1906)	1904	1906	Gidgegannup
Dyke & W Smith (1905); Bunnings (1906)	1905	1910	Gidgegannup
Buckingham	1905	1907	South Kalamunda
Buckingham	1907	1909	Keysbrook
Buckingham	1909	1911	Serpentine
Patterson	1910	1913	Mundaring Weir
Groth	1918	1919	Sawyers Valley
Wilson	1918	1920	Wooroloo
Robinson	1918	1919	Keysbrook
Groth	1919	1920	Keysbrook
Bunney	1919	1921	Kelmscott
Curtis, Chisholm & Co.	1921	1929+	Bedfordale
Smailes, Weston, Leibow	1922	1929	Pickering Brook

APPENDIX 6

Early sawmills in Dwellingup District.

SAWMILL OWNER(S)	OPENED	CLOSED	LOCATION
Big mills (>7000 m^3/year output)			
Whittakers	1902	1946	North Dandalup
Millars	1904	1961	Nanga
Millars	1910	1930	Marrinup
South West Timber Hewers Co-op (1910); State Sawmills No. 5 (1920)	1910	1960	Holyoake
Railway Dept No. 2	1911	1963	Banksiadale
Medium sized mills (3500-7000 m^3/year output)			
McDowell, Gill McDowell Jarrah Co; Millars (1902)	1895	1903	Waroona
Bunnings	1898	1901	North Dandalup
Gill McDowell, Millars (1902) '11 Mile Mill'	1902	1904	Waroona Dam
Gill McDowell, Millars (1902) 'No. 5 Mill'	1908	1910	Near Nanga Road
Port, Honey & Co No. 1	1911	1929	Pindalup
Railway Dept No. 1 (leased to Holmes)	1912	1914	Dwellingup
State Sawmills No. 4	1913	1924	Wuraming
South West Hewers Co-op (1913); Plavin (1918); Australian Lumber Co. (1923)	1913	1928	Inglehope, Plavins
Port & Co. No. 2	1923	1929	Pindalup
State Sawmills No. 4	1924	1951	Hakea
Port & Co. No. 8	1925	1929	Duncans
Small mills (<3500 m^3/year output)			
Tuckey	1885	1886	Marrinup
Hannans	1895	1900	Marrinup
Goodrich & Massey	1896	?	North Dandalup
Shearer, Weatherhead & Co.	1897	1899	North Dandalup
Parkers	1899	?	Serpentine
Frank & Finlay	1900s	?	Karnet
Teesdale-Smith & Timms	1902	?	East Pinjarra
Frawleys	1904	?	Karnet
Lyalls	1904	1905	Pinjarra
Patterson	1913	1925	Amphion
Federal Trading and Engineering	1919	1920	Pinjarra
Australian Lumber Co. No. 1 & 2	1920	1921	Hotham
Mann	1920	1921	Pinjarra
Sundercombe	1927	?	Waroona
Forsyth	1928	1929	Murray River
Waroona Sawmilling Co.	1929	?	Waroona

APPENDIX 7

Early sawmills in Mornington District.

SAWMILL OWNER(S)	OPENED	CLOSED	LOCATION
Big mills (>7000 m^3/year output)			
Millars; Bunnings(1983)	1895	Still open	Yarloop
Millars	1896	1919	Hoffman old
Millars	1898	1961	Mornington
Canning Jarrah Co. (1899); Millars (1902)	1899	1920	Wellington
Millars	1920	1964	Hoffman new
Medium sized mills (3500 m^3 - 7000 m^3/year output)			
Millars	1895	1898	Benger
Millars	1897	1909	Waterous
Port (1893); Jarrah Timber & Wood Paving Corp. (1898) No. 1 mill	1893	1901	Gervasse
Jarrah Timber & Wood Paving Corp. No. 2 mill	1898	1902	Worsley
Jarrah Timber & Wood Paving Corp. (1898) No. 3 mill; Millars (1902)	1899	1902	Worsley
Millars No. 4 mill	1899	1904	Klondyke
Lyall (1904); Bunnings (1907)	1904	1968	Lyalls
South West Timber Hewers Co-op	1909	1911	Lucknow Mungalup
Buckingham (1911); State Building Supplies (1954); Hawker Siddeley (1961)	1911	1968	Muja
Lewis & Reid No. 1 (1911); Bunnings (1923)	1911	1925	Allanson
Lewis & Reid No. 2 (1913); Bunnings (1923)	1913	1925	Harris River
Wandoo Timber Co. (1913); Bunnings (1914)	1913	1930+	Muja
Millars spot mills (3)	1920	1928	Wellington
Australian Lumber Co.	1920	1927	Bowelling
Bunnings	1920	1926	Lowden
Millars (Trees Limited)	1920	1958	Treesville
State Sawmills No. 6A	1920	1923	Worsley
State Sawmills No. 6B	1923	?	Windy Ridge Road
Westralian Timber & Trading	1924	1926	Maroondale (Loc 1)
State Sawmills No. 6C	1925	1926	Potters Gorge, River Road
State Sawmills No. 6D	1926	1927	Groom Road
State Sawmills No. 6E	1927	1928	Harnett Road
State Sawmills No. 6	1928	1930	Sneaker Road
Small mills (<3500 m^3/year output)			
Clifton	1845	1875+	Australind
M C Davies	1875	1884	Pile Road
M C Davies	1875	1884	Worsley
Bunbury Jarrah Timber Co.	1881	1882	Ferguson Road
Port	1894	1898	Crooked Brook
Teesdale-Smith & Timms (1894); Port (1895)	1894	1895	Boyanup
Wright	1895	1901+	Dardanup (Crooked Brook)
Hooker '17 Mile Mill'	1895	1899	Boyanup
H J Yelverton	1895	?	Bunbury
Law	1895	1896	Samson Brook
Williams (3 spot mills)	1896	1913	Harvey Weir
McCoy, (later Ferguson)	1897	1914	Logue Brook
McDevitt & Mitchell	1897	1899	Drakesbrook
Canning Jarrah Co. spot mill	1897	1899	Wellington

Appendix 7 (continued)

Hooker	1898	1899	Bunbury
Atkins & Law, later leased to Port	1898	1899+	Worsley
Drysdale	1904	1905	Picton
Bunnings	1906	1908	Hamilton Hill
Harnetts	1910s	?	Beela
Coolup Milling Co.	1914	1920	Coolup
R Palmer	1919	1922+	Collie
Harnett	1919	1929+	Gervasse
McSweeney	1920	1921	Boyanup
Plavin	1920	1925	Bowelling
Lewis & Stirk	1920	1926	Shotts
Connell	1920	?	Mungalup
Amalgamated Colleries	1920	1929+	Collie
Port & Co.	1920s	?	Waroona
Bunnings 'Preston Valley Sawmills'	1921	1925	Yabberup
Collie Land & Timber No. 1 (McCluskeys)	1921	1925+	Shotts area
Connell No. 2	1924	1927	Collie
Jackson & Rodgers	1925	1926	Boyanup
Collie Land & Timber No. 2	1925	1927	Shotts area
Mumballup Timber Syndicate	1925	1929	Mumballup
Collie Land & Timber No. 3 (1928); Douglas Jones (1933)	1928	1960+	Harris River
Worsley Timber No. 1	1928	?	Worsley
Worsley Timber No. 2	1928	?	Worsley

APPENDIX 8
Early sawmills in Blackwood District.

SAWMILL OWNER(S)	OPENED	CLOSED	LOCATION
Big mills (>7000 m³/year output)			
Westralian Jarrah Forests Co. (1898); WA Timber Corporation (1899)	1898	1926	Greenbushes
Jarrah Wood & Sawmills Co. (1899); Millars (1902)	1899	1983	Jarrahwood
Sexton & Drysdale (1906); McLean Bros & Rigg (Vincent); Bunnings (1914) 'Preston Valley Sawmills'	1906	1925	Noggerup
WA Jarrah Sawmilling Co. (Bartram); Kauri Timber Co. (1912)	1908	1925	Barrabup
Millars 'East Kirup Mill'	1910	1928	Grimwade
Kauri Timber Co.	1914	1925	Ellis Creek
Kauri Timber Co. (1925); Douglas Jones (1961); Millars; Bunnings (1983)	1925	Still open	Nannup
Medium size mills (3500 m³ - 7000 m³/year output)			
WA Jarrah Timber Co.	1883	1888	Harrington
Lyall, McDowell (1902); Bunnings (1905)	1894	1940	Argyle
Teesdale-Smith & Timms (1894); Yelverton (1895); Imperial Jarrahwood Corp. (1897)	1894	1898	Donnybrook
Port (1893); Jarrah Timber & Wood Paving Corp. (1898) '24 Mile Mill'	1893	1899	N of Donnybrook
Port, Baxter & Prince No.1 mill	1894	1902	Irishtown Road
Baxter & Prince	1894	1896	Argyle Block

Appendix 8 (continued)

Baxter & Prince No. 2 mill	1896	1902	Irishtown Road
Baxter & Prince (Preston Timber Co.)(1899); WA Jarrah Sawmilling Co. (1906)	1899	1909	Kirup
Baxter & Prince spot mills (2)	1902	1906 ?	Donnybrook Block
Millars	1908	1910	Kirup
Adelaide Timber Co.	1908	1987	Wilga
Swan Sawmills (Fergusons)	1914	1921	Lowden
Swan Sawmills (1920); Millars (1923)	1920	1929	Claymore
Lewis & Reid	1921	1929+	Mullalyup
Sussex Timber Co. (Nicholson)	1923	1929+	Dellerton
Timber Corporation	1926	1931	Woop Woop
Small mills (<3500 m^3/year output)			
Baxter	1895	1899	5 km S of Donnybrook
Koetze	1895	1896	Bridgetown
J Scott	1896	1900	Hester
Jarrah Timber & Wood Paving Corp. (Port)	1897	1900	Donnybrook
Imperial Jarrah Wood Corp. (Yelverton) (1898); Millars (1902)	1898	1903	Newlands
Adelaide Timber Co.	1899	1907	North Greenbushes
Sexton & Drysdale	1905	1906	Queenwood
Hodder & Stoughton	1901	?	S of Boyanup
Plewright & Mann	1905	1907	Balingup
Adelaide Timber Co.	1907	1908	East Greenbushes
Donnybrook Sawmills	1914	1919	Brookhampton
Mitchell & Ryan	1916	1922+	Jayes Road
Martin	1918	1922+	Queenwood
Connell	1918	1920	Hester
Griffith	1919	1922	Donnybrook
Machin	1919	?	Bridgetown
Grist, Nicholas & Co.	1920	?	Donnybrook
Smith	1920	1921	Barrabup
Bunnings 'Preston Valley Sawmills'	1920	1925	Lowden
Holdsworth	1920	1929+	Hester
Thompson	1921	1922	Argyle
Whistler Bros	1921	1927	Dinninup
Jenkins	1922	1930+	Balingup
Colsen	1926	?	Nannup

APPENDIX 9

Early sawmills in South West Capes District.

SAWMILL OWNER(S)	OPENED	CLOSED	LOCATION
Big mills (>7000 m^3/year output)			
West Australian Jarrah Timber Co.	1870	1878	Lockeville
M C Davies	1899	1913	Jarrahdene
Medium sized mills (3500 m^3 - 7000 m^3/year output)			
M C Davies	1882	1901	Karridale
West Australian Jarrah Timber Co.	1883	1888	Goodwood
M C Davies	1886	1910	Boranup
Forests Department (tuart mill)	1920	1930	Ludlow
WA Jarrah Forests 'Pilgrims Mill' (1924); Adelaide Timber Co. (1929); Worsley Timber Co. (1984)	1924	Still open	Witchcliffe
Small mills (<3500 m^3/year output)			
H J Yelverton	1858	1864	Quindalup
H J Yelverton (1864); Imperial Jarrah Wood Corp. (1897)	1864	1900	Station Gully
M C Davies	1881	1882	Coodardup
M C Davies (tuart mill)	1881	1882+	Capel
Imperial Jarrah Wood Corp. (1900); Millars (1902)	1900	1906	W of Treeton
Payne	1918	1919	Capel
Farley	1919	1922	Capel
Grist & Nicholas	1921	?	Goodwood Road
Margaret River Timber Co.	1923	1926+	Margaret River
Bonola	1925	1926	Alexandra Bridge
Scott	1926	1929+	Capel
Busselton Sawmills	1927	1929+	Yallingup

APPENDIX 10

Early sawmills in Manjimup District.

SAWMILL OWNER(S)	OPENED	CLOSED	LOCATION
Big mills (>7000 m^3/year output)			
Lyall & Drysdale (1911); Wilgarrup K & J Co (Millars) (1912); Bunnings (1983)	1911	?	Jardee
State Sawmills (1912); Hawker Siddeley (1961); Bunnings (1970)	1912	Still open	Deanmill
WA Timber Corporation (1921); Millars (1931)	1921	1983	Palgarup
Medium sized mills (3500 m^3 - 7000 m^3/year output)			
Wheatley (1910); Bethell (1912)	1910	1917	Donnelly River
Lewis & Reid (1923); Bunnings (1925)	1923	1948	Yornup
Australian Lumber Co.	1924	1927	Alco
Small mills (<3500 m^3/year output)			
Nelson Co-op Soc.	1913	?	Palgarup
Machin	1918	1922+	Glentulloch
Smith	early 1900s	1916	Winnejup

APPENDIX 11

Early sawmills in Pemberton District.

SAWMILL OWNER(S)	OPENED	CLOSED	LOCATION
Big mills (>7000 m^3/year output)			
State Sawmills No. 2 & 3; Hawker Siddeley (1961); Bunnings (1970)	1914	Still open	Pemberton
Medium sized mills (3500 m^3 - 7000 m^3/year output)			
Nil			
Small mills (<3500 m^3/year output)			
State Sawmills (spot mill)	1913	1914	Pemberton
Carrig	1924	1926+	Northcliffe

APPENDIX 12

Early sawmills in Walpole District.

SAWMILL OWNER(S)	OPENED	CLOSED	LOCATION
Medium sized mills (3500 m^3 - 7000 m^3/year output)			
Millars	1896	1905	Scotsdale
Small mills (<3500 m^3/year output)			
Keith	1910	1922+	Hay River
Saw	1919	1922+	Bow River

APPENDIX 13

Early sawmills in Albany District.

SAWMILL OWNER(S)	OPENED	CLOSED	LOCATION
Big mills (>7000 m^3/year output)			
Millars	1896	1905	Denmark
Medium sized mills (3500 m^3 - 7000 m^3/year output			
Nil			
Small mills (<3500 m^3/year output)			
Egerton-Warburton	1880	?	King River
Millars	1884	1888	Torbay
Millars	1889	1890	Albany
Millars	1890	1893	Torbay
Millars	1895	1896	Denmark
Douglas	1912	1922+	Denmark
Denmark Timber Co.	1916	1920	Denmark
Flay	1918	1923	Parry Inlet
Harper	1918	1922+	Albany
Hawkins	1919	1922+	Porongurup
Bennetts, Stokes	1919	1922	Gledhow
Groth & Adams	1920	1922	Marbellup
Douglas Bros	1921	?	Kalgan River
Steele	1921	1922	Albany
Forte	1921	1922	Marbellup

CALMScience 2 (3): 225-230 (1997)

Mount Bakewell, an important remnant of natural vegetation in the York area

S.J. PATRICK

Science and Information Division, Western Australian Herbarium, Department of Conservation and Land Management, Como, Western Australia 6152

ABSTRACT

Mount Bakewell is an important site for conservation, being one of few areas near York to retain some natural vegetation. This contains some rare taxa, and is also the type locality of six plant species, collected there in 1839 by J.A.L. Preiss. A provisional checklist of plant species is provided, and notes on rare, threatened and unusual species found there. Notes on the early collections of Preiss are also included.

INTRODUCTION

Mount Bakewell rises to 457 m above sea level, and dominates the town of York, which is situated at its foot. It is the highest point of the Dyott Range, on the north side of the town. The area is a rich agricultural region and was settled early in the history of Western Australia, so that the natural vegetation remaining on Mount Bakewell is an important remnant of the original bushland that occurred on the hills before much of it was cleared. There is no public road to the summit, which has minimized access to the natural vegetation, so that it generally remains in good condition. Until recently, management rested largely with the surrounding landholders.

Ownership of part of the remnant vegetation on Mount Bakewell is divided between a number of private individuals and the Shire of York, while other sections consist of either unvested and vested reserves, or freehold land owned by the State and Commonwealth governments. The mountain is an important site for telecommunications masts, and the summit is also an official Trig Point. Mount Bakewell also has great significance for Aboriginal people, and has its own Dreamtime legend.

The summit of Mount Bakewell is composed of massive quartzite, which is resistant to erosion and therefore forms areas of high relief, similar to Mount Brown, Red Knob and the Needling Hills in the same district. Patches of a quartzose duricrust have developed over the quartzite band. A quartz-feldspar-biotite gneiss is exposed on the southern and western slopes and to the north there is quartz-feldspar gneiss (Wilde and Lowe 1978).

The quartzite gives rise to soils which support wandoo (*Eucalyptus wandoo)* woodland, while york gum (*E. loxophleba*) woodlands occur on the more basic soils of the gneiss, which are fertile red loams, some of which are high in the landscape. The sandy areas support a species-rich heath and shrubland, and there are woodlands of rock sheoak (*Allocasuarina huegeliana)* on many of the lower slopes (Beard 1979).

The most recent bushfire took place in 1985, when a hot summer fire burnt the whole area of bushland. Subsequently, the vegetation has regenerated well, although there is some weed invasion.

This paper documents the plants currently known to exist in the area, together with their status, and a brief review of collecting history, with special reference to Preiss.

SPECIES CHECKLIST

A short checklist (Appendix 1) of the species occurring on Mount Bakewell has been compiled from several sources. A number of botanists have visited the locality during the 20th century, in every decade except the 1930s. These include Oswald Sargent, Charles Gardner and Fred Lullfitz. Their collections have been incorporated into the list as have those of several staff members of the Western Australian Herbarium, both past and present, who have also collected there. Finally, 26 species collected in 1839, by Ludwig Preiss, and listed in *Plantae Preissianae,* have been included (Appendix 2).

However, fairly extensive areas of undisturbed natural vegetation remain on Mount Bakewell, which have not been fully surveyed. It is probable the list would be considerably increased if a thorough survey were made.

PLANTS OF CONSERVATION VALUE

A number of the species found on Mount Bakewell are of particular significance. Some are formally recognized and gazetted as Declared Rare Flora or are on the Priority Flora List, prepared by the Department of Conservation and Land Management, for taxa which appear to be rare but are in need of further survey. These are described.

Declared Rare Flora

These are 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.

Thomasia montana is gazetted as Declared Rare Flora. It is a shrub growing to about 1 m in height, with oblong to ovate-cordate leaves which have short, stellate hairs. The flowers are in long stalked racemes. Each flower has a mauve calyx, *c.* 15 mm in diameter, divided to about the middle into five lobes. The petals are minute, dark purple in colour. Mount Bakewell is the type locality of this species, the plant having been collected there in 1839 by Ludwig Preiss. *Thomasia montana* has not been recollected at Mount Bakewell but is known to occur further south in the Beverley to Pingelly area.

Priority 1 - Poorly known Taxa

These are poorly known and are known from one or a few populations (generally less than 5), which are under threat and are under consideration for declaration as Rare Flora but are in urgent need of further survey.

Senecio gilbertii is listed as a Priority 1 taxon. It is an erect perennial plant growing to 1.5 m tall. Its deeply divided leaves are densely clothed with woolly, white hairs on the undersides. There are numerous heads of tubular, yellowish flowers.

S. gilbertii has also been recorded in the past from three localities in the jarrah forest between Bindoon and Wooroloo. The population occurring on Mount Bakewell is the most easterly known for the species, and is the only currently known population as it has not been refound recently at any of the other known localities.

Priority 4 - Rare Taxa

These are considered to have been adequately surveyed and, while being rare (in Australia), are not currently threatened by any identifiable factors. They require monitoring every 5-10 years.

Three taxa are listed as Priority 4, namely:

Caladenia integra was included on the 1989 Schedule of Declared Rare Flora. It is an orchid growing to 50 cm tall, with a long narrow leaf, and one or two flowers on each flowering stalk. The lateral sepals are upswept, and the greenish labellum has a dark tip and smooth edges. It was first recorded from Mount Bakewell in 1907, and in 1986 was found to be represented there by a large population in the recently burnt sheoak woodlands. In 1989 it was known from only a few populations between York and Kendenup but has since been found to be more common, occurring in rock sheoak woodland around granites.

Hemigenia platyphylla is a low shrub to 0.6 m in height, with opposite, obovate leaves which are covered with minute glandular hairs intermixed with longer ones. The flowers are lilac in colour. Mount Bakewell is the type locality of this species, where it is still represented by a large population around the summit. It was thought to occur only at this locality until recently, but is now known from the Stirling Ranges, with isolated records from Dwellingup, Harvey River and West River. Recent taxonomic study indicates that it is a variety of *H. incana*, distinguished by the long glandular hairs on the leaves and calyx (Rye[1] personal communication).

Hibbertia montana is a low shrub to about 0.5 m tall, with oblong to obovate, hairy leaves and yellow, five-petalled flowers. This species occurs from Mount Bakewell south to the Narrogin area. It has been confused in the past with *H. commutata* but differs in having the numerous stamens closely grouped around the four to five hairy carpels, completely hiding them. *H. commutata* has spreading stamens, grouped loosely into three bundles, exposing the carpels from above (Wheeler 1984). *H. montana* was known only from Mount Bakewell, the type locality, until populations were found at other localities in the central wheatbelt during survey for the species in 1983. It grows commonly around the summit and upper slopes of Mount Bakewell.

Apart from the recorded presence of these species, the vegetation of this area has other values, and warrants a full botanical survey. For example, a species of the cabbage family, *Lepidium phlebopetalum*, was collected there recently. This species is poorly recorded in the wheatbelt and is generally regarded as occurring in the more arid regions of the State. Some specimens of grass tree, *Xanthorrhoea drummondii*, growing on the higher areas are particularly fine, one having been measured at over 6 m in height. This specimen is thought to be over 300 years old.

EARLY PLANT COLLECTIONS FROM MOUNT BAKEWELL COLLECTED BY J.A.L. PREISS

The German botanist and naturalist, J.A.L. Preiss, visited Western Australia from the end of 1838 to 1842, and during his stay made substantial botanical collections. These, together with those of James Drummond, are important for early taxonomic studies of the Western Australian flora. Many of the specimens that Preiss collected formed the basis of the botanical publication, *Plantae Preissianae* (Lehmann 1844-1848).

From a search of *Plantae Preissianae* it has been ascertained that Preiss collected at least 26 species from Mount Bakewell, mainly on 5th, 8th, 11th, 12th and 13th September 1839. Six of the collections are type

[1] Barbara Rye, Western Australian Herbarium, Department of Conservation and Land Management, Como, Western Australia 6152.

specimens, the names *Acacia restiacea, Colobandra platyphylla (= Hemigenia platyphylla), Hibbertia montana, Leucopogon obtusatus, Thomasia montana, Trymalium wichurae(= Cryptandra wichurae)* having been based on them. Three of these taxa, *Hemigenia platyphylla, Hibbertia montana,* and *Thomasia montana* are rare, *T. montana* being gazetted as Declared Rare Flora, the others are listed as Priority 4, Rare Flora. *Acacia restiacea, Cryptandra wichurae* and *Leucopogon obtusatus* are more common and widespread species.

Although Mount Bakewell has been visited many times by botanists since 1839, 16 of the 26 species that Preiss collected there have not been recollected since. It is possible that some no longer occur there, the area of natural vegetation having been considerably reduced, particularly on the lower slopes. However, this further highlights the need for more extensive survey of the area.

MANAGEMENT

Management of Mount Bakewell has been difficult in the past, owing to its diffuse ownership. A draft plan was prepared in the mid-1980s, by the State Planning Commission, proposing the formation of a Regional Park, to include private property as well as the reserves on Mount Bakewell: however, this plan was not implemented.

More recently, a Management Plan for this important area has been prepared by a consultant for the Shire of York and the York Land Conservation District Committee, with funding from the State Landcare Program and the Shire of York (Underwood 1996).

The implementation of this plan will result in a consolidation of Crown lands into one reserve, vested in the Shire of York and managed for the purpose of preservation of Mount Bakewell's natural bushland.

ACKNOWLEDGEMENTS

I thank Roger Underwood, whose work on the Management Plan for Mount Bakewell rekindled my interest in the area and provided much background information, and Dr Neville Marchant for his advice on Preiss's collecting localities.

REFERENCES

Beard, J.S. (1979). *The Vegetation of the Perth Area, WA.* Vegmap Publications, Applecross.

Lehmann, J.G.C. (ed.) (1844-1848). *Plantae Preissianae.* Hamburg, Germany.

Marchant, N.G. (1990). The Western Australian collecting localities of J.A.L.Preiss. *In* Short, P. (ed.) *History of Systematic Botany in Australia.* pp. 131-135. Australian Systematic Botany Soc. (inc.). South Yarra, Vic.

Underwood, R. (1996). *A management plan for Mt. Bakewell.* Shire of York, Western Australia.

Wheeler, J.R. (1984). Taxonomic notes on some Western Australian species of *Hibbertia* (Dilleniaceae). *Nuytsia* 5(1), 31-42.

Wilde, S.A. and Lowe, G.H. (1978). Perth, Western Australia. 1:250 000 Geological Series-Explanatory Notes. Geological Survey of Western Australia, Perth.

APPENDIX 1

List of the flora recorded for Mount Bakewell. Introduced species are marked with an asterisk *.

Acacia baxteri
Acacia gilbertii
Acacia lasiocarpa var. *sedifolia*
Acacia multispicata
Acacia pulchella var. *pulchella*
Acacia ramosissima
Acacia restiacea
Acacia saligna
* *Aira cupaniana*
Allocasuarina huegeliana
Allocasuarina humilis
Astroloma pallidum
Astroloma serratifolium var. *placidum*
Bracteantha bracteata
Burchardia umbellata
Caladenia filifera
Caladenia flava ssp. *flava*
Caladenia integra
Caladenia longiclavata
Calothamnus quadrifidus
Calytrix breviseta ssp. *stipulosa*
Calytrix sapphyrina
Chorizema aciculare ssp. *aciculare*
Conostylis setigera
Cryptandra wichurae
Cyanicula gemmata
Daviesia angulata
Dampiera eriocephala
Dampiera lavandulacea
Dillwynia sp. A
Dioscorea hastifolia
Diplopeltis huegelii
Diuris longifolia
Drakonorchis barbarossa
Dryandra armata
Dryandra sessilis
* *Echium plantagineum*
Elythranthera emarginata
Eucalyptus accedens
Eucalyptus calophylla
Eucalyptus drummondii
Eucalyptus loxophleba
Eucalyptus wandoo
Gastrolobium calycinum
Gastrolobium parviflorum
Gastrolobium parvifolium
Glischrocaryon aureum
Gompholobium knightianum
Gompholobium tomentosum
Grevillea vestita
Guichenotia sarotes
Hakea gilbertii
Hakea incrassata
Hakea preissii
Hakea trifurcata
Hemigenia incana
Hemigenia platyphylla
Hibbertia enervia
Hibbertia montana
Hibbertia rupicola
* *Homoglossum watsonium*
Hyalosperma glutinosum
Hypocalymma angustifolium
Isopogon dubius
Kennedia prostrata
Labichea lanceolata ssp. *brevifolia*
Lasiopetalum glabratum
Laxmannia squarrosa
Lechenaultia biloba
Lepidium phlebopetalum
Leptospermum erubescens
Leucopogon gracillimus
Leucopogon obtusatus
Melaleuca radula
Nemcia ilicifolia
Nemsia spathulata
Nuytsia floribunda
Olearia rudis
Opercularia vaginata
Petrophile heterophylla
Phyllanthus calycinus
Pimelea imbricata var. *piligera*
Pimelea sylvestris (large flowered form)
Platysace juncea
Podolepis lessonii
Podotheca gnaphalioides
Pseudanthus virgatus
Pterostylis sp.
Ptilotus sp.
Rhodanthe manglesii
Senecio gilbertii
Sollya heterophylla
Sowerbea laxiflora
Stackhousia pubescens
Stylidium breviscapum
Stylidium ciliatum
Stylidium repens
Stypandra glauca
Thomasia foliosa
Thomasia montana
Thysanotus patersonii
Trachymene ornata
Trachymene pilosa
Trymalium floribundum ssp. *floribundum*
Trymalium ledifolium var. *lineare*
Trymalium ledifolium var. *rosmarinifolium*
Wurmbea tenella
Xanthorrhoea drummondii

APPENDIX 2

A complete list of plants collected by Preiss from Mount Bakewell and cited in *Plantae Preissianae*, volumes 1 and 2 (Lehmann 1844-1848).

Current Name	Name in Plantae Preissianae	Vol. and page in Plantae Preissianae	Preiss no.	Date of collection
Acacia gilbertii Meisn.	*Acacia nigricans* (Labill.) R. Br. var. *subracemosa* Meisn.	1: 20	891	5.9.1839
Acacia lasiocarpa Benth. var. *sedifolia* (Meisn.) Maslin	*Acacia cygnorum* Benth.	1: 22	892,894, 896	5.9.1839
Acacia ramosissima Benth.	*Acacia ramosissima* Benth.	1: 16	940	30.3.?
Acacia restiacea Benth.	*Acacia restiacea* Benth.	1: 3	971	8.9.1839
Astroloma serratifolium (DC.) Druce	*Astroloma candolleanum* Sond.	1:302	466	5.9.1839
Calytrix sapphirina Lindl.	*Calycothrix empetroides* Schauer	1:105	195	-
Chorizema aciculare (DC.) C.A. Gardner ssp. *aciculare*	*Chorizema henchmanni* R. Br.	1: 34	1048	9.1839
-	*Chorizema baueri* Benth.	1: 34	1037	8.9.1839
Cryptandra wichurae (Nees) F. Muell.	*Trymalium wichurae* N. ab E	2:281	1220*	11.9.1840
?*Dillwynia* sp. A (Marchant *et al.* 1987)	*Dillwynia acicularis* Sieb.	1: 62	875	5.9.1839
Gastrolobium calycinum Benth.	*Gastrolobium calycinum* Benth.	1: 69	836	12.9.1839
Gastrolobium parviflorum (Benth.) Crisp	*Oxylobium parviflorum* Benth.	1: 31	801	5.9.1839
Gastrolobium parvifolium Benth.	*Gastrolobium parvifolium* Benth.	1: 69	1017	12.9.1839
Glischrocaryon aureum (Lindl.) Orchard	*Laudonia aurea* Lindl.	1:159	2067	-
Gompholobium knightianum Lindl.	*Gompholobium knightianum* Lindl.	1: 40	1104	12.9.1839
Hemigenia platyphylla (Bartl.) Benth.	*Colobandra platyphylla* (Bartl.) Benth.	1:358	2319	5.9.1839
Hibbertia enervia (DC.) Hoogland	*Pleurandra hibbertioides* Steudel	1:265	2164	8.9.1839
Hibbertia montana Steud.	*Hibbertia montana* Steud.	1:270	2135	5.2.1839
Laxmannia squarrosa Lindl.	*Laxmannia squarrosa* Lindl.	2: 42	1588	8.9.1839
Leucopogon gracillimus DC.	*Leucopogon gracillimus* DC.	1:312	395	13.9.1839
Leucopogon obtusatus Sond.	*Leucopogon obtusatus* Sond.	1:313	395 ex parte	13.9.1839
Nemcia spathulata (Benth.) Crisp	*Gastrolobium spathulatum* Benth.	1: 71	800	8.9.1839
Petrophile heterophylla Lindl.	*Petrophile heterophylla* Lindl.	1:501	658	12.9.1839
Pseudanthus virgatus (Klotzsch) Muell. Arg.	*Chrysostemon virgatus* Klotzsch.	2:232	1230	12.9.1839
Stackhousia monogyna Labill.	*Stackhousia pubescens* A. Rich.	1:180	1972	8.9.1839
Thomasia montana Steud.	*Thomasia montana* Steud.	1:230	1661	5.9.1839

*1220 *Trymalium wichurae*, was collected 11.9.1840, 'in confragosis montis Blackwell (York)'. This location is presumed to be in error for Mount Bakewell, although the year of collection is also later than for all Preiss's collections from that location. However, there are many inconsistencies of date of collection cited in *Plantae Preissianae* (Marchant 1990).

Of the 26 species collected by Preiss at Mount Bakewell, sixteen have not been recorded there since. These are:

Acacia ramosissima
Acacia restiacea
Calytrix sapphyrina
Chorizema aciculare
Chorizema baueri
Cryptandra wichurae
Dillwynia sp. A
Gastrolobium calycinum
Gastrolobium parvifolium
Laxmannia squarrosa
Leucopogon gracillimus
Leucopogon obtusatus
Nemcia spathulata
Petrophile heterophylla
Pseudanthus virgatus
Thomasia montana

CALMScience 2 (3): 231-246 (1997)

Flora and vegetation of the eastern goldfields ranges, Part I: Helena and Aurora Range

NEIL GIBSON[1], MICHAEL N. LYONS[1] AND BRENDAN J. LEPSCHI[2]

[1]Science and Information Division, Department of Conservation and Land Management, Wildlife Research Centre, PO Box 51, Wanneroo, Western Australia 6065.

[2]Science and Information Division, Department of Conservation and Land Management, WA Herbarium, Locked Bag 104, Bentley Delivery Centre, Western Australia 6983.

SUMMARY

A study was undertaken of the flora and plant communities of the Helena and Aurora Range within the Coolgardie Bioregion of Western Australia. The range is formed from banded ironstone and basalts and is surrounded by an outwash plain derived from these units. Fifty-five quadrats were established and data from these were used to define six community types that were highly correlated with topographic position and slope. A total flora of 324 taxa was recorded from the range, of which 303 were native and 21 were introduced.

One species of Declared Rare Flora and 10 taxa listed on CALM's priority flora list were found on the range. Four taxa appear to be endemic to the Helena and Aurora Range, one of which had not previously been collected. None of these taxa are currently reserved. A further five taxa are restricted to banded ironstone ranges or associated soils within 100 km of the Helena and Aurora Range and two of these are not reserved.

The floristic classification is in broad agreement with previous descriptions of the range but documents finer scale patterning than has previously been reported. A key to the major community types is provided. Data are not yet available to determine the conservation status of the community types identified. Only a small proportion of the Bungalbin vegetation system is presently managed for conservation.

INTRODUCTION

While the ranges of the eastern goldfields of Western Australia have had a long history of geological exploration owing to their highly prospective nature, comparatively little detailed information is available on the flora and fauna of these ranges. A regional survey has been undertaken of the flora and fauna of the region and results have been published in 12 cell reports (see Dell *et al.* 1985); these reports do not, however, provide detailed information on individual ranges. Botanical survey work has been undertaken in recent years to gather detailed floristic information from a number of the ranges in the goldfields. The work reported here describes the flora and vegetation of the Helena and Aurora Range.

The Helena and Aurora Range is located 180 km west-north-west of Kalgoorlie and 50 km north-north-east of Koolyanobbing (Fig. 1). It lies within the Coolgardie Bioregion which is dominated by eucalypt woodland (Beard 1990; Thackway and Creswell 1995). The climate is semi-arid mediterranean with an annual rainfall of 200-300 mm (Beard 1990). The lower slopes and valleys around the range are dissected by numerous exploration gridlines.

The range itself is composed of Archaean banded ironstones in two stratigraphic units separated by a basalt layer. The range is surrounded by an outwash plain derived from these units (Chin and Smith 1983), and is one of the most spectacular in the eastern goldfields, reaching 702 m.

Beard (1972) first described the major structural vegetation formations in the study area. He grouped his structural units into vegetation systems and defined the vegetation of the banded ironstones of the Helena and Aurora Range as forming part of the Bungalbin System. Beard included in this system the ironstone areas of the Hunt Range, the Watt and Yendilberin Hills to the east, the Mt Jackson Range to the west, a small unnamed range of hills to the north and the Koolyannobbing Range to the south. He described the vegetation of these ranges as thickets dominated by *Acacia quadrimarginea, Acacia tetragonophylla, Dryandra arborea* (on rocky outcrops) and *Allocasuarina acutivalvis* with understoreys of such shrubs as *Dodonaea* spp., *Eriostemon brucei, Eremophila* spp., *Enchylaena tomentosa*, and *Grevillea paradoxa*. The lower slopes of the Helena and Aurora Range and valley systems would fall into the *Eucalyptus salmonophloia - E. salubris* association of his very broad Jackson system. Keighery (1980) confirmed the occurrence of *Dryandra arborea* shrublands in the Die Hardy Ranges, Mt Jackson, Koolyanobbing Range, Mt Dimer, the Hunt Range and the Helena and Aurora Range.

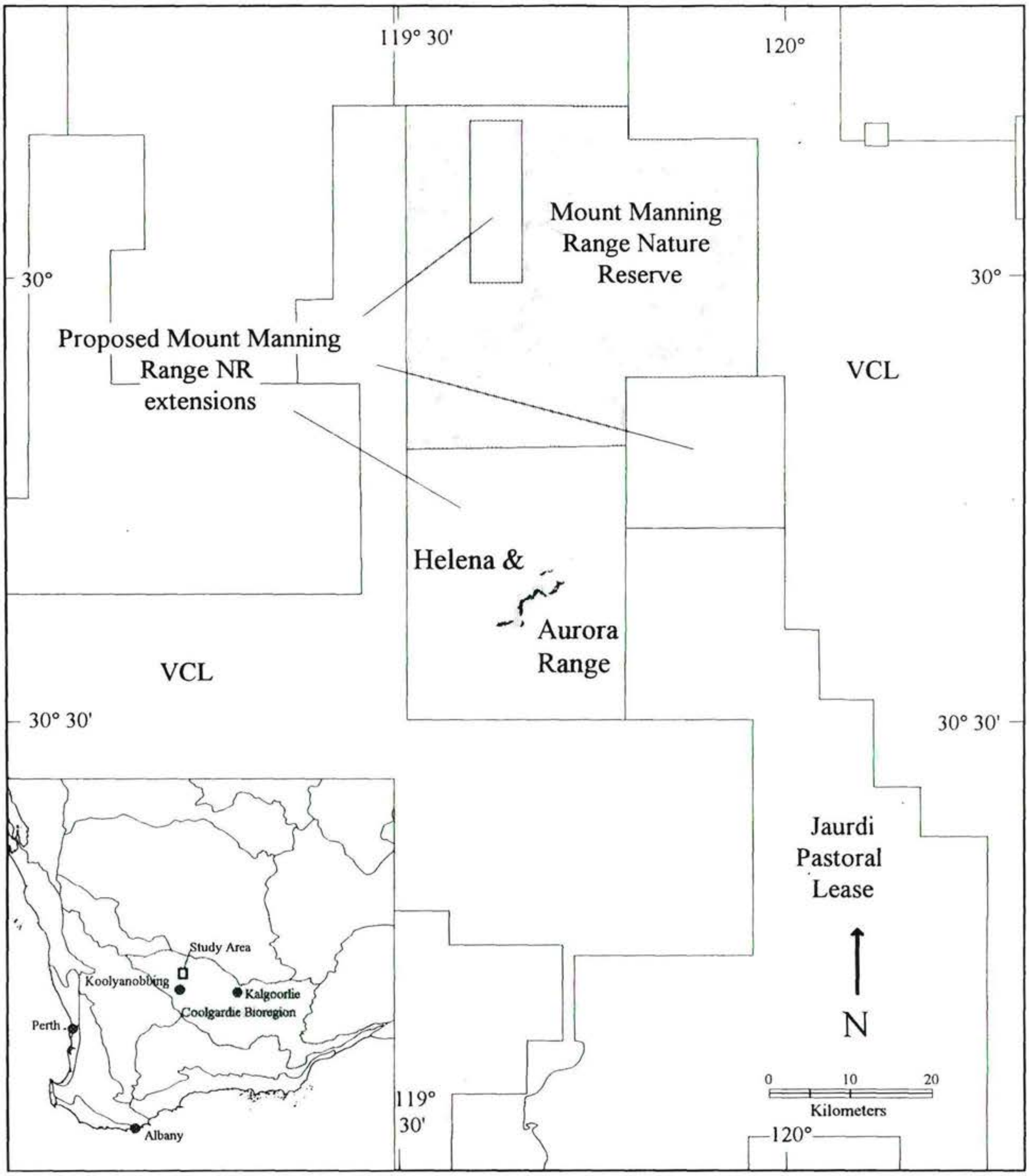


Figure 1. Location of study area and position within the Coolgardie Bioregion.

In a broad regional survey Newbey and Hnatiuk (1985) describe the vegetation of the Helena and Aurora Range under the heading, 'Hills (banded ironstone formation)'. They briefly describe the major structural units seen on the Helena and Aurora Range and note the *Dryandra arborea* shrublands on the steep upper slopes with *Eucalyptus ebbanoensis* mallee on the upper and lower slopes and *Acacia aneura* low woodland on the pediment. They also note small areas of *Eucalyptus wandoo (=E. capillosa* ssp. *capillosa)* near the crest of the range.

Both Beard's survey and the later biological survey of the eastern goldfields were undertaken to provide regional overviews. Consequently the individual ranges were not sampled intensively. Indeed, only two sites from the Helena and Aurora Range are described in detail (Newbey and Hnatiuk 1985). The only other report on the vegetation of the study area is that of Henry-Hall (1990), which details reserve recommendations for the southern goldfields. In the section on the proposed Bungalbin Hill extension to the Mt Manning Nature Reserve, Henry-Hall describes the diverse nature of the vegetation of the range and provides detailed descriptions of some of the structural units.

The aim of the present work was to undertake a detailed floristic survey of the range to compile a detailed flora list for the range and the surrounding outwash areas, and to describe the vegetation patterning of this area.

METHODS

Fifty-five 20 m x 20 m quadrats were established on the range, its lower slopes and the outwash plain (Fig. 2). These sites were selected with the aim to cover the major geographical, geomorphological and floristic variation found in the area. Care was taken to locate sites in the least disturbed vegetation available in the area being sampled. Some difficulty was experienced in reaching the uplands of the western half of the Aurora Range owing to lack of vehicle access, but several traverses carried out on foot indicated that an adequate sampling of the major vegetation types of the tops and upper slopes was achieved. No attempt was made to sample the Tertiary sand plain that surrounds the Helena and Aurora Range (Chin and Smith 1983).

Within each site all vascular plants were recorded. Twenty-seven primarily upland sites were established in the last week of July 1995. These sites were revisited and a further 28 sites were established in the last week of September 1995. Data on topographical position, slope, aspect, percentage litter, percentage bare ground, percentage exposed rock, vegetation structure and condition were collected from each site. Topographical position was scored on a subjective three-point scale from ridge tops and upper slopes (1), to midslopes (2), and to lower slopes and broad flats (3). Slope was scored on a

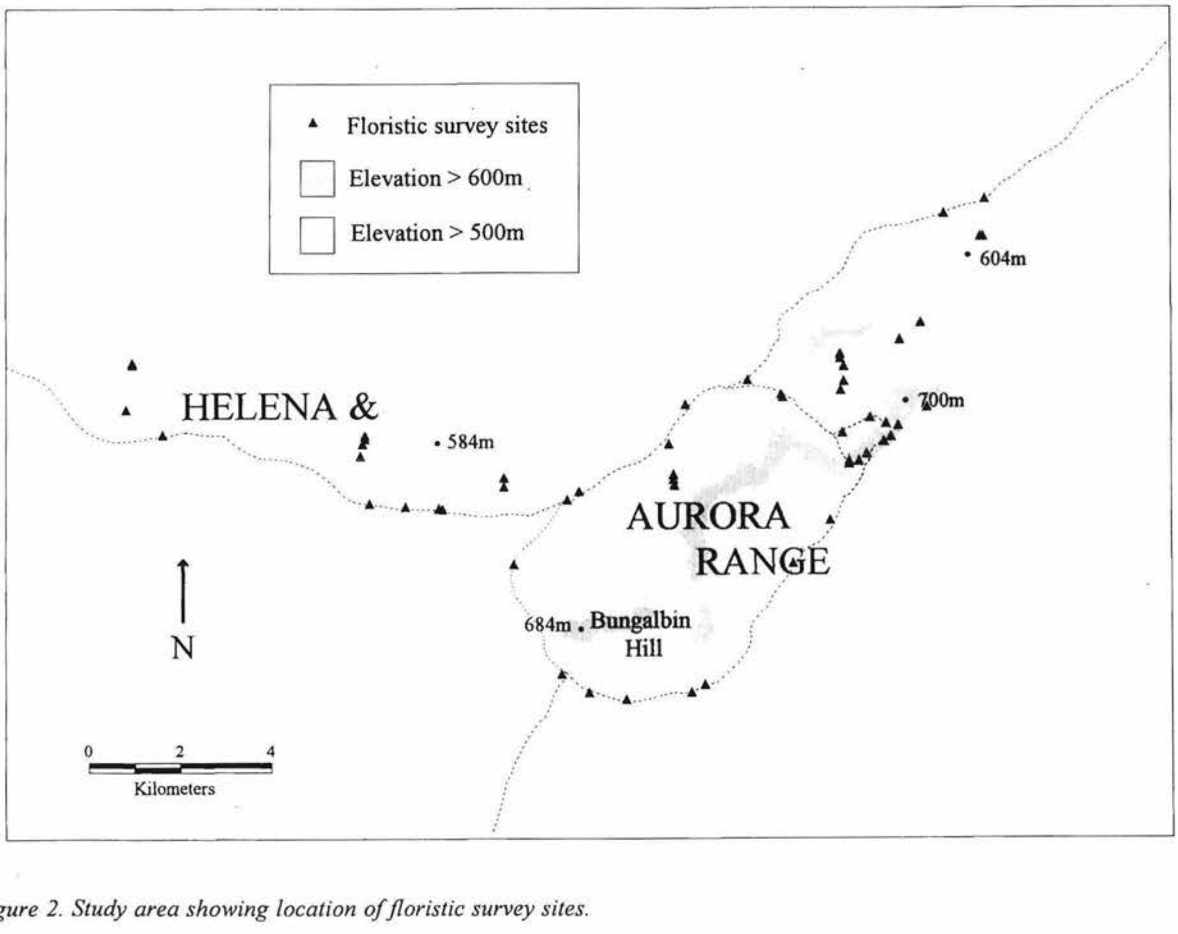


Figure 2. Study area showing location of floristic survey sites.

one to three scale from flat (<5°) to steep (>20°). Aspect was recorded as one of 16 cardinal directions. Vegetation structure was recorded using Muir's (1977) classification. All sites were permanently marked with four steel fence droppers and their positions fixed using a global positioning system (GPS) unit.

Sites were classified according to similarities in species composition based on presence/absence data. In these analyses only perennial species were used to facilitate comparisons with classifications from other ranges in the area (Gibson and Lyons 1995).

The site and species classifications undertaken used the Czekanowski coefficient and 'unweighted pair-group mean average' fusion method (UPGMA, Sneath and Sokal 1973) using the PATN software package (Belbin 1993). Statistical relationships between site groups for such factors as species richness, slope, aspect, were tested using Kruskal-Wallis non parametric analysis of variance and Mann Whitney U-tests (Siegel 1956). In a preliminary analysis ordination of the sites showed essentially the same pattern as the classification and will not be discussed further.

Nomenclature follows Green (1985) and current usage at the Western Australian Herbarium (PERTH). Selected voucher specimens will be lodged in PERTH.

RESULTS

Flora

A total of 324 taxa (species, subspecies and varieties) were recorded from the Helena and Aurora Range. The flora list was compiled from taxa found within the 55 plots or the adjacent area, from opportunistic collections and from confirmed records held in PERTH (Appendix 1). Of these 324 taxa, 303 are native and 21 are introduced. The largest families represented were the Asteraceae (50 native taxa and 6 introduced), Myrtaceae (30 taxa), Poaceae (12 native taxa and 8 introduced), Mimosaceae (17 taxa), Chenopodiaceae (14 taxa), Myoporaceae (14 taxa), Goodeniaceae (11 taxa), Fabaceae (10 taxa), and Proteaceae (10 taxa). This pattern is typical of the flora of the South Western Interzone (Newbey and Hnatiuk 1985). Good rains were experienced in the winter and early spring of 1995, reflected by the large numbers of annuals and geophytes recorded (Table 1; Appendix 1).

The most common genera were *Eucalyptus* (19 taxa), *Acacia* (17 taxa), and *Eremophila* (14 taxa). Introduced species were generally not a major component of the vegetation.

During the survey one species of Declared Rare Flora (DRF) was recorded along with 10 other taxa on CALM's priority flora list (CALM 1996). Two new populations of the DRF *Tetratheca aphylla* were located, as were new populations of some of the 10 priority taxa (Table 2). Previously one species of DRF and five priority taxa were known from the range (CALM 1994).

Acacia adinophylla ms appears to be endemic to the Helena and Aurora Range. The understorey of the side slopes of the range is dominated by another range endemic, the undescribed grass *Neurachne* sp. Helena & Aurora (K.R. Newbey 8972). This taxon is extremely widespread but as yet has not been collected from any other range in the area. *Tetratheca aphylla* also appears to be endemic to the massive ironstones of the range. (One collection in PERTH indicating a population 10 km to the north of Bungalbin Hill is likely to be in error and should read 10 km NE of Bungalbin Hill.) *Stenanthemum newbeyi* was previously believed to be restricted to Helena and Aurora Range and nearby hills (Rye 1995), however, recent field work has recorded this species on banded ironstones at Ennuin Station some 80 km to the south-west (Gibson and Lyons *unpublished data*).

TABLE 1
Lifeform spectrum of the flora of the Helena and Aurora Range.

LIFEFORM	PERCENTAGE
Annual grasses	5.2
Annual herbs	33.3
Annual sedges	0.6
Geophytes	5.9
SUBTOTAL	45.1
Perennial grasses	0.9
Perennial herbs	4.0
Perennial sedges	0.6
Shrubs	41.0
Mallee	3.7
Trees	4.6
SUBTOTAL	54.8

TABLE 2
Declared Rare Flora and Priority Flora found during the survey indicating the number of new populations located (CALM 1996).

TAXON	CURRENT PRIORITY LISTING	NUMBER OF NEW POPULATIONS
Acacia adinophylla ms	1	2
Acacia cylindrica	3	1
Daviesia purpurascens	4	3
Gnephosis intonsa	1	1
Grevillea erectiloba	4	3
Grevillea georgeana	3	1
Leucopogon breviflorus	2	6
Phlegmatospermum eremaeum	2	1
Prostanthera magnifica	4	1
Stenanthemum newbeyi	1	5
Tetratheca aphylla	R	2

Several other species (*A. cylindrica, Grevillea erectiloba* and *G. georgeana*) appear to be restricted to the banded ironstone ranges (or associated soils) within 100 km of Bungalbin Hill.

An undescribed species of *Leucopogon* was collected from a cliff line approximately 3 km east of Bungalbin Hill. This taxon (*Leucopogon* sp. Helena & Aurora BJL 2077) was locally abundant, growing in association with *Tetratheca aphylla,* but was not encountered elsewhere on the range. Another undescribed taxon, *Mirbelia* sp. Helena & Aurora (BJL 2003), was also collected on the range. This species has previously been collected from two locations, one north of the Hunt Range and the second in the Watt Hills. Both locations lie some 60 km from Bungalbin Hill. It is recommended that both these taxa be listed on CALM's priority flora list as Priority 1 and Priority 2 respectively (Table 3).

Daviesia purpurascens has recently been delisted from DRF to Priority 4. Data from this survey support this reassessment. This species was found to be very widespread on the range, occupying both the massive ironstone tops as well as the side and midslopes.

Echinopogon ovatus was collected at the base of the same cliff line at which *Leucopogon* sp. Helena & Aurora (BJL 2077) was found. This grass is known from only six collections in Western Australia, one from near Onslow and the rest in the Margaret River-Nannup area. It is recommended that this species also be listed on CALM's priority flora list as Priority 2 (Table 3). The range is also the eastern limit of *Conostylis argentea* and represents the furthest inland record of any *Conostylis* (Hopper *et al.* 1987).

Vegetation

For the floristic analysis two species had to be amalgamated into a species complex owing to the difficulty of differentiating between them (*Vulpia myuros* and *V. muralis*). Only material that could be identified down to at least species level was included in the analysis (*c.*99 per cent of records). In the 55 quadrats established on the Helena and Aurora Range, 233 taxa were recorded, 117 of which were perennials. Twenty-seven perennials occurred at only one site. These singletons have little effect on the community classification and were excluded from the analysis. As a result the final data set consisted of 90 taxa in 55 sites. Species richness ranged from three to 20 taxa per site, with individual taxa occurring in two to 36 of the 55 sites.

Multivariate analysis can assist in sorting both site and species data such that patterns in species composition are more easily seen. The decision as to the number of site and species groups defined is subjective and related to the scale of pattern of interest (Kent and Coker 1992). In this analysis site groups are discussed at the six group level and species groups at the nine group level, which best reflected the scale of patterning seen in the field.

TABLE 3

Taxa from the study area requiring priority listing and the number of known populations.

TAXON	RECOMMENDED PRIORITY LISTING	NUMBER OF KNOWN POPULATIONS
Leucopogon sp. Helena & Aurora (BJL 2077)	1	1
Mirbelia sp. Helena & Aurora (BJL 2003)	2	3
Echinopogon ovatus	2	5

The dendrogram shows the six community types recognized in the analysis (Fig. 3). The primary division seen in the dendrogram separates skeletal and weathered soils of the uplands and slopes (community types 1 to 4) from the deeper calcareous fertile soils of the valley bottoms (community types 5 and 6). This can also be clearly seen in the sorted two-way table generated from the site and species classifications (Table 4). These data are consistent with the patterning reported by Newbey and Hnatiuk (1985).

Community types 1 and 2 are largely confined to the ridge tops and upper slopes of the Helena and Aurora Range. Both community types develop on skeletal yellow or red soils. Taxa in species group H are typical species of community type 1; these include *Acacia quadrimarginea, Grevillea zygoloba, Allocasuarina acutivalvis, Melaleuca nematophylla, Dryandra arborea* and *Calycopeplus paucifolius* (Table 4). This community is generally dominated or codominated by the species listed above. Average species richness was 14.7 taxa per plot.

Community type 2 was entirely restricted to the massive ironstone tops, the upper slopes and breakaways of the range. This community was generally dominated by either *Eucalyptus ebbanoensis* or, below the small breakaways, by *Eucalyptus capillosa* ssp. *capillosa.* Taxa from species group B, H and I are most consistently present, but with a lower representation of taxa from species group H compared with community type 1. Average species richness was 13.6 taxa per plot.

The open side slopes of the Helena and Aurora Range are primarily occupied by community type 3. This community is generally dominated or codominated by *Eucalyptus ebbanoensis* and/or *E. corrugata*, with an understorey dominated by the *Neurachne* sp. Helena & Aurora (KRN 8972). Occasionally this community may be dominated by *Acacia* spp. rather than the eucalypt species. Species richness was lower with an average of 10.5 taxa per plot. Typical species of this community are taxa in species groups A and B. Taxa in species groups D, F, G, H and I are completely or almost completely lacking from this community type (Table 4).

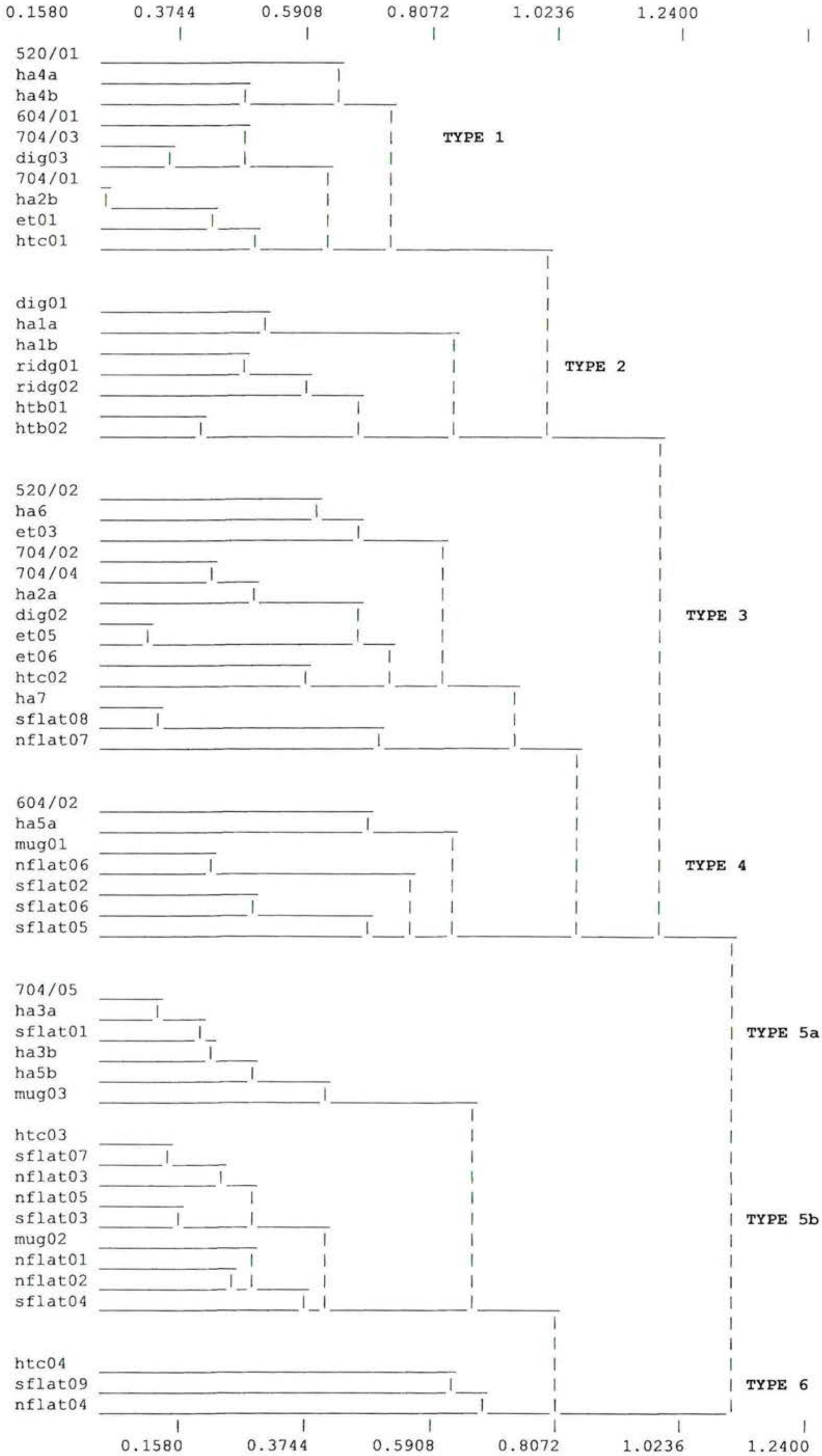


Figure 3. Dendrogram of the sites from the Helena and Aurora Range area showing the six group level classification.

TABLE 4

Sorted two way table of the Helena and Aurora Range sites showing species occurrence (rows) by community type (site codes appears as columns).

```
                                                                   COMMUNITY TYPE
                                                 1        2          3          4      5a      5b      6
                                                                                                          SPECIES
                                                                                                           GROUPS
                                          |5hh67d7heh|dhhrrhh|5he77hdeehhsn|6hmnsss|7hshhm|hsnnsmnns|hsn
                                          |2aa00i0att|iaaiitt|2at00aitttaff|0auffff|0afaau|tffffufff|tff
                                          |04444g420c|gllddbb|060442g00c7ll|45gllll|43135g|cllllglll|cll
                                          |/ab//0/b10|0abgg00|/ 3//a0560 aa|/a0aaaa|/aabb0|0aaaa0aaa|0aa
                                          |0  0030  1|1  0012|0  00 2  2 tt|0 1tttt|0 t  3|3tttt2ttt|4tt
                                          |1  13 1   |   12  |2  24      00|2  0000|5 0   | 0000 000| 00
                                          |          |       |           87|   6265|  1   | 7353 124| 94
                                          +----------+-------+-------------+-------+------+---------+---
                                          |          |       |             |       |      |         |
                                          |          |       |             |       |      |         |
Acacia acuminata                          |          |       |          ***|       |   *  |         |
Acacia prainii                            |          |       | **       ***|       |      |         |
Acacia resinimarginea                     |          |       |  *       ** |     **|      |         |
Phebalium canaliculatum                   |          |       |  *       ** |      *|      |         |
Cassytha melantha                         |          |       |  *       *  |       |      |         |        A
Daviesia purpurascens                     |          | *     |*     **  *  |       |      |         |
Eremophila rugosa ms                      |          |       |      **  ** |       |      |      ** |
Santalum spicatum                         |   * *    |      *|       ** * *|       |      |         |
Acacia adinophylla ms                     |  *       |       | **    *     |       |      |         |
Acacia eremophila                         |          |       |* *          |       |      |         |
Grevillea haplantha ssp. haplantha        |          |       |  *     *    |       |      |         |
                                          +----------+-------+-------------+-------+------+---------+---
Acacia erinacea                           |          |       |**   *  *    |       |      |     **  |
Maireana radiata                          |          |       | *           |       |*     |     *   |
Acacia tetragonophylla                    |          | *   * |             |       | *  **|         |
Dodonaea microzyga                        |          |     * |        *    |       |      |         |
Dodonaea lobulata                         |         *|    ***| *  *        |       |      |         |
Eremophila oppositifolia                  |          |  *****| *  **       |*      |     *|*        |
Scaevola spinescens                       |          |     **|***          |*      |**   *|        *|
Westringia cephalantha                    |          |  ** * |***     * *  |       |      |         |        B
Eucalyptus corrugata                      |          |       |*  ********* |       |***** |         |
Eucalyptus ebbanoensis                    |  *   *   |***  **|********* ** |*      |****  |         |
Neurachne sp. Helena & Aurora (KNR 8972)  |**********|***   *|********** **|*******|******|         |
Ptilotus obovatus                         |         *|*   *  |*  **  *    *|       |******|      *  | **
Olearia muelleri                          |  *       |****** |**   ****  * | *     |*** * |***** ** | *
Stipa elegantissima                       |   *******|* *****|      **  ***| * *** |******|*********|**
Olearia pimeleoides                       | *       *|*    **|  *     **** | * ****|***   |         |
                                          +----------+-------+-------------+-------+------+---------+---
Acacia aneura                             |     *    |       |             |  ***  |      |         |
Hakea minyma                              |          |       |          ** |    ** |      |         |
Prostanthera grylloana                    |    **    |       |           * |    ***|      |         |
Acacia coolgardiensis ssp. effusa         |    *     |       |             |    *  |      |         |        C
Brachychiton gregorii                     |    *     |       |             |       |     *|         |
Eremophila latrobei                       | *  *     |       |             |       |      |         |
                                          +----------+-------+-------------+-------+------+---------+---
Acacia colletioides                       |          |       |  *          | *     |   *  |   **    |
Eucalyptus longicornis                    |          |       |             |       |      | * **    |
Eucalyptus yilgarnensis                   |          |       |             |       |      |   **    |
Eucalyptus sheathiana                     |          |       |             |       |      |** *   * |        D
Eremophila interstans                     |          |       |             |       |      |*       *|
Eremophila scoparia                       |          |       |             |       |      |*** *   *|
Eremophila ionantha                       |          |       |*            |    *  |      |    *   *|
                                          +----------+-------+-------------+-------+------+---------+---
Atriplex nummularia                       |          |       |*            |       | ***  |*********|
Sclerolaena diacantha                     |          |       |             |       | *****| ********|  *
Atriplex vesicaria                        |          |       |             |       |   * *|*********|* *
Maireana georgei                          |          |       |    **   *   | *     |******|*** *****|
Maireana trichoptera                      |          |*      |*   *        |       |******| *** *** |
Enchylaena tomentosa                      |          |*      |            *|       |     *|     *   | *
Eremophila decipiens ssp. decipiens ms    |          |       |          ***| *   * |   * *|      *  |
Rhagodia drummondii                       |          |       |            *|       | * * *|      *  |        E
Senna artemisioides ssp. filifolia        |  *       |       |*         ***|       |** ** |  *** *  |
Eucalyptus salmonophloia                  |          |       |             |       |      |      ***|
Maireana tomentosa ssp. tomentosa         |          |       |             |       |     *|      *  |
Sclerolaena fusiformis                    |          |       |             |       |  *  *|     ** *|
Bossiaea walkeri                          |          |       |             |  *    |      |       * |
Eucalyptus transcontinentalis             |          |       |             |       |      |     * * |
Exocarpos aphyllus                        |      *   |*     *|      *      |       |      |    *  * |
                                          +----------+-------+-------------+-------+------+---------+---
```

Table 4 (continued)

	COMMUNITY TYPE 1	2	3	4	5a	5b	6	SPECIES GROUPS
	5hh67d7heh	dhhrrhh	5he77hdeehhsn	6hmnsss	7hshhm	hsnnsmnns	hsn	
	2aa00i0att	iaaiitt	2at00aitttaff	0auffff	0afaau	tffffufff	tff	
	04444g420c	g11ddbb	060442g00c711	45g1111	43135g	c1111g111	c11	
	/ab//0/b10	0abgg00	/ 3//a0560 aa	/a0aaaa	/aabb0	0aaaa0aaa	0aa	
	0 0030 1	1 0012	0 00 2 2 tt	0 1tttt	0 t 3	3tttt2ttt	4tt	
	1 13 1	12	2 24 00	2 0000	5 0	0000 000	00	
			87	6265	1	7353 124	94	
Acacia hemiteles					*		*	
Eucalyptus loxophleba ssp . smooth bark (Brooker & Kleinig 1990)			*	*	*			
Eucalyptus salubris						*	*	F
Solanum orbiculatum ssp. orbiculatum			*		*	*	*	
Stipa platychaeta			*			*	*	
Acacia assimilis ssp. atroviridis	* *							
Allocasuarina campestris	* *							
Thryptomene appressa	* *							G
Baeckea elderiana	*			*				
Eucalyptus hypochlamydea ssp. hypochlamydea ms				* *				
Acacia quadrimarginea	****** *	**		*	*			
Eremophila clarkei	** ** *	**	**	**				
Grevillea zygoloba	** *** **	** *	*	** *	*			
Allocasuarina acutivalvis	*********	*						
Eriostemon brucei ssp. brucei	***** ***	**						
Calycopeplus paucifolius	**** ****	* *						
Hibbertia exasperata	* * ******							
Melaleuca nematophylla	*** * ****							
Dianella revoluta var. divaricata	*******	*		**** *				H
Leucopogon breviflorus	** ****	*		*				
Alyxia buxifolia	** *	*******						
Dryandra arborea	******	*** *						
Stenanthemum newbeyi	* ****	*****						
Chamaexeros macranthera	**							
Conostylis argentea	**							
Lepidosperma aff. angustatum	**	*						
Mirbelia sp. Helena and Aurora (BJL 2003)	***							
Comesperma integerrimum	* *	* *			*			
Eremophila granitica	**	* *	*	*	** * *			
Dodonaea viscosa		**						
Tetratheca aphylla		***						I
Melaleuca leiocarpa	**	**						
Eremophila gibbosa	*	*						
Sida calyxhymenia	*					*		
Eucalyptus capillosa ssp. capillosa		**					*	
Santalum acuminatum		* *						

Community type 4 was restricted to the lower slopes and flats below the range. It was a species-poor community (in terms of perennials) with an average species richness of 7.9 taxa per plot. This community was variously dominated by *Acacia aneura, A. resinimarginea* or *A. acuminata*, or occasionally by *Eucalyptus ebbanoensis* and/or *E. hypochlamydea* ssp. *hypochlamydea* ms. Where eucalypts dominated, the understorey included taxa such as *Grevillea zygoloba* and *Eremophila clarkei,* species more typical of upland areas. The only understorey species that were largely constant to this group were *Neurachne* sp. Helena & Aurora (KRN 8972), *Austrostipa elegantissima, Olearia pimeleoides* and *Dianella revoluta* (Table 4). It differed from community type 5, which also occurs on the flats below the range, by the almost complete lack of chenopod species.

Community type 5 consisted of the eucalypt woodlands on the flats below the range with a diverse chenopod understorey. No single eucalypt species consistently dominated this community type, with species such as *Eucalyptus salmonophloia, E. salubris, E. longicornis, E. sheathiana, E. transcontinentalis, E. ebbanoensis* and *E. corrugata* dominating at different sites. Taxa in species group E (mainly chenopods) largely defines this group (Table 4). This group was quite species-rich with an average of 13.1 taxa per plot. This group can be further subdivided into two subgroups. Type 5a are those woodlands close to the change in slope where *E. ebbanoensis* and *E. corrugata* form an overstorey over chenopods and *Neurachne* sp. Helena & Aurora (KRN 8972). Type 5b is more typical of the extensive flats between the ranges where these slope species decline.

Indeed type 5a can be considered transitional between community type 3 and type 5b.

The final community type consists of three heterogenous species-poor quadrats (average species richness 4.7 taxa per plot). One quadrat appears to be related to the *Eucalyptus capillosa* ssp. *capillosa* stands classified into community type 2 and the other two quadrats appear to be species-poor examples of community type 5. The numerical techniques used in this analysis are known to be sensitive to species richness (Sneath and Sokal 1973).

PHYSICAL CORRELATES

It is clear from the above community descriptions that one of the primary correlates with community type is topographic position and slope class. Significant differences were found between community means for these parameters (Table 5). Community type 2 was entirely restricted to massive ironstone tops and upper slopes, while community type 1 extended down to the midslopes where suitable outcropping of banded ironstone occurred. Both community types were restricted to the steeper slope classes (Table 5). Community type 3 occurred at an intermediate position in the landscape and consequently occurred across a broader range of slope classes. Community types 4 and 5 occurred low in the landscape, generally on gentle slopes.

There were also significant differences between the community types in percentage exposed rock and percentage litter cover (Table 5). Percentage exposed rock showed a similar pattern to slope, with highest degree of rock exposure in those community types on the steepest slopes while percentage litter cover showed the inverse pattern.

Significant differences in species richness were found between different community types (Table 5). The species-poor community type 6 had significantly fewer species than all other community types except for type 4. The shrublands on the massive tops (community type 1) were significantly richer than community types 3 (side slopes) and 4 (lower slopes) but had a similar richness to eucalypt-chenopod woodlands (type 5) of the valley flats. The other upland community type (type 2) had a lower richness than community type 1 and was again significantly richer than community type 4.

It is interesting to find the highest species richness of perennial taxa at both ends of a presumed productivity gradient. Community types 1 and 2 occur on skeletal soils on massive banded ironstones while community type 5 occurs on deep clay rich soils of the outwash plain.

DISCUSSION

Little detailed survey work has been carried out on the individual ranges of the eastern goldfields, but some recent work has been completed on the Bremer Range (*c.* 240 km to the south-east) and the Parker Range (some 130 km to the south) (Table 6) (Gibson and Lyons 1995).

The higher number of taxa recorded at the Helena and Aurora Range compared with the other two ranges most likely reflects a seasonal effect (Table 1). Good rains prior to the 1995 season led to a profusion of annual taxa compared with that of the 1994 season (when the other ranges were sampled), which was very poor for annual species and geophytes.

Similar numbers of priority taxa have been recorded from the ranges indicating the poor state of knowledge of a significant number of taxa from these range systems. This is further borne out by the first collection of one or two taxa on each range for a limited survey effort, generally less than 10 days per range.

The data also show significant biogeographical differences in the most species rich genera between the Helena and Aurora Range and the ranges to the south. *Eucalyptus* and *Melaleuca* numbers decline toward the

TABLE 5

Mean values by community type for topographic position (1 = upland and upper slopes, 2 = midslopes, 3 = lower slopes and valley bottom), slope class (1 = flat to 3 = steep), degree of rock outcrop in plot (1 = < 25 percent outcrop, 2 = 25-50 per cent outcrop 3 = > 50 per cent outcrop), degree of litter cover in plot (using same classes as rock exposure) and species richness. Means which are not significantly different (P > 0.05 Mann Whitney U-test) are indicated by superscript of same letter.

	TOPOGRAPHIC POSITION	SLOPE CLASS	DEGREE OF ROCK OUTCROP	DEGREE OF LITTER COVER	SPECIES RICHNESS
Type 1	1.10^{a}	2.70^{a}	2.80^{ab}	1.40^{ab}	14.70^{a}
Type 2	1.00^{a}	2.57^{ab}	3.00^{a}	1.00^{a}	13.57^{ab}
Type 3	1.85^{b}	2.08^{bc}	2.31^{ac}	1.31^{ab}	10.54^{bc}
Type 4	2.71^{c}	1.74^{c}	1.71^{cd}	1.43^{ac}	7.86^{cd}
Type 5	2.53^{c}	1.73^{c}	1.53^{d}	2.00^{c}	13.13^{ab}
Type 6	2.33^{bc}	1.67^{ac}	1.67^{bcd}	2.33^{bc}	4.67^{d}

TABLE 6

Comparison of the floras of the Helena and Aurora Range, the Bremer Range and the Parker Range.

	HELENA & AURORA RANGE	BREMER RANGE	PARKER RANGE
Flora	324	268	256
Declared Rare Flora	1	1	-
Priority taxa	10	6	8
Taxa - first collections	1	2	2
Eucalyptus spp.	19	30	29
Acacia spp.	17	17	20
Eremophila spp.	14	11	7
Melaleuca spp.	5	19	14

north, while *Acacia* numbers stay roughly constant and numbers of *Eremophila* spp. increase northward.

The current survey has identified three taxa that should be listed on the CALM priority list. Two taxa (*Leucopogon* sp. Helena & Aurora (BJL 2077) and *Mirbelia* sp. Helena & Aurora (BJL 2003)) have very limited distributions while the third (*Echinopogon ovatus*) has an outlying population in the Helena and Aurora Range (main distribution in Margaret River-Nannup area, but also with a record from Onslow). The taxonomy of *Echinopogon ovatus* clearly needs expert review.

Our data and records from the WA Herbarium show that four species appear to be endemic to the Helena and Aurora and a further five taxa are regional endemics (found within 100 km) of the banded ironstone ranges and associated soils of this area (Table 7). The majority of these taxa are unreserved.

The vegetation patterning encountered on the range was highly correlated with topographic position and substrate (as in Gibson and Lyons 1995). Two community types were restricted to upper slopes, there was a broad midslope community type and two community types were found on the lower slopes and flats. This classification, although based only on presence/absence data, accords well with the structural descriptions of Beard (1972), Newbey and Hnatiuk (1985) and Henry-Hall (1990), but provides more detail, allows recognition of more community types, and shows the relationships between these community groups.

Given the strong correlations with substrate and topographic position it was possible to generate a key to the major floristic units found on the range (Table 8), it should also be possible to map the floristic units from good quality aerial photography.

Some of the floristic units showed some degree of internal heterogeneity and with further sampling it may be possible to describe further subtypes. For example, community type 2 contains two sites dominated by *Eucalyptus capillosa* ssp. *capillosa* which are structurally distinct from the other quadrats in this group. One quadrat in community type 6 also appears to be a depauperate example of this subunit.

Similarly, community type 4 has potential for subdivision into an *Acacia aneura* subgroup, an *Acacia resinimarginea* subgroup and a eucalypt subgroup. More data would need to be collected from these communities to determine subgroup structure.

Community type 6 does not appear to be a natural group. One quadrat appears to be related to community type 2 while the other two quadrats appear to be related to community type 5. In a classification of the full data set (perennials, geophytes and annuals) the *E. capillosa* ssp. *capillosa* quadrat falls with the other quadrats dominated by this species (community type 2), but the remaining two quadrats form the centre of a small group of species-poor sites restricted to the flats. Further sampling of this community type is needed to clarify its relationships with other communities of the flats.

TABLE 7

Local and regional endemic taxa.

TAXON	ENDEMIC STATUS	RESERVATION STATUS
Acacia adinophylla	Endemic to Helena & Aurora Range	Not reserved
Leucopogon sp. Helena & Aurora (BJL 2077)	Endemic to Helena & Aurora Range	Not reserved
Neurachne sp. Helena & Aurora (KRN 8972)	Endemic to Helena & Aurora Range	Not reserved
Tetratheca aphylla	Endemic to Helena & Aurora Range	Not reserved
Acacia cylindrica	Regional endemic	Known from 1 reserve
Grevillea erectiloba	Regional endemic	Known from 2 reserves
Grevillea georgeana	Regional endemic	Known from 1 reserve
Mirbelia sp. Helena & Aurora (BJL 2003)	Regional endemic	Not reserved
Stenanthemum newbeyi	Regional endemic	Not reserved

TABLE 8

Key to the major floristic community types found on the Helena and Aurora Range.

1. Upland or midslope sites on massive banded ironstone.	
2. Shrublands or woodlands not dominated by eucalypt species.	*Community type 1*
2. Woodlands dominated by *Eucalyptus ebbanoensis* and/or *E. corrugata* or *E. capillosa* ssp. *capillosa* with *Alyxia buxifolia* and/or *Stenanthemum newbeyi* in understorey.	*Community type 2*
1. Midslope or valley bottoms not on massive banded ironstones.	
3. Midslope community dominated by *Eucalyptus ebbanoensis* and/or *E. corrugata* over *Neurachne* sp. Helena & Aurora (KRN 8972), chenopods absent.	*Community type 3*
3. Lower slope or valley.	
4. Community type generally dominated by *Acacia* spp. or if dominated by eucalypts then with *Eremophila clarkei* and *Grevillea zygoloba* present.	*Community type 4*
4. Community dominated by eucalypts over chenopod shrublands	*Community type 5*

The endemics and near endemics of the Helena and Aurora Range are completely unreserved. Beard (1972) places the vegetation of the range into his Bungalbin system, a small part of which occurs on Jaurdi Station to the east. CALM holds the lease to this station and has recommended the northern area become a Nature Reserve and the southern area become State forest (CALM 1994; Fig. 1). As yet it is not possible to determine whether the community types found on the Helena and Aurora Range also occur on the banded ironstone areas on Jaurdi Station. The bulk of Beard's Bungalbin vegetation system occurs from the Helena and Aurora Range west to the Mt Jackson area. None of this area is in the current reserve system.

It is regrettable that past exploration activity in the area was not rehabilitated. Tracks and gridlines left in this environment take many years to recover owing to the slow growth rates found in these areas. Some of the tracks left on steeper slopes show significant erosion.

The results of this study support the recommendations of Keighery (1980), Henry-Hall (1990) and CALM (1994) that the Helena and Aurora Range should be declared a Nature Reserve for the protection of flora and the conservation of the banded ironstone vegetation communities.

ACKNOWLEDGEMENTS

This work was part of a flora and fauna survey of the Helena and Aurora Range partially funded by a grant from the Australian Nature Conservation Agency. We would like to thank Andy Chapman from CALM's Goldfields office for his organization of this project and the Goldfields Region staff for assistance in the field. The following people are thanked for assistance with identifications in their particular field of expertise: Steve Hopper, Greg Keighery, Bruce Maslin, Barbara Rye, Malcom Trudgen, and Paul Wilson. Terena Lally and two referees provided helpful comment on earlier drafts.

REFERENCES

Beard, J.S. (1972). *The vegetation of the Jackson area, Western Australia.* Vegmap Publications, Perth.

Beard, J.S. (1990). *Plant Life of Western Australia.* Kangaroo Press, Kenthurst.

Belbin, L. (1993). PATN – Pattern analysis package. CSIRO Division of Wildlife and Ecology, Canberra.

CALM (1994). *Regional management plan 1994-2004 - Goldfields region.* Department of Conservation and Land Management, Western Australia.

CALM (1996). *Declared Rare and Priority flora list -* 21/10/1996. Unpublished Report, CALM, Western Australia.

Chin, R.J. and Smith, R.A. (1983). Jackson, Western Australia. 1: 250 000 geological series - explanatory notes. Geological Survey of Western Australia, Perth.

Dell, J., How, R.A., Newbey, K.R., and Hnatiuk, R.J. (1985). The biological survey of the eastern goldfields of Western Australia. Part 3 Jackson - Kalgoorlie study area. *Records of the Western Australian Museum Supplement* **23.**

Gibson, N., and Lyons, M.N. (1995). *Floristic survey of the Bremer and Parker Ranges of the eastern goldfields of Western Australia.* Unpublished Report for the Australian Heritage Commission prepared by the Department of Conservation and Land Management, Western Australia.

Green, J.W. (1985). *Census of the vascular plants of Western Australia.* Department of Agriculture, Perth, Western Australia.

Henry-Hall, N.J. (1990). *Nature conservation reserves in the Eastern Goldfields, Western Australia. (Southern two thirds of CTRC System 11).* Unpublished Report to EPA (Western Australia) Red Book Task Force.

Hopper, S.D., Purdie, R.W., George, A.S. and Patrick, S.J. (1987). *Conostylis. Flora of Australia* **45**, 57-110.

Keighery, G.J. (1980). Notes on the biology, distribution and conservation of *Dryandra arborea* (Proteaceae). *Western Australian Naturalist* **14**, 212-213.

Kent, M. and Coker, P. (1992). *Vegetation description and analysis: a practical approach.* Belhaven Press, London.

Muir, B.G. (1977). Biological survey of the Western Australian wheatbelt, Part II. *Records of the Western Australian Museum Supplement* **3.**

Newbey, K.R. and Hnatiuk, R.J. (1985). Vegetation and Flora. In: The biological survey of the eastern goldfields of Western Australia. Part 3 Jackson - Kalgoorlie study area. *Records of the Western Australian Museum Supplement* **23**, 11-38.

Rye, B.L. (1995). New and priority taxa in the genera *Cryptandra* and *Stenanthemum* (Rhamnaceae) of Western Australia. *Nuytsia* **10**, 255-305.

Siegel, S. (1956). *Non parametric statistics for behavioural sciences.* McGraw-Hill, New York.

Sneath, P.H.A. and Sokal, R.R. (1973). *Numerical taxonomy: The principles and practice of numerical classification.* Freeman, San Francisco.

Thackway, R. and Creswell, I.D. (eds)(1995). *An interim biogeographical regionalisation for Australia: a framework for establishing the national system of reserves, version 4.0.* Australian Nature Conservation Agency, Canberra.

APPENDIX 1

Flora List for the Helena and Aurora Range.

This list includes all taxa from both the sampling quadrats and the opportunistic collections and confirmed records from PERTH. Nomenclature follows Green (1985) and current usage at PERTH (ms denotes a manuscript name,
* indicates an introduced taxa).

Family: Adiantaceae
Cheilanthes austrotenuifolia
Cheilanthes brownii
Cheilanthes lasiophylla
Cheilanthes sieberi ssp. *sieberi*

Family: Aizoaceae
Gunniopsis quadrifida
* *Mesembryanthemum nodiflorum*
Tetragonia sp.

Family: Amaranthaceae
Ptilotus aervoides
Ptilotus carlsonii
Ptilotus drummondii var. *drummondii*
Ptilotus exaltatus
Ptilotus gaudichaudii
Ptilotus holosericeus
Ptilotus obovatus

Family: Anthericaceae
Arthropodium curvipes
Thysanotus patersonii

Family: Apiaceae
Daucus glochidiatus
Hydrocotyle rugulosa
Trachymene ornata
Trachymene pilosa
Uldinia ceratocarpa

Family: Apocynaceae
Alyxia buxifolia

Family: Asclepiadaceae
Rhyncharrhena linearis

Family: Asphodelaceae
Bulbine semibarbata

Family: Aspleniaceae
Pleurosorus rutifolius

Family: Asteraceae
Actinobole uliginosum
Angianthus tomentosus
Bellida graminea
Blennospora drummondii
Brachyscome ciliaris
Brachyscome iberidifolia
Brachyscome perpusilla
Calotis hispidula
* *Centaurea melitensis*
Cephalipterum drummondii
Ceratogyne obionoides
Chrysocephalum semicalvum
Chthonocephalus pseudevax
Euchiton sphaericus
Gilberta tenuifolia
Gilruthia osbornei
Gnephosis intonsa
Hyalosperma demissum
Hyalosperma glutinosum ssp. *glutinosum*
* *Hypochaeris glabra*
Isoetopsis graminifolia
Lawrencella davenportii
Lawrencella rosea
Lemooria burkittii
Leucochrysum fitzgibbonii
Millotia myosotidifolia
Minuria cunninghamii
Olearia decurrens
Olearia exiguifolia
Olearia humilis
Olearia muelleri
Olearia pimeleoides
* *Osteospermum clandestinum*
Podolepis canescens
Podolepis capillaris
Podolepis lessonii
Podotheca gnaphalioides
Pogonolepis stricta
* *Pseudognaphalium luteoalbum*
Rhodanthe laevis
Rhodanthe manglesii
Rhodanthe oppositifolia
Rhodanthe pygmaea
Rhodanthe rubella
Rhodanthe stricta
Schoenia cassiniana
Senecio glossanthus
Senecio picridioides
Senecio quadridentatus
* *Sonchus oleraceus*
* *Sonchus tenerrimus*
Streptoglossa liatroides
Trichanthodium skirrophorum
Triptilodiscus pygmaeus
Waitzia acuminata
Waitzia citrina

Family: Boraginaceae
Halgania sp. 1 (BJL 2049)
Halgania sp. 2 (BJL 2082)

Family: Brassicaceae
Arabidella sp. Goldfields (P.G. Wilson 7183)
Lepidium oxytrichum
Lepidium phlebopetalum
Phlegmatospermum eremaeum
* *Sisymbrium irio*
Stenopetalum filifolium
Stenopetalum robustum

Family: Caesalpiniaceae
Senna artemisioides ssp. *filifolia*
Senna cardiosperma ssp. *cardiosperma*
Senna pleurocarpa var. *pleurocarpa*

Family: Campanulaceae
Wahlenbergia tumidifructa

Family: Caryophyllaceae
* *Cerastium glomeratum*
Stellaria filiformis

Appendix 1 (continued)

Family: Casuarinaceae
Allocasuarina acutivalvis
Allocasuarina campestris

Family: Chenopodiaceae
Atriplex nummularia
Atriplex vesicaria
Enchylaena tomentosa
Halosarcia halocnemoides
Maireana georgei
Maireana radiata
Maireana tomentosa ssp. *tomentosa*
Maireana trichoptera
Rhagodia drummondii
Rhagodia preissii ssp. *preissii*
Sclerolaena diacantha
Sclerolaena drummondii
Sclerolaena fusiformis
Sclerolaena obliquicuspis

Family: Chloanthaceae
Newcastelia viscida

Family: Colchicaceae
Wurmbea tenella

Family: Convolvulaceae
Convolvulus erubescens

Family: Crassulaceae
Crassula colorata

Family: Cupressaceae
Callitris glaucophylla

Family: Cyperaceae
Isolepis congrua
Lepidosperma aff. *tenue* (KRN 9197)
Lepidosperma aff. *angustatum*
Schoenus nanus

Family: Dasypogonaceae
Chamaexeros macranthera
Lomandra effusa

Family: Dilleniaceae
Hibbertia exasperata

Family: Droseraceae
Drosera macrantha ssp. *macrantha*

Family: Epacridaceae
Leucopogon breviflorus
Leucopogon sp. Helena & Aurora (BJL 2077)

Family: Euphorbiaceae
Calycopeplus paucifolius
Monotaxis occidentalis
Poranthera microphylla

Family: Fabaceae
Bossiaea walkeri
Daviesia benthamii ssp. *acanthoclona*
Daviesia purpurascens
Mirbelia depressa
Mirbelia microphylla
Mirbelia sp. Helena and Aurora (BJL 2003)
Swainsona canescens
Swainsona kingii
Swainsona oliveri
Templetonia sulcata

Family: Geraniaceae
* *Erodium cicutarium*
Erodium crinitum
Erodium cygnorum ssp. *cygnorum*

Family: Goodeniaceae
Brunonia australis
Dampiera lavandulacea
Dampiera spicigera
Goodenia berardiana
Goodenia havilandii
Goodenia mimuloides
Goodenia occidentalis
Goodenia peacockiana
Goodenia pinnatifida
Scaevola spinescens
Velleia rosea

Family: Haemodoraceae
Conostylis argentea

Family: Haloragaceae
Gonocarpus nodulosus
Haloragis gossei
Haloragis trigonocarpa

Family: Juncaginaceae
Triglochin sp.

Family: Lamiaceae
Prostanthera campbellii
Prostanthera grylloana
Prostanthera magnifica
Westringia cephalantha
Westringia rigida

Family: Lauraceae
Cassytha melantha

Family: Lobeliaceae
Lobelia gibbosa

Family: Loganiaceae
Phyllangium paradoxum

Family: Loranthaceae
Amyema miquelii
Amyema preissii
Lysiana casuarinae

Family: Malvaceae
Lavatera plebeia
Lawrencia repens
Sida aff. *spodochroma*
Sida calyxhymenia
Sida excedentifolia ms

Family: Mimosaceae
Acacia acuminata
Acacia adinophylla ms
Acacia aneura
Acacia assimilis ssp. *atroviridis*
Acacia colletioides

Appendix 1 (continued)

Acacia coolgardiensis ssp. *effusa*
Acacia cylindrica
Acacia eremophila
Acacia erinacea
Acacia hemiteles
Acacia hystrix ssp. *hystrix* ms
Acacia aff. *multispicata*
Acacia prainii
Acacia quadrimarginea
Acacia resinimarginea
Acacia steedmanii
Acacia tetragonophylla

Family: Myoporaceae
Eremophila alternifolia
Eremophila clarkei
Eremophila decipiens ssp. *decipiens*
Eremophila gibbosa
Eremophila granitica
Eremophila interstans
Eremophila ionantha
Eremophila latrobei
Eremophila maculata ssp. *brevifolia* ms
Eremophila oldfieldii
Eremophila oppositifolia
Eremophila rugosa ms
Eremophila saligna
Eremophila scoparia

Family: Myrtaceae
Baeckea elderiana
Calothamnus gilesii
Eucalyptus aff. *oleosa*
Eucalyptus calycogona
Eucalyptus capillosa ssp. *capillosa*
Eucalyptus celastroides
Eucalyptus clelandii
Eucalyptus corrugata
Eucalyptus cylindrocarpa
Eucalyptus drummondii
Eucalyptus ebbanoensis
Eucalyptus ewartiana
Eucalyptus hypochlamydea ssp. *hypochlamydea* ms
Eucalyptus longicornis
Eucalyptus loxophleba ssp. smooth bark (Brooker & Kleinig 1990)
Eucalyptus ravida
Eucalyptus salmonophloia
Eucalyptus salubris
Eucalyptus sheathiana
Eucalyptus transcontinentalis
Eucalyptus yilgarnensis
Homalocalyx thryptomenoides
Leptospermum roei
Melaleuca eleuterostachya
Melaleuca leiocarpa
Melaleuca nematophylla
Melaleuca radula
Melaleuca uncinata
Rinzia carnosa
Thryptomene appressa

Family: Ophioglossaceae
Ophioglossum lusitanicum

Family: Orchidaceae
Caladenia incensa ms
Caladenia incrassata ms
Caladenia microchila ms
Caladenia saccharata
Cyanicula amplexans ms
Pterostylis aff. *nana*
Pterostylis picta
Thelymitra aff. *macrophyllum*

Family: Orobanchaceae
* *Orobanche minor*

Family: Oxalidaceae
Oxalis perennans

Family: Phormiaceae
Dianella revoluta var. *divaricata*

Family: Pittosporaceae
Cheiranthera filifolia
Pittosporum phylliraeoides

Family: Plantaginaceae
Plantago aff. *hispidula* (N. Gibson & M. Lyons 1732)
Plantago drummondii
Plantago turrifera

Family: Poaceae
* *Aira caryophyllea*
Amphipogon caricinus var. *caricinus*
Austrostipa elegantissima
Austrostipa platychaeta
Austrostipa trichophylla
Bromus arenarius
* *Bromus diandrus*
* *Bromus rubens*
Danthonia caespitosa
Danthonia setacea
Echinopogon ovatus var. *pubiglumis*
Elymus scaber
Eragrostis dielsii
Eragrostis eriopoda
* *Hordeum glaucum*
Neurachne sp Helena & Aurora (KRN 8972)
* *Pentaschistis airoides*
* *Rostraria pumila*
* *Vulpia bromoides*
* *Vulpia myuros - muralis* complex

Family: Polygalaceae
Comesperma integerrimum

Family: Polygonaceae
Muehlenbeckia adpressa
Muehlenbeckia cunninghamii

Family: Portulacaceae
Calandrinia corrigioloides
Calandrinia eremaea

Family: Proteaceae
Dryandra arborea
Grevillea acuaria
Grevillea erectiloba
Grevillea georgeana
Grevillea haplantha ssp. *haplantha*

Appendix 1 (continued)

Grevillea nematophylla
Grevillea paradoxa
Grevillea zygoloba
Hakea minyma
Hakea preissii

Family: Rhamnaceae
Stenanthemum intricatum
Stenanthemum newbeyi

Family: Rubiaceae
* *Galium aparine*
* *Galium murale*

Family: Rutaceae
Eriostemon brucei ssp. *brucei*
Eriostemon tomentellus
Phebalium canaliculatum
Phebalium tuberculosum

Family: Santalaceae
Exocarpos aphyllus
Santalum acuminatum
Santalum lanceolatum
Santalum spicatum

Family: Sapindaceae
Dodonaea inaequifolia
Dodonaea lobulata
Dodonaea microzyga
Dodonaea rigida
Dodonaea stenozyga
Dodonaea viscosa

Family: Solanaceae
Nicotiana occidentalis
Nicotiana rotundifolia
Solanum hoplopetalum
Solanum lasiophyllum
Solanum orbiculatum ssp. *orbiculatum*
Solanum plicatile

Family: Sterculiaceae
Brachychiton gregorii
Keraudrenia integrifolia
Rulingia cuneata
Rulingia luteiflora
Rulingia magniflora

Family: Thymelaeaceae
Pimelea microcephala

Family: Tremandraceae
Tetratheca aphylla

Family: Urticaceae
Parietaria cardiostegia

Family: Zygophyllaceae
Zygophyllum apiculatum
Zygophyllum eremaeum
Zygophyllum fruticulosum
Zygophyllum ovatum

CALMScience 2(3): 247-266 (1997)

Defining indicators and standards for recreation impacts in Nuyts Wilderness, Walpole-Nornalup National Park, Western Australia

SHANNON L. MORIN[1], SUSAN A. MOORE[2] AND WAYNE SCHMIDT[3]

[1]Major Project Review Unit, Habitat and Enhancement Branch, Department of Fisheries and Oceans, Stn 327, 555 West Hastings Street, Vancouver BC V6B 5GB, Canada.

[2]School of Environmental Science, Division of Science, Murdoch University, South Street, Murdoch, Western Australia 6150.

[3]Parks, Recreation, Planning and Tourism Division, Department of Conservation and Land Management, Locked Bag 104, Bentley Delivery Centre, Western Australia 6983.

ABSTRACT

A central issue in wilderness management is not the number of users *per se*, but the impacts those users can have on environmental conditions and the quality of experience of other visitors. This study draws on two recreation planning frameworks, the limits of acceptable change and visitor impact management, to translate management goals into quantitative management objectives through indicators and standards. Potential indicators and standards were identified, via a mailback survey conducted in 1995, for Nuyts Wilderness Area on the south coast of Western Australia.

Environmental conditions of greatest influence on the quality of visitor experience were amount of litter, inadequate disposal of human waste, presence of wildlife, walk trail erosion, vegetation loss and tree damage. Standards were determined for two biophysical indicators - tree damage and vegetation loss - and four social indicators - number and size of groups, litter and human-made structures (e.g. signs). Respondents had the lowest level of tolerance and set the highest standards for litter and damage to trees. Tolerance levels for social effects such as the number of other groups seen were higher. Standards were similar across sites for all indicators except vegetation loss where respondents were more willing to accept change at the camp-site than elsewhere.

These results suggest that management efforts can be differentially directed toward indicators of greatest concern, such as litter and tree damage. The study findings also suggest that managing to meet the expectations of 50 per cent of visitors regarding acceptable and unacceptable impacts is feasible, especially where impacts do not currently exceed acceptable levels, whereas striving to meet the expectations of 75 per cent of visitors requires reducing impacts by at least half. Such reductions may be impossible and create unrealistic expectations among visitors and managers alike.

INTRODUCTION

An important issue in wilderness management is not the number of users *per se*, but the impacts those users can have on the environmental conditions of the area and the quality of experience of other visitors. It is these impacts that can potentially affect the ecological integrity and conservation value of the area as well as the quality of the recreational experience. Given that any use will produce at least some impact managers, in close consultation with the users of a wilderness area, need to identify where and to what extent varying degrees of change are appropriate and acceptable.

This study draws on two planning approaches: the Limits of Acceptable Change (LAC) wilderness management planning framework (Stankey *et al.* 1985) and the Visitor Impact Management (VIM) framework (Graefe *et al.* 1990). Both frameworks enable management goals, which are generally qualitative in nature, to be translated into quantitative management objectives through the use of indicators and standards. Thus, achieving environmental goals is determined by standards which are monitored through the use of suitable indicators.

A key research need in the LAC process has long been identified as the identification of indicators and standards (Stankey *et al.* 1985; Stankey and Lucas 1985; McCool 1989). Social research can help provide data about the preferences, expectations and judgements of impact acceptability held by visitors to wilderness areas which can in turn be used to establish biophysical and social standards for an area (Stankey and Lucas 1985). These standards express how much change in the various indicators is considered appropriate and acceptable.

The objective of the study reported in this paper was to apply elements of the LAC and VIM planning frameworks to the identification and formulation of indicators and associated standards for the management of recreation impacts in Nuyts Wilderness Area (Nuyts) in Walpole-

Nornalup National Park on the south coast of Western Australia. Identification of indicators and standards reflecting the broader ecological integrity of the area is also essential, but was beyond the scope of this study. The recreation standards identified and formulated are most likely a subset of a broader suite of ecologically-directed measures.

Nuyts was selected because it has a long history of bushwalking and overnight camping and because of its designation as a wilderness zone in the Walpole-Nornalup National Park Management Plan (CALM 1992). The area shows evidence of degradation from recreational use with some areas of erosion and damage to vegetation, however, the acceptability or otherwise of these effects of visitor use have not been quantified making it difficult for managers to know whether management actions are needed.

Information on indicators and standards was gathered via a mailback survey conducted in 1995. Respondents were asked to provide feedback regarding four management sub-units, namely: walk trails, camp-site, beach coves, and Mt Hopkins. Potential respondents were drawn from the visitor book, for the period January to June 1995, left at the main entrance to Nuyts.

Based on the survey results, environmental conditions of greatest influence on the quality of visitor experience were amount of litter, inadequate disposal of human waste, presence of wildlife, walk trail erosion, vegetation loss and bare ground, and human damage to trees. Standards were determined for two biophysical indicators - tree damage and vegetation loss/bare ground - and four social indicators - number and size of groups, litter and human-made structures (e.g. signs). Respondents had the lowest level of tolerance and set the highest standards for amount of litter and damage to trees. Tolerance levels for social effects such as the number of other groups seen were higher. Standards were similar across sites for all indicators except vegetation loss where respondents were more willing to accept change at the camp-site than elsewhere.

These results suggest that management efforts can be differentially directed toward indicators of greatest concern, such as litter and tree damage. The study findings also suggest that managing to meet the expectations of 50 per cent of visitors regarding acceptable and unacceptable impacts is feasible, especially where impacts do not currently exceed acceptable levels, whereas striving to meet the expectations of 75 per cent of visitors requires reducing impacts by at least half. Such reductions may be impossible and create unrealistic expectations among visitors and managers alike.

DETERMINING RECREATION IMPACTS IN WILDERNESS AREAS

In many wilderness areas, recreation use has become a major concern as the impacts of such use threatens to adversely affect both the integrity of natural ecosystems and the quality of the experience for visitors (Stankey *et al.* 1990). Formulating methods that provide for the appropriate recreational use of an area while maintaining resource impacts at an acceptable level has been a persistent problem for park managers both in Australia (Prosser 1986; Absher 1994) and North America (Stankey *et al.* 1985; Roggenbuck *et al.* 1993; BC Forest Service 1995).

Resolution of this 'appropriate use/acceptable impact' dilemma requires the recognition of the unavoidable consequences of recreation in natural areas (Prosser 1986). This leads to the inevitable acceptance that any human use of a natural area will lead to some change in the condition of that area. With use comes changes in the biophysical and social conditions of the area; soils are compacted, vegetation and wildlife are disturbed and the level of social interaction increases.

One of the central goals of wilderness management is to identify the desired resource, social, and managerial conditions and express them as explicit, measurable standards to be maintained or restored in wilderness areas (Stankey *et al.* 1990). The focus of management thus shifts from the traditional approach of attempting to define maximum use levels, to the identification of the desired conditions and to thus manage use levels and other parameters so that impacts do not exceed these conditions (Shelby and Heberlein 1986).

In developing a wilderness management program, managers and the public must recognize that the management of wilderness areas is based on value judgements. As few people make identical value judgements, the task facing agency managers is one of gaining consensus among wilderness users regarding what constitutes the desired wilderness conditions and consequently, how those conditions should be maintained. Inherent in this collective value judgement is the recognition that management of wilderness is actually the management of wilderness users and their impacts (Lucas 1973). Therefore, to determine the amount of change that will be considered acceptable involves a subjective value judgement. Decisions that reflect value judgements need to be made with the support, consent and agreement of both managers and users. This implies that wilderness planning and management is essentially a socio-political process incorporating biophysical and social data and agency policies.

Determination of recreation impacts in wilderness areas is best undertaken with full knowledge of the paradigms within which such decisions are made. The influential paradigms include recreation carrying capacity, and the LAC and VIM planning frameworks.

Recreation Carrying Capacity

Traditionally, recreational use levels in wilderness areas have been addressed through the concept of carrying capacity. The carrying capacity paradigm was developed from a biological model used to determine the appropriate levels of animal use of forage resources (Wagar 1964). This biological concept was applied to wilderness areas in the United States (US) in the 1960s when a surge in use of wilderness areas led to concerns about burgeoning impacts. Wagar's (1964) work broadened carrying capacity to include social as well as ecological capacity (Stankey *et al.* 1990). Thus, recreational carrying capacity had two main components: an ecological capacity - the impact on the physical-biological resource (i.e. soils and vegetation) - and a social capacity, that is, the impact on the character of the recreational experience.

Recreational carrying capacity was originally articulated as a method of conceptualizing problems, however, it was misinterpreted and applied as a use-limit policy, thus confusing recreational carrying capacity as a concept for examining problems with use limits as a method for restricting access (McCool 1989). Carrying capacity was also viewed as an idea whose application was only constrained by the level of effort and ingenuity of managers and researchers rather than as the result of a judgemental process (Stankey *et al.* 1990). It was seen as a product of technical assessment rather than a decision based on a combination of value judgements that weight resources and social impacts along with human needs and values.

The carrying capacity concept failed to generate practical use limits and also failed in its assumption that regulation of use would solve the problems of resource impact (McCool 1989). Also, during the 1980s it became apparent that variances in human behaviour were as influential in causing impacts as the actual numbers of visitors (Cole and Hammitt 1987). The recognition that much of the biophysical impact caused by recreational use occurred at low levels of use (Cole 1985) completely contradicted the basis on which recreational carrying capacity was implemented - as a use-limit policy - thus rendering the concept inadequate in assisting the resolution of visitor impact problems. Many researchers argued that the concept should be abandoned (Wagar 1964; Bury 1976).

These realizations about the inability of the carrying capacity concept to provide an answer regarding 'how much use is too much', the rephrasing of the question to 'how much change is acceptable', and recognition of the importance of value judgements spawned separate yet parallel efforts to develop a more adequate framework for managing recreational use and its associated impacts. The conceptual planning frameworks - LAC and VIM - represent efforts to correct deficiencies in the traditional carrying capacity paradigm of recreation management.

Limits of Acceptable Change Planning Framework

The Limits of Acceptable Change (LAC) planning framework (Stankey *et al.* 1985) represents a major alternative approach to the carrying capacity issue, hingeing on the recognition that some level of change is inevitable and therefore decisions regarding how much change is acceptable to users and managers must be made. In summary, the LAC system as developed by Stankey *et al.* (1985) establishes a process for deciding what environmental and social conditions are acceptable and helps identify management actions required to protect or achieve those conditions. The Recreation Opportunity Spectrum (ROS) planning framework complements the LAC system by providing a process for recognizing and designating opportunity classes with different levels of recreational use, however, it leaves the selection of indicators and standards to LAC (Clark and Stankey 1979).

Five general stages summarize the steps of the LAC process (Table 1). First, the management problems and issues for an area are identified and recreation opportunity classes or zones defined and described (Steps 1 and 2). This first stage provides the broad context for the remainder of the planning process. Second, the acceptable and achievable environmental resource and social conditions are defined by a series of measurable parameters (Step 3). Third, the relationships between the existing conditions and those judged as being acceptable conditions are analysed (Steps 4 and 5). Fourth, management guidelines and actions are identified and formulated to best achieve the acceptable conditions (Steps 6 and 7). Last, a program of post-implementation monitoring and evaluating the effectiveness of the prescribed management actions is initiated.

The LAC process also embraces public involvement, being based on the recognition that the public can provide an important and substantial body of expertise in the planning process (Stankey *et al.* 1985). The public also provide the judgements essential for the selection of standards for acceptable impacts. Perhaps the most important strength of LAC lies in its continued public

TABLE 1

A comparison of the steps in the LAC and VIM planning frameworks (Sources: Stankey *et al.* 1985; Graefe *et al.* 1990).

STEPS	LAC	VIM
1	Identify area concerns and issues	Review of database
2	Define and describe opportunity classes	Review of management objectives
3	*Select indicators of resource and social conditions*	*Identify measurable indicators*
4	Inventory resource and social conditions	*Select standards for indicators*
5	*Specify standards for resource and social conditions*	Assess current conditions of impact indicators
6	Identify alternative opportunity class allocations	Identify probable causes of impacts
7	Identify management actions for each alternative	Identify a range of alternative management strategies
8	Evaluate and select an alternative	Implement selected strategies
9	Implement actions and monitor conditions	

participation which virtually guarantees successful planning outcomes (Knopf 1989).

This study addressed Steps 3 and 5 (italicized in Table 1), the selection of indicators and specification of standards for resource and social conditions. The 'best indicators' are those which reflect the highest degree of naturalness of the wilderness ecosystem under examination and the social quality of the wilderness experience. Monitoring of all the parameters of the wilderness ecosystem is essentially impossible, thus the 'key' wilderness quality indicators must be identified and monitored. A few criteria should be taken into account when selecting these key indicators: they should be capable of being measured in cost-effective ways at acceptable levels of accuracy; the condition of the indicator should reflect some relationship to the amount/type of use occurring; social indicators should be related to user concerns; and the condition of the indicator should be responsive to management control (Stankey *et al.* 1985).

Setting standards, the aim of the fifth step of the LAC process (Table 1), assigns quantitative standards for resource and social indicators. These adopted standards provide a basis for judging whether a particular condition is acceptable or not; they establish the 'limits of acceptable change' for the resource and social conditions. While setting standards is a judgemental process, the process is explicit, traceable, and subject to public involvement and review. Standards related to appropriate use conditions are best derived with the input of visitors themselves. Standards are not meant to be idealistic goals but conditions that managers feel can be achieved over a reasonable time period. Thus, standards should be stringent enough to be meaningful, but not so stringent that they can not be attained. In formulating standards, there needs to be a balance between using existing conditions to lend realism to the specific standards, professional judgement, and public input.

Standards will often be an expression of the typical situation of an area expressed in terms of probabilities. For example, a standard for daily contacts while travelling might be expressed as 'interparty contact levels on the trail will not exceed two per day on at least 90 per cent of the days during the summer use period'. This recognizes the high degree of resource and social variability in a wilderness system which makes specific, absolute standards unrealistic, especially during peak periods of visitor numbers during a few days or weeks of the year.

LAC has been applied extensively in the US with the most intensive application directed at the Bob Marshall Wilderness Complex in Montana (Stankey *et al.* 1990). It has provided standards against which the effectiveness or otherwise of management actions, such as visitor education, area closure and infrastructure development, have been evaluated. The framework has not been comprehensively applied in Australia, although there has been limited application in the Australian Alps in eastern Australia, and Fitzgerald River National Park in Western Australia.

Visitor Impact Management Planning Framework

The Visitor Impact Management (VIM) planning framework (Graefe *et al.* 1990) is the result of a study initiated by the US National Parks and Conservation Association (NPCA) which had two main objectives: to review and synthesize the existing literature on recreational carrying capacity and visitor impacts and then build on this existing knowledge to formulate a method for managing visitor impacts in the variety of areas within the US National Park system (Graefe *et al.* 1990). Similar to the evolution of LAC, VIM can be viewed as an alternative to the original carrying capacity concept.

VIM is intended to provide a planning framework for controlling or reducing undesirable impacts of recreational use, based on the principle that both the environment and the quality of the recreational experience are complex and are influenced by a number of factors besides use levels. Use limits provide only one potential strategy for reducing visitor impacts: it is important to remember the lessons learned from previous studies that found only weak or indirect relationships between impacts and overall use levels (Kuss and Graefe 1985; Graefe *et al.* 1990). Thus, in many situations establishing use capacities and limits may do little to reduce the impact problems they were intended to solve, whereas other potential management strategies may be quite effective in reducing the impact conditions (Graefe 1989). The VIM process is also built on the widely accepted recognition that effective management involves both scientific and judgemental considerations (Graefe *et al.* 1990).

The steps of the VIM process (Table 1) essentially deal with four basic issues: the identification of problem conditions or unacceptable visitor impacts (Step 1), identification of indicators and standards based on management objectives for the area (Steps 2-4), determination of potential causal factors affecting the occurrence and severity of the unacceptable impacts (Steps 5 and 6), and selection and implementation of potential management strategies for ameliorating the unacceptable impacts (Steps 7 and 8).

As this study addressed the selection of indicators and standards, only these parts of the VIM process will be discussed (Steps 3 and 4). The third step involves identifying measurable indicators for specific management objectives. These objectives must be consistent with existing legislation and policy while being specific for the area, describing the environmental conditions and visitor experience to be provided. Similar to the third step in the LAC process, this step is based on selecting the most important variables to serve as the 'key' indicators of the desired conditions. Also, the same criteria to be considered in selecting key indicators in the LAC process applies in the VIM process. Step 4 of the VIM process focuses on selecting standards, similar to Step 5 of the LAC process.

VIM has been applied in several US national parks (e.g. Great Smoky Mountains National Park, Glacier

National Park) and has also served as the basis for studies in other areas (Buck Island Reef, US Virgin Islands) (Graefe 1989). In Australia, a recent application of VIM has been undertaken at Jenolan Caves Reserve in New South Wales (Mandis Roberts Consultants 1995). Similarly to LAC, VIM has provided standards against which the effectiveness of management actions to ameliorate recreation impacts can be assessed.

VIM and LAC are similar processes in that they are both concerned with the impacts of recreation, including impacts on both the natural environment and the quality of the visitor experience. And, both frameworks rely on the use of indicators and standards as a means to define unacceptable impacts (Table 1). They also differ in several ways. VIM has an explicit step aimed at identifying the probable causes of impacts, while LAC places greater emphasis on defining recreation opportunity classes and developing alternative class allocations. To date, applications of VIM have tended to focus on the management of relatively localized visitor impact problems (e.g. Logan Pass, Glacier National Park) in contrast to the emphasis within LAC on large scale wilderness planning applications (e.g. Bob Marshall Wilderness Complex).

RESEARCH METHODS

This study was based on a literature review and mailback questionnaire. The literature review concentrated on a review of wilderness management research, specifically related to the theory and application of LAC and VIM approaches, and identification of appropriate indicators and standards for the limits of change related to recreation impacts. The results of the literature review were used to provide direction and focus for the formulation of a mailback visitor questionnaire targeted at recent visitors to Nuyts Wilderness area.

Mail survey participants were drawn from the visitor logbook at the main trail-head into Nuyts. Upon entering Nuyts, visitors are asked to sign visitor registration sheets. The sample population for this study was visitors who filled in the logbook between 31 January 1995 and 29 June 1995. Not all visitors may have filled in the log and only visitors who entered their names with a sufficiently detailed address received a questionnaire. Thus, the results may not be a true reflection of the total population of Nuyts visitors, only the sub-population who entered their name and address details. A total of 150 mailback questionnaires was sent to Nuyts visitors.

Prior to the survey proper, a pilot survey was conducted to identify any potential misunderstandings associated with the format or manner of question presentation. A sample of 10 people, including CALM staff, University colleagues, and Nuyts visitors randomly chosen from the registration sheets, was used for the pilot test. The minor problems revealed by the pilot test, plus recommendations by this group of respondents, resulted in corrections to the question wording and style before the survey proper commenced.

The survey proper was distributed by mail, with potential respondents receiving an introductory letter, the questionnaire and stamped self-addressed return envelope. The introductory letter briefly explained the objectives of the study. Approximately two months after the initial survey was distributed, a follow-up letter and copy of the survey were sent to Nuyts visitors who had yet to respond.

The questionnaire had five parts. The first part included questions about when, how often, who with, and for how long people visited Nuyts. It also asked about activities while visiting. The second part sought visitors' reasons for visiting Nuyts providing a list of items and an importance ranking from not at all important to extremely important.

The third part was the heart of the questionnaire. It included questions about visitors' preferences regarding current conditions and the quality of their experience. Again a list of items was provided and respondents were asked to assign an importance to each item. The next two questions asked respondents to assign a maximum acceptable level, in numbers and in several cases as a percentage, for potential impacts including tree damage, vegetation loss/bare ground, number and size of groups of people seen or heard, litter, human-made structures (such as signs), and camp-fire rings for each of four management sub-units. These potential impacts or indicators were drawn from the literature and surveys conducted in other wilderness areas.

Ideally, the indicators should have been provided by visitors. The approach used may have resulted in some important indicators being omitted and unimportant indicators being included. This problem could have been alleviated by conducting two surveys; the first to identify the most important indicators and the second to set standards. This approach is time-consuming and potentially results in attrition of respondents as they find the process tedious. The approach we took, based on one survey and a core set of indicators, is widely used in this research field.

The last question in the third part of the questionnaire asked respondents their views, from strongly support to strongly oppose, on potential management actions to deal with threats to Nuyts. The fourth part of the questionnaire gathered further information on social indicators and standards, specifically group numbers and size. The last part gathered information on the origin of visitors, their age and education level.

The survey data were collated and analysed using the software spreadsheet program Excel 5.1. Analysis focused on providing general survey statistics such as visitor and visit characteristics, determining indicators and standards, and assessing the social acceptability of a range of potential management actions. Literature concerning LAC, recreation impacts, and processes for defining indicators and associated standards were used to direct analysis.

Nuyts Wilderness Area in Walpole-Nornalup National Park (Fig. 1) on the south coast of Western Australia was the selected study site for several reasons. First, it is one

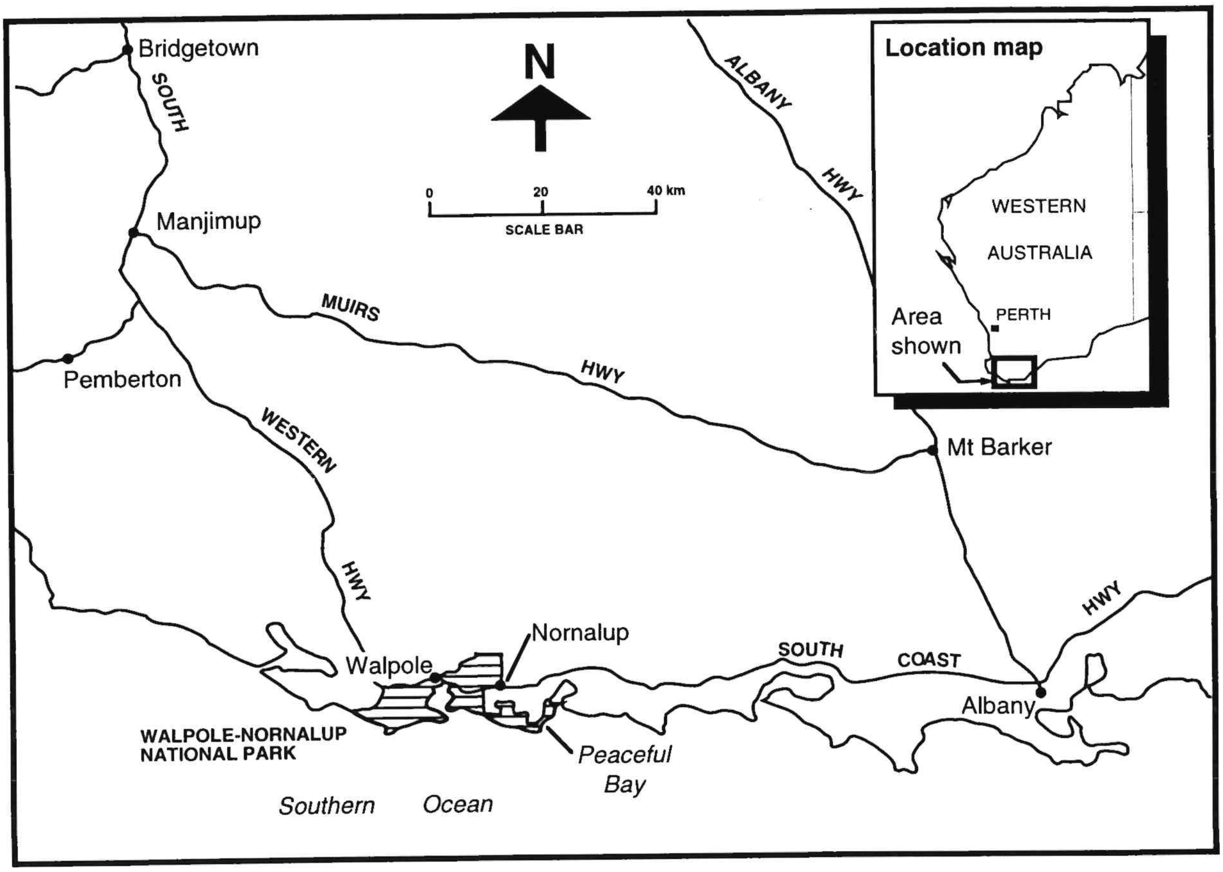


Figure 1. Location of Walpole-Nornalup National Park (Source: CALM 1992).

of the small number of areas zoned as wilderness in Western Australian national parks through formal management plans. According to the CALM zoning system for national parks (Anon. n.d.), wilderness zones are extensive areas which are good representations of each of the natural history themes of the park and which will be maintained in a wilderness state. Only certain activities requiring limited, primitive, visitor facilities appropriate to a wilderness experience will be allowed. Limits will be placed on numbers of users. No motorized access will be permitted and management actions will ensure that visitors are dispersed.

Nuyts was also selected for this study because a management plan had been recently completed (in 1992) for Walpole-Nornalup National Park including Nuyts Wilderness. The management plan provided three main objectives for Nuyts: to maximize the naturalness and remoteness of the area; maintain opportunities for wilderness-dependent experiences such as solitude while encouraging minimum impact activities; and rehabilitate degraded areas. Establishing such objectives is a critical step in both the LAC and VIM processes and made it possible for this study to address the next steps of identifying indicators and selecting standards.

In this study, the wilderness zoning accorded to Nuyts by the Walpole-Nornalup National Park Management Plan (CALM 1992) is recognized as a single opportunity class. This is consistent with Step 2 of the LAC process (Table 1). Following Step 1 of the VIM process, four visitor management sub-units within Nuyts were identified: at or beside walk trails, at the camp-site, at or around the coves (Aldridge and Thompson Coves), and at or around Mt Hopkins (Fig. 2). Designation of these sub-units was based on three important considerations: that the areas within each sub-unit had similar management requirements, they were likely to experience similar impacts, and together they covered all (most) areas likely to experience visitor impacts.

Covering an area of approximately 4500 ha, Nuyts occupies the south-western third of Walpole-Nornalup National Park on the south coast of Western Australia (Fig. 1). Recreational access is by foot via three main points: from the west from either Crystal Springs (2-3 km north-west of Nuyts), Mandalay Beach or Long Point, from the north at Deep River near Tinglewood, and one water access point near the mouth of Nornalup Inlet to the east (Fig. 2). The main access (entry/exit) point to Nuyts is the Deep River trail-head near Tinglewood.

Within Nuyts the main walk trail consists of an old vehicle track which leads from the Deep River entry to Thompson Cove and the camp-site. From this main trail, a series of shorter trails lead to Mt Hopkins, Aldridge Cove and Crystal and Boggy Lakes (Fig. 2). Facilities in the area include two bridges which cross the Deep River and a swampy tributary, markers for the first kilometre of the trail, and an information board and visitor registration sheets at the Deep River trail-head.

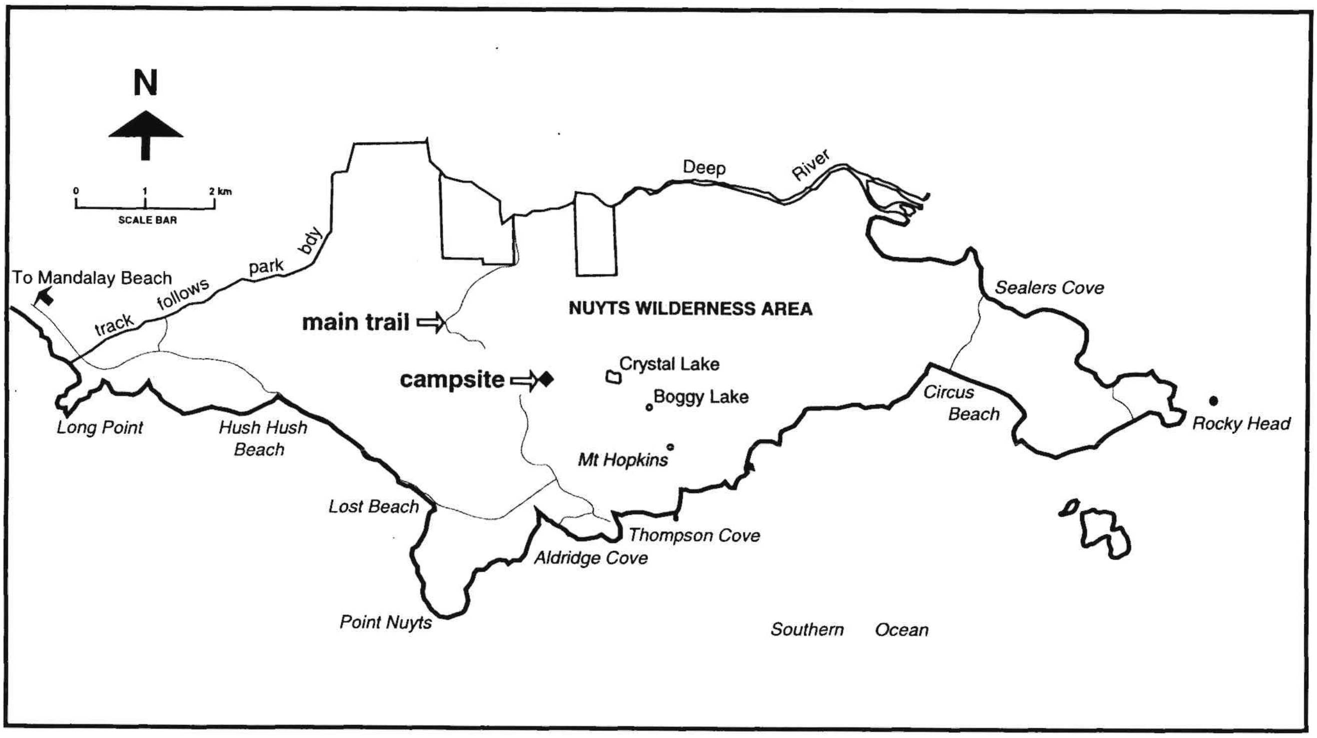


Figure 2. Location of the management sub-units used in this study (Source: CALM 1992).

RESULTS

Response Rate

A total of 150 surveys were mailed to Nuyts visitors, of which 16 per cent were undeliverable owing to insufficient address details or the person had moved. The response rate excluding the nondeliverable fraction was 76 per cent (86 people).

Visitor and Visit Characteristics

The two largest age groups of visitors to the area were those 26-40 years of age (45 per cent of respondents) and 41-60 years of age (36 per cent of respondents). A total of 17 per cent were aged 15-25, while only 1 per cent were under 15 and none were over 60. Most respondents lived in Perth (64 per cent) with 12 per cent from the Shire of Manjimup, 13 per cent from other areas of Western Australia, 7 per cent from interstate, and 4 per cent from overseas. A high number of respondents indicated they had completed post-graduate studies (32 per cent), while another 38 per cent had completed university or college degrees. This gives a total of 70 per cent of respondents with tertiary qualifications.

The number of previous visits ranged from two to more than 100 with most respondents having visited six times or less (65 per cent). The majority of respondents (60 per cent) visit Nuyts once a year. The largest proportion of respondents visited the area in April, followed by February and May.

The length of stay varied, however, the largest proportion stayed for one day or less (35 per cent), with 18 per cent staying for one night, 27 per cent for 2 or 3 nights and few staying more than four days or less than half a day. Respondents visited with family (39 per cent) or friends (38 per cent), while 14 per cent were alone and 10 per cent were with a club or organized group. The most common group size was two people (59 per cent of respondents). A substantial number of respondents were part of large groups: 16 per cent of respondents were part of a group of five or more people. Most respondents (73 per cent) saw two or less groups per day and over half (66 per cent) felt they had seen about the right number of groups on their most recent visit.

Activities undertaken by more than half of the respondents during their last visit included appreciating nature (98 per cent), walking for exercise (94 per cent), solitude (80 per cent), viewing wildlife (68 per cent), and photography (52 per cent). Other activities included camping, bird-watching, socializing, swimming and environmental education. Less than a quarter of respondents participated in beachcombing, picnicking or fishing.

The survey also investigated respondents' reasons for visiting Nuyts. Reasons were listed from previous studies by Roggenbuck *et al.* (1993) and the BC Forest Service (1995). When the results for extremely important and very important were combined, the most popular reasons given were to be in and enjoy wilderness, to view scenery, to enjoy an area free of vehicles, to enjoy outdoor activities, and solitude (Table 2). Fishing and camping were regarded as not very to not at all important.

TABLE 2

Reasons for visiting Nuyts Wilderness Area.

REASONS FOR VISITING	EXTREMELY IMPORTANT	VERY IMPORTANT	SOMEWHAT IMPORTANT	NOT VERY IMPORTANT	NOT AT ALL IMPORTANT
	Percentage of respondents[a]				
To be in and enjoy wilderness	70	24	6	0	0
To enjoy area free of vehicles	64	21	12	1	3
For solitude	44	29	20	4	3
To get away from city	42	25	15	9	9
To view scenery	41	49	10	0	0
To spend time with companion(s)	28	30	25	9	8
To enjoy outdoor activities	28	49	21	3	0
Physical exercise/challenge	17	42	33	5	3
To observe wildlife	17	34	34	15	0
To camp	16	24	13	13	33
To learn about nature (environmental education)	13	22	37	26	3
To fish	1	4	14	20	61

[a] percentages have been rounded to the nearest whole percentage therefore do not necessarily sum to 100 per cent in every case

Potential Indicators

Quality of experience was examined by asking respondents to indicate the importance of each of 16 items in influencing the quality of their most recent visit. Both biophysical and social factors or conditions were included (Table 3). Some of the listed items were drawn from Roggenbuck *et al.* (1993) and the BC Forest Service (1995) and others were formulated specifically for Nuyts. The intent was to identify potential indicators for monitoring visitor impacts, based on the premise that the best indicators are conditions of importance to visitors.

The following comments combine both the very and moderately important responses to give an overview of conditions that were at least moderately important to respondents. The two most important conditions were social: amount of litter and inadequate disposal of waste. The next four most important were all biophysical impacts: presence of wildlife, erosion of trails leading to the Coves, amount of vegetation loss or bare ground around the Coves, and number of trees damaged around the camp-site (Table 3). Other important social conditions were the number of people in a group, the number of groups camping within sight or sound, and evidence of camp-fires. An open-ended question which asked respondents to note additional environmental impacts resulted in comments regarding inadequate disposal of human waste, litter, and erosion at the Coves.

These results can also be considered on a site-by-site basis. For the Coves and on or beside trails, trail erosion was important. For the camp-site, an important condition was the number of trees damaged by humans. For all three management sub-units, the amount of vegetation loss or bare ground was important.

When the not at all and only slightly important responses were combined, width of trails appeared least important to respondents. For several conditions, such as the number of other groups seen along trails and width of trails, there was a spread of importance ratings from very important to not at all important (Table 3).

Standards for Potential Indicators

To determine standards for potential indicators, respondents were asked to suggest maximum acceptable levels before their experience would be changed for a list of impacts including trees damaged by humans, vegetation loss or bare ground, number and size of groups encountered, litter, human-made structures (e.g. signs) and camp-fire rings. In their responses, some people were unwilling to accept that use of an area results in some level of impact and so they provided a value of zero for the indicators, a standard which in many cases is impossible to achieve. Respondents were also asked to indicate the maximum acceptable levels as a percentage of the undisturbed area for tree damage and vegetation loss/bare ground. Two different forms of this question were asked to determine possible differences in responses evoked by different styles of questions. More people responded to the percentage questions than the questions requesting a number.

Results were further interpreted to provide two standards, one more stringent than the other, for each indicator. Researchers such as Roggenbuck *et al.* (1993)

TABLE 3

Environmental conditions influencing the quality of visitors' experiences in Nuyts Wilderness Area.

CONDITIONS	VERY/EXTREMELY IMPORTANT	MODERATELY IMPORTANT	SOMEWHAT IMPORTANT	NOT VERY/SLIGHTLY IMPORTANT	NOT AT ALL IMPORTANT
	Percentage of respondents[a]				
The amount of litter	71	15	3	5	6
Inadequate disposal of human waste	68	15	5	5	6
The presence of wildlife	47	36	12	5	0
Erosion of trails leading to Coves	43	29	14	10	4
Vegetation loss and bare ground around Coves	42	24	12	13	9
Number of trees damaged around camp-site	40	28	10	14	8
Erosion along main trail	35	26	19	12	9
Amount of vegetation loss and bare ground around camp-site	29	32	19	10	9
Amount of vegetation loss and/or bare ground along trails	29	30	17	12	13
The number of people in a group	27	31	19	10	12
Number of other groups camping within sight or sound of my camp-site	27	27	16	18	12
Evidence of camp-fires	26	27	22	21	5
Width of trail (size)	21	20	20	28	11
The presence of signs	21	29	25	13	13
Number of trails	18	30	30	16	5
Number of other groups seen along trails	14	32	28	15	10

[a] percentages have been rounded to the nearest whole percentage therefore do not necessarily sum to 100 per cent in every case

and the BC Forest Service (1995) use two standards, one based on the impact acceptable to 50 per cent of visitors and the other on the impact acceptable to 75 per cent of visitors. The 75 per cent standard is more stringent than the 50 per cent one as it implies acceptability to three-quarters rather than half of all visitors. For example, in the Rattlesnake Wilderness, Montana, the 50 per cent standard for percentage vegetation loss/bare ground around camp-sites was 17 per cent while the more stringent 75 per cent standard was 10 per cent loss (Roggenbuck *et al.* 1993).

These percentages, especially 50 per cent, are used because it is impossible to have total agreement between visitors. Therefore, managing to meet the expectations of at least half of them should ensure some level of satisfaction (Watson *et al.* 1992; Roggenbuck *et al.* 1993; BC Forest Service 1995). In this study, the 50 per cent and 75 per cent standards were calculated using cumulative percentages[4]. Standards for trees damaged by humans, vegetation loss or bare ground, number of groups, size of groups, litter and human-made structures (e.g. signs) were then derived. The standards calculated and included in Table 4 use numbers not percentages, as the latter were only collected for two of the six indicators.

The benefits of using numbers versus percentages are explored further in the Discussion.

Regarding damage to trees, many respondents when asked about acceptable numbers of damaged trees were only willing to accept very low levels of damage: the 50 per cent standard was two trees and the 75 per cent standard one tree for all four management sub-units (Fig. 3a; Table 4). When respondents were asked to provide a percentage, they appeared more lenient regarding the acceptable level of change. The 50 per cent standard for the camp-site was up to 7 per cent of trees damaged, while for the walk trails it was up to 4 per cent and for the Coves and Mt Hopkins it was 3 per cent (Fig. 3b). The 75 per cent standard for all management sub-units was 2 per cent. Both the numbers and percentages indicate a low level of tolerance for change. The response rate was greater when respondents were asked for a percentage (response rate of 78 per cent) rather than when they were asked for a number (response rate of 62 per cent).

In terms of the acceptable area of bare ground or vegetation loss, more damage was accepted at the camp-site than elsewhere in Nuyts. For the camp-site, the 50 per cent standard was 11 m^2 and 75 per cent standard was up to 8 m^2 (Fig. 4a; Table 4). For the other sites, the 50 per

[4] Cumulative percentage is the percentage of cases in a distribution at or below that value (Bohrnstedt and Knoke 1988, p.50).

TABLE 4

50 per cent and 75 per cent standards for potential indicators.

	SITE STANDARDS (50 % AND 75 %)							
POTENTIAL INDICATOR	TRAILS		CAMP-SITE		COVES		MT HOPKINS	
STANDARDS	50%	75%	50%	75%	50%	75%	50%	75%
Damaged Trees (no.)	2	1	2	1	2	1	2	1
Bare Ground (m^2)	2	1	11	8	3	0	1	0
Group Numbers (no.)	5	4	4	3	4	3	4	3
Group Size (no.)	6	4	6	4	6	4	6	4
Litter (no. of pieces)	1	0	1	0	1	0	1	0
Signs (no.)	3	1	2	1	1	1	1	1

cent standard was more stringent: 3 m^2 at the Coves, 2 m^2 along the walk trails and 1 m^2 at Mt Hopkins. For the 75 per cent standard, again there was a lack of tolerance of damage in these three sub-units: 1 m^2 along walk trails and zero at the Coves and Mt Hopkins. Percentage responses, similarly to the numeric responses, indicated respondents were more tolerant of vegetation loss at the camp-site than in the other three management sub-units (Fig. 4b). A greater number of people responded to this question when they were asked for a percentage (71 per cent of survey respondents) rather than a maximum acceptable area in square metres (44 per cent of survey respondents).

Standards for a suite of social indicators including number and size of groups, amount of litter and number of human-made structures (e.g. signs) were also sought. Two questions were used to gauge respondents' views on the maximum number of groups they would accept seeing per day before the quality of their experience was reduced. One question asked respondents to provide a number for each management sub-unit and another asked them to circle a number already provided for the whole of Nuyts. Respondents were also asked how many groups they had encountered: 23 per cent of respondents saw no groups, 50 per cent saw one or two groups, 19 per cent saw from three to five groups and 8 per cent saw from six to 10 groups. None had seen more than 10 groups.

The 50 per cent standard for number of groups encountered, based on the site-by-site figures, was five groups per day along the walk trails and four groups per day at the camp-site, Coves and Mt Hopkins (Fig. 5; Table 4). The 75 per cent standard shows a similar trend, with up to four groups sighted per day acceptable along the walk trails and a maximum of three groups in the other management sub-units. Using the general figures obtained, the 50 per cent standard was up to six groups and the 75 per cent standard was up to four groups. These general figures are slightly more lenient than the site-specific standards.

Even more so than the maximum acceptable number of groups, there was virtually no difference across sites regarding maximum acceptable group size (Fig. 6). The 50 per cent standard based on the site-by-site figures was up to six people per group for all management sub-units (Table 4). The 75 per cent standard for all management sub-units fell to four people. Using the general figures obtained, the 50 per cent standard was up to eight people and the 75 per cent standard was six people. These general figures are more lenient than the site-specific standards, a similar difference between question responses to that obtained in the group number questions.

The next social indicator examined was litter. The majority of respondents were intolerant regarding litter, with a 50 per cent standard of up to one piece of litter and a 75 per cent standard of zero for all four management sub-units (Fig. 7). The good response rate for this question of 65 per cent indicated that participants felt particularly strongly about the issue and/or the question was easy to answer.

The last social indicator for which standards were sought was the number of human-made structures such as signs. Both the 50 per cent and 75 per cent standards reflect a greater tolerance for human-made structures along walk trails than elsewhere, with respondents tolerating up to three structures along walk trails compared with two structures at the camp-site, and one at the Coves and Mt Hopkins (Fig. 8; Table 4). The 75 per cent standard was equally restrictive across all sites, with up to one structure tolerated.

Information was also collected on visitors' tolerances regarding camp-fires although no acceptability standards were calculated because camp-fires have been banned in Nuyts (CALM 1992). Nearly all respondents indicated they would accept zero camp-fire rings around Mt Hopkins (92 per cent) and on or beside walk trails (97 per cent). They were more willing to accept camp-fire rings at the Coves and camp-site, with 45 per cent and 67 per cent of respondents respectively tolerant of one or more fire rings at these sites.

For all of the standards there was a small number of respondents who were tolerant of higher levels of impacts.

Tolerance then rapidly declined to the 50 per cent and 75 per cent standards. The shape of the curves in Figures 3 - 8 illustrates this rapid decline. For most of the indicators studied, about 20 per cent of visitors were much more tolerant of change than the remainder. The only exception was area of vegetation loss (Figs 4a and 4b), especially for the camp-site, where the curve takes longer to drop and flatten because respondents were more tolerant regarding the extent of change than they were for other indicators.

Potential Management Actions

Overall, respondents supported all the potential management actions. When the results for strongly support and support were combined, the six most preferred potential management actions were, in descending order of preference: to educate users more about minimal impact use and camping techniques; rehabilitate degraded areas; take remedial action to stop the spread of dieback by foot

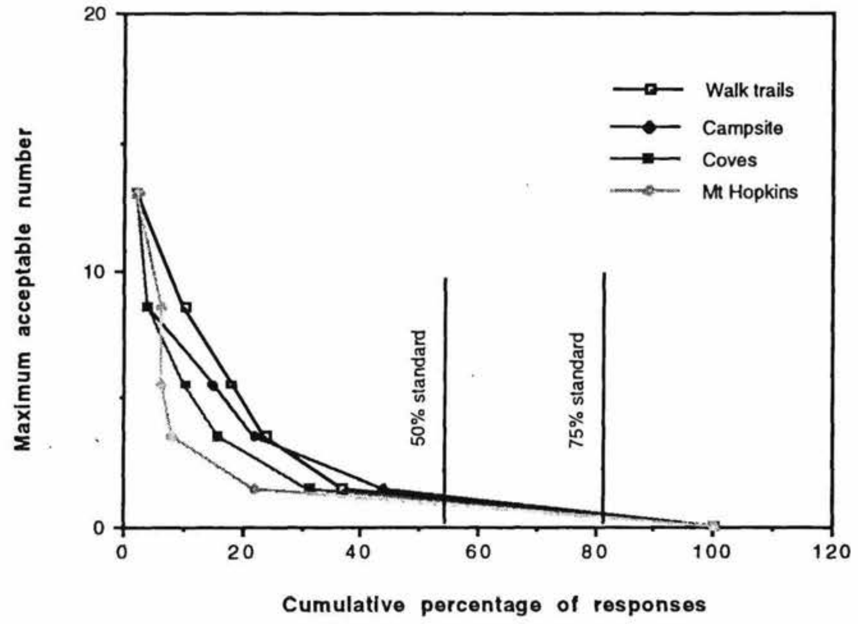


Figure 3a. Maximum acceptable number of trees damaged by humans (n=53).

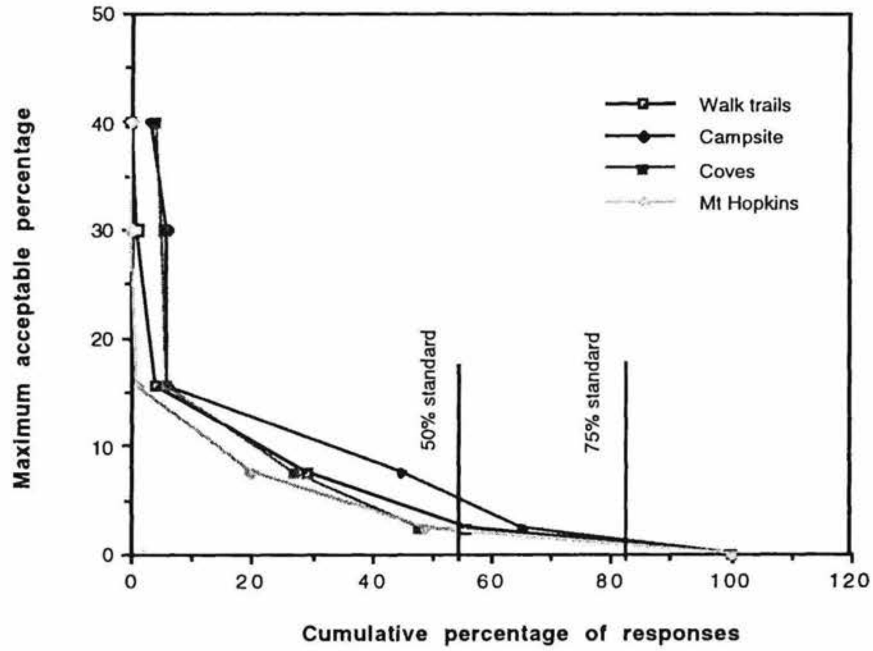


Figure 3b. Maximum acceptable percentage of trees damaged by humans (n=67).

traffic into the area; provide instructive maps of the area at main trail-head at Tinglewood; limit the number of people per group; and discourage the use of over-used areas (Table 5).

DISCUSSION

Visit and Visitor Characteristics

Successfully managing wilderness areas depends on an understanding of the use such areas receive as well as visit

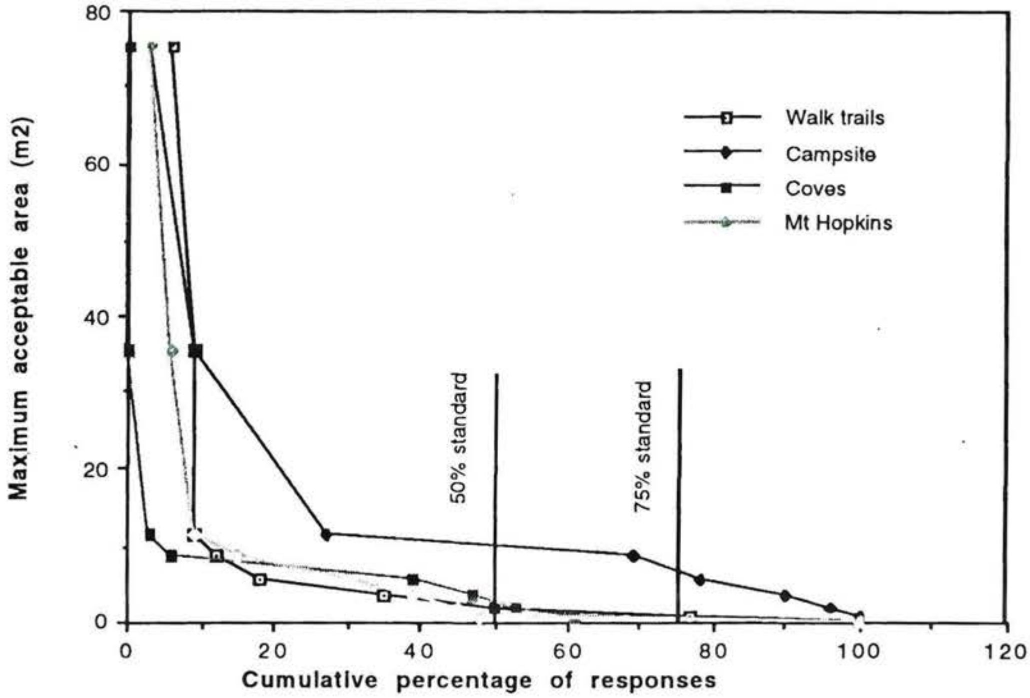


Figure 4a. Maximum acceptable area of vegetation loss or bare ground (m²) (n=38).

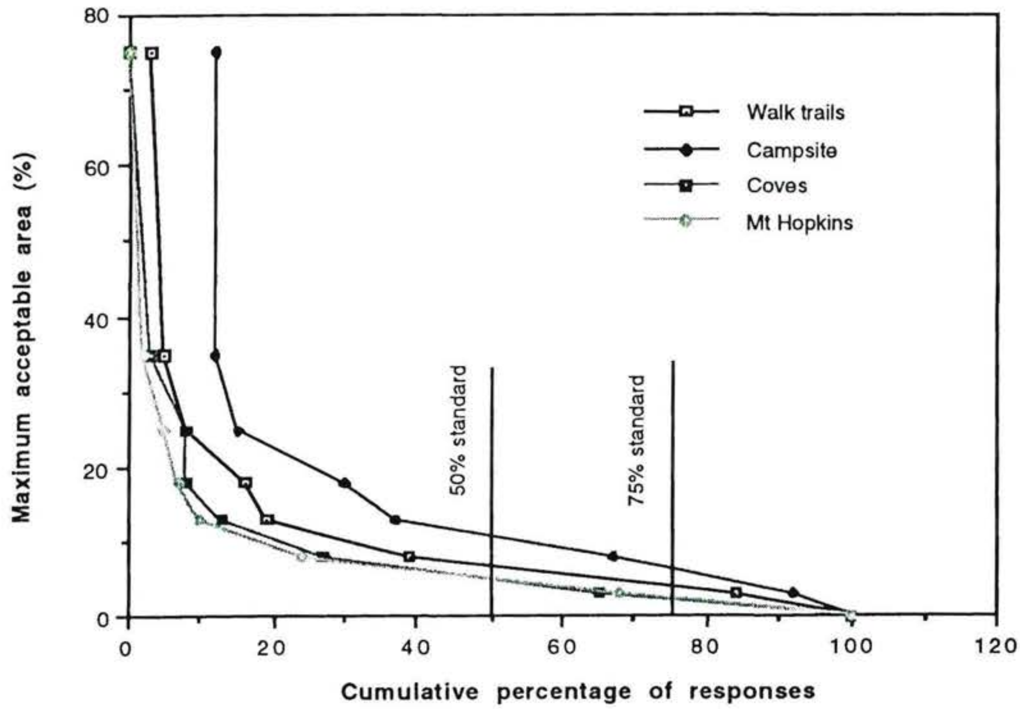


Figure 4b. Maximum acceptable area of vegetation loss or bare ground (%) (n=61).

and visitor characteristics. Activities undertaken by visitors to Nuyts are remarkably homogenous, with almost all visitors appreciating nature, walking for exercise, and enjoying the solitude. Lucas (1990) found that, typically, visitors participate in a wider variety of activities including photography, nature study, and swimming, and to a lesser degree fishing and hunting. This is in contrast to use of Australian wilderness where hunting has never been regarded as acceptable.

Enjoying an area free of vehicles was important to 85 per cent of Nuyts visitors, reflecting the current widespread access available to four-wheel-drive vehicles in some parts of Australia. There are few sections of the Western Australian coastline which are not currently accessible by four-wheel-drive vehicle. In contrast, many wilderness areas in the US are too rugged for vehicle access and, in addition, there is a long tradition of large

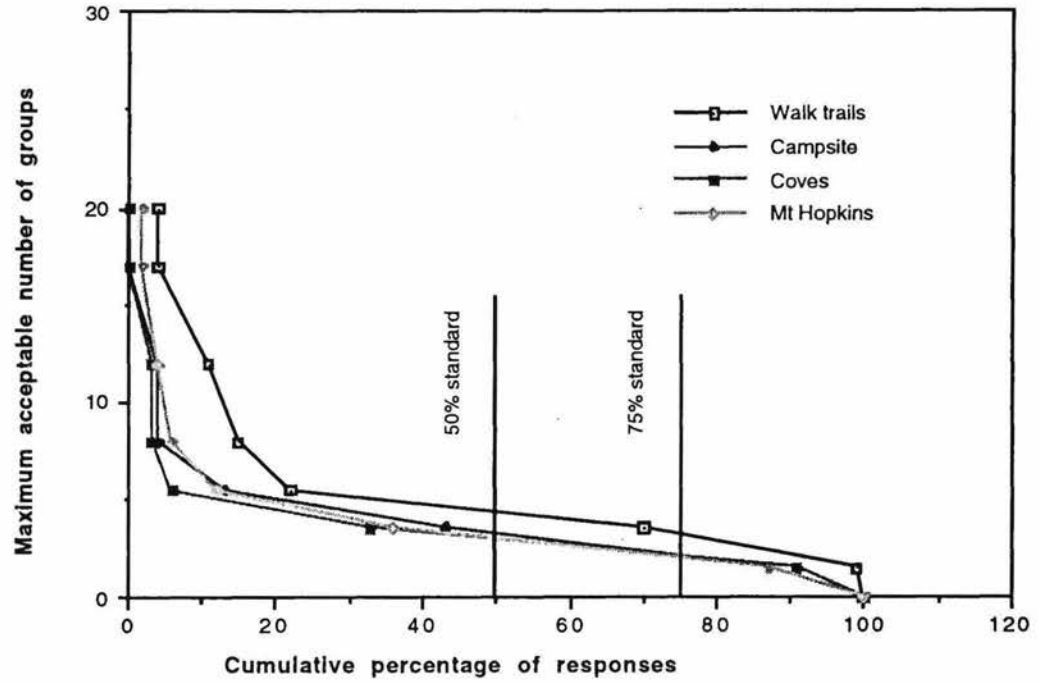


Figure 5. Maximum acceptable number of groups encountered on one day (n=52).

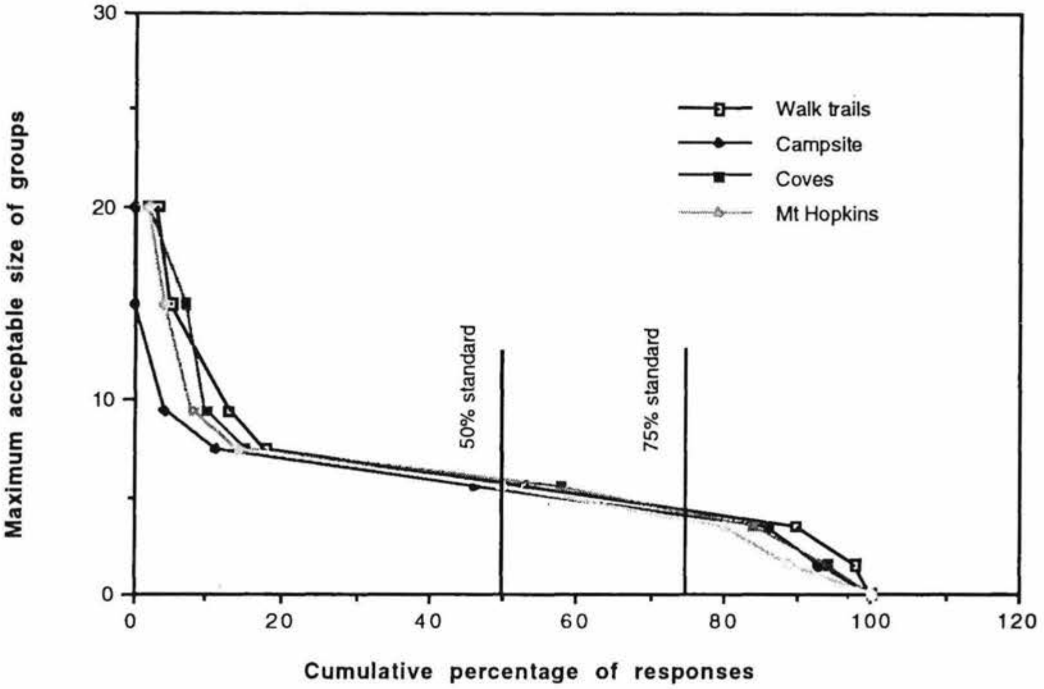


Figure 6. Maximum acceptable size of groups encountered on one day (n=51).

areas available only to non-motorized access, either on foot or using livestock such as horses.

Understanding who wilderness users are is important for both policy and management decisions. Policy is influenced by the knowledge of who receives the benefits gained from wilderness use while management, especially the use of information and education, requires knowledge of user characteristics and values (Lucas 1990). Nearly all studies agree that the most distinguishing characteristic of users of designated wilderness areas is their high education levels (Roggenbuck and Lucas 1987). With few exceptions, 60 to 85 per cent of visitors to such areas have attended college or university and 20 to 40 per cent have gone on to postgraduate study (Lucas 1990). The results of this study are consistent with these previous findings as a significant portion of visitors (70 per cent) had completed some form of tertiary education.[5] Thus,

[5] Australians of all education levels seek wilderness experiences, generally outside designated wilderness areas. Higher education levels have only been linked to use of designated wilderness areas.

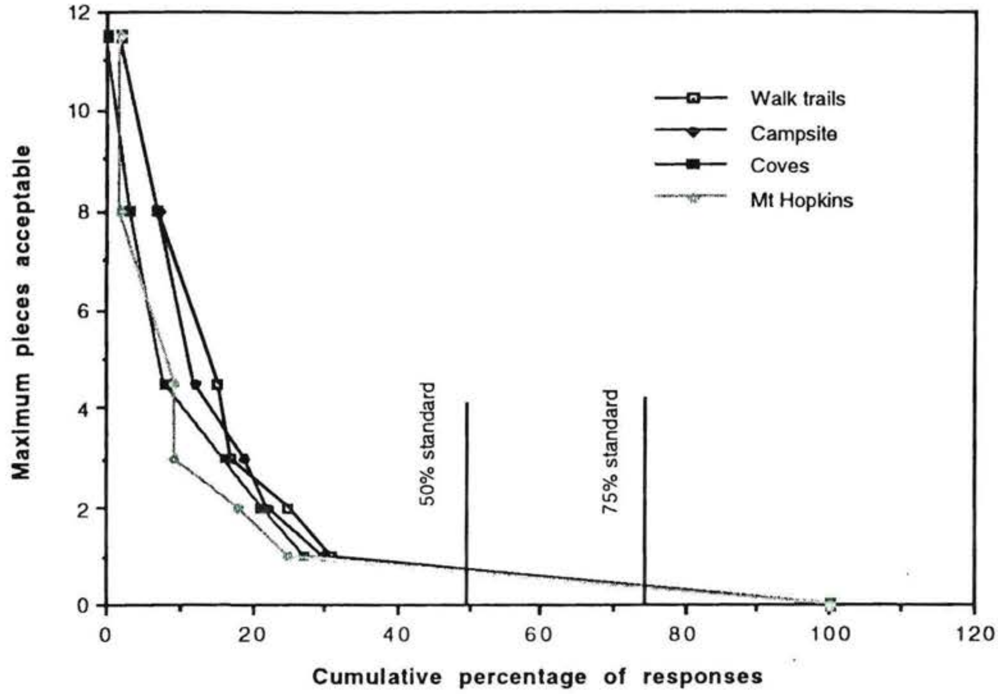


Figure 7. Maximum pieces of litter acceptable on one day (n=59).

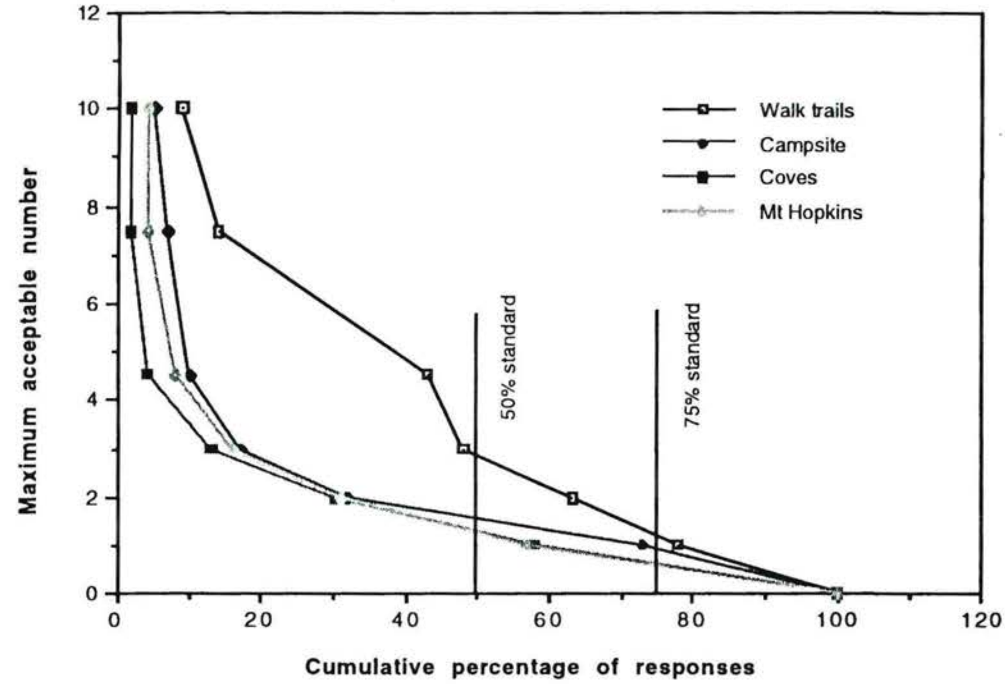


Figure 8. Maximum acceptable number of human-made structures such as signs (n=53).

TABLE 5
Survey respondents' attitudes toward potential management actions in Nuyts Wilderness Area.

POTENTIAL MANAGEMENT ACTION	STRONGLY SUPPORT	SUPPORT	NEITHER SUPPORT NOR OPPOSE	OPPOSE	STRONGLY OPPOSE
	Percentage of respondents[a]				
Educate users more about minimal impact and camping tchniques	78	20	3	0	0
Rehabilitate degraded areas	70	25	5	0	0
Take remedial action to stop the spread of dieback disease by foot traffic into the area	56	35	8	1	0
Provide instructive maps of area at main trail-head (Tinglewood)	47	42	9	1	1
Discourage use of over-used areas	41	41	9	9	1
Limit the number of people per group	43	37	11	6	3
Provide minimal structures such as stairs and boarding to protect fragile areas	41	38	11	5	5
Temporarily close areas	35	41	11	13	0
Limit length of stay during peak times	28	50	8	14	1
Provide more Rangers in area to provide information and education	27	41	27	5	0
Limit use (e.g. type, level)	22	49	15	11	3
Introduce a voluntary user fee for the management of Nuyts Wilderness Area	21	46	18	6	9
Provide signs for direction	21	38	9	22	10
Provide more Rangers in area to enforce existing regulations	19	34	34	13	1

[a] percentages have been rounded to the nearest whole percentage therefore do not necessarily sum to 100 per cent in every case

relatively sophisticated explanations about interactions between parts of the environment and the often complex reasoning behind potential regulations affecting users can be provided as part of general visitor information.

Typically, visitors to wilderness areas in the US come from all over the country but most live relatively close to the area visited (Lucas 1990). Our results are consistent with this previous finding: the majority of Nuyts visitors came from the south-west of Western Australia and of these, 64 per cent were from Perth, so they live relatively close to Nuyts. Given that most visitors are 'locals', pre-trip information and educational material can be provided from outlets in the south-west, especially from Perth. In the US, wilderness visitors tend to be younger than the general population, yet all age groups are fairly well represented (Roggenbuck and Lucas 1987; Lucas 1990). The age of visitors in the Nuyts study varied from other findings, with Nuyts visitors fairly evenly split between the 26-40 and 41-60 age groups.

Most Nuyts visitors stayed for up to a day (35 per cent) or between one and three days (45 per cent), usually once a year. Lucas (1990), in his review of wilderness use and users in the US, found that the length of stay in most wildernesses is short with many small and medium-sized wilderness areas being predominantly day-use areas. Wilderness areas in the eastern US had average stays of two or three days with 25 to 50 per cent being day use (Lucas 1990). Trips of a week or more accounted for less than one-tenth of all visits, even in large wilderness areas such as the Bob Marshall Wilderness Complex (Lucas 1990). Thus, for Nuyts as for many wilderness areas in North America, decreasing the length of stay as a means of reducing impacts would be ineffective because most people stay for short periods only, three days or less.

Over half of the survey respondents visited Nuyts with only one other companion. Roggenbuck and Lucas (1987) found in their study of wilderness use and user characteristics in the US that the size of wilderness visitor parties is generally small, with 50 to 75 per cent of parties comprising from two to four people.

Potential Indicators

Respondents were more concerned about biophysical impacts such as erosion, vegetation loss and tree damage than they were about social conditions such as number and size of groups (Table 3). This probably reflects respondents' views that current use levels, although they may be leading to biophysical impacts, are not resulting in a decline in their social experience. The majority of respondents saw two or less groups per day and felt this was the right number. In Canada, impacts on biophysical conditions were similarly the most important in determining the quality of visitors' recreational experience (BC Forest Service 1995). On the other hand, results of wilderness visitor surveys in the US indicate more concern with social conditions such as crowding, conflict among visitors and littering than with resource conditions such as camp-site and trail impacts (Lucas 1990).

The level of concern about trail erosion, vegetation loss and damage to trees mirrors similar concerns expressed in relation to Fitzgerald River National Park on the south coast of Western Australia (CALM 1991). The amount of vegetation loss and damage to trees, especially by pack animals, have been widely chosen as indicators of impact at camp-sites in numerous other wilderness areas (e.g. Bob Marshall Wilderness Complex - Stankey *et al.* 1990). Denuded ground vegetation as a result of camping activities (e.g. Mt Rainier National Park Wilderness Management Plan, Washington State), the number of impacted sites per 640 acres (291 ha), and square feet (m^2) of barren core (Bob Marshall Wilderness Complex LAC Plan, Flathead National Forest, Montana) are other commonly-used indicators of camp-site condition. Watson *et al.* (1992) in their study of three wilderness areas in the southern US found that visitors regarded litter, tree damage and wildlife seen as the most important indicators. The least important influence on visitor experiences was the number of trail encounters with other groups on the trail (Watson *et al.* 1992).

For the three wilderness areas examined by Watson *et al.* (1992) and in the Nuyts study, the number of animals seen and presence of wildlife respectively were important influences on visitors' evaluations of the quality of their wilderness experience. However, the density of wildlife in wilderness and even the presence of wildlife are largely beyond managers' control. Thus, use of the number of animals seen as an indicator of wilderness quality in the LAC framework is of little value. It is, however, important for managers to continue to protect wilderness wildlife from human impacts both inside and originating outside the wilderness (Watson *et al.* 1992).

Two social impacts were of the greatest concern to Nuyts visitors: littering and inadequate disposal of human waste. Litter was also an important indicator in the US (Lucas 1990; Watson *et al.* 1992). Human waste disposal has not been used as an indicator elsewhere because of health issues associated with such a monitoring program.

Other social conditions of importance to Nuyts visitors were number of people in a group and the number of other groups camped within sight or sound. The indicator 'the number of camp-sites within sight or sound of others' has been widely used elsewhere (Bob Marshall Wilderness Complex LAC Plan, Flathead National Forest, Montana; Hickory Creek and Allegheny Islands LAC Task Force, Allegheny National Forest, Pennsylvania; Mt Trumball/Mt Logan Wilderness Management Plan, Utah). In the British Columbia (BC) study (BC Forest Service 1995), behaviour of people in other groups was the most important social condition to other visitors, followed by the number of other groups at camp-sites, the size of groups encountered, and the number of other groups along trails.

Standards for Potential Indicators

Several features of the standards results are immediately striking and warrant discussion: first, impacts such as litter and tree damage for which visitors have limited tolerance and second, the similar levels of change acceptable, with several noticeable exceptions, at very different sites. Other features of the results such as different responses to questions about standards depending on whether people were asked to give a number or a percentage also warrants mention.

For litter, 50 per cent of respondents were willing to accept only one piece of litter or less anywhere in Nuyts. Cumulating these responses for 75 per cent of respondents gave an increased intolerance, with no litter being acceptable. In the BC survey, both 50 per cent and 75 per cent of respondents indicated they would accept from zero to one piece of litter per site (BC Forest Service 1995). Watson *et al.* (1992) found that 75 per cent of respondents were unwilling to see any litter at any sites. Many studies have found that visitors react particularly negatively to littering and even small amounts of litter evoke strong responses. Littering is often viewed as a violation of strongly held norms and thus, as evidence of abuse rather than normal use (Lucas 1990).

There was also great intolerance across sites regarding damage to trees. For all four sites, the 50 per cent standard was two damaged trees per site and the 75 per cent standard was one. Trees are important to visitors because they are a very visible part of the natural landscape; also, on the south coast of Western Australia they provide protection from the wind and sun for both day visitors and campers. Thus, they hold considerable aesthetic and utilitarian value for visitors.

There were strong similarities across sites for the 50 per cent and 75 per cent standards. For tree damage, litter and group size these standards were the same for all four management sub-units (Table 4). Roggenbuck *et al.* (1993, p.195) noted in their study across four wilderness areas that there 'is surprisingly broad agreement across areas on what are acceptable wilderness conditions'. For conditions of great concern in Nuyts such as litter and tree damage, restrictive and high standards were desired by visitors at all four sites. The uniformity in acceptable group size - a 50 per cent standard of six people per group and a 75 per cent standard of four people per group - across Nuyts indicates that groups larger than six persons were unacceptable to many respondents at any site.

Standards for numbers of groups encountered in a day were also very similar across all four sites, with a slightly higher tolerance for number of encounters along walk trails but otherwise standards, both 50 per cent and 75 per cent, were uniform (Table 4). Slightly higher tolerance along walk trails is based on the briefness of encounters while people are travelling contrasted with lower tolerances for numbers of other groups at destinations such as camp-sites, viewpoints and coastal, day-use destinations such as the beach coves. Similar results have been found in the US where visitors are similarly less tolerant of larger numbers of groups at destinations and more accepting of such encounters while transiting along trails (Roggenbuck *et al.* 1993).

In the US visitors expressed more stringent 50 per cent standards for camp-sites than given in the Nuyts study, preferring a maximum of one other group within sight or sound of their camp-site (Roggenbuck *et al.* 1993). Visitors to US wilderness areas also express dissatisfaction about the numbers of groups encountered in such areas. Nuyts visitors appeared satisfied with existing levels of use in terms of numbers of groups encountered. In this study 98 per cent of respondents saw five groups or less which equates with the supported 50 per cent standard of four or five groups. Thus, camp-site use in Nuyts has not reached the level where visitors are expressing dissatisfaction.

Two exceptions to uniformity of standards across sites were those for area of bare ground and signs. Visitor views regarding standards are realistic; they reflect the type of use areas are exposed to and the expectations visitors have regarding such areas. As such, they have a far greater tolerance of bare ground/vegetation loss at camp-sites than at other sites. Bare ground is an advantage at camp-sites because it provides suitable places for pitching tents. In the BC survey (BC Forest Service 1995), respondents accepted similar areas of vegetation loss/bare ground to that of Nuyts visitors: 50 per cent of respondents indicated a maximum of 9 m^2 of vegetation loss compared with the Nuyts finding of up to 11 m^2. Nuyts visitors were also tolerant of some vegetation loss along trails and at the Coves as a consequence of recreational use (Table 4). Mt Hopkins, as the most pristine site, had extremely stringent standards indicated by most respondents, with a 50 per cent standard of 1 m^2 and 75 per cent standard of 0 m^2.

Human-made structures were not generally tolerated by survey respondents, although this tolerance was somewhat greater along the trails; for the 50 per cent standard up to three structures along trails, two structures at the camp-site and one at the Coves and Mt Hopkins. This is, in part, similar to responses of Canadian wilderness users who appear similarly intolerant of such structures, with respondents accepting only one structure at most sites. In North America there is a tradition of un-signposted wilderness, although in most wilderness areas on that continent walk trails are well-worn and immediately obvious; therefore signs are unnecessary. In Australian wilderness areas walk trails are often not obvious, may be infrequently used and signs would be useful to provide direction. These reasons help explain the tolerance of Nuyts' respondents for up to three structures along walk trails and the lesser tolerance exhibited by North American wilderness users.

For most wilderness recreation standards, achieving the more restrictive 75 per cent rather than 50 per cent standard, that is, satisfying three-quarters rather than half of the visitors, means reducing the acceptable impact by at least half (Roggenbuck *et al.* 1993). Achieving the 75 per cent standard for tree damage, bare ground (especially at the Coves and Mt Hopkins), litter or signs at Nuyts requires twice the level of stringency and potentially at least twice the resources as managing to maintain the 50 per cent standard (Table 4). For example, for tree damage, achieving the 50 per cent standard means limiting damage between monitoring events to two trees per site. Achieving the 75 per cent standard requires halving the impact over the monitoring interval to one tree per site.

Number of groups encountered and group size showed less variation between the two standards with a one-quarter reduction in acceptable impact from the 50 per cent standard of four or five groups encountered per day needed to meet the 75 per cent standard of three or four groups and a one-third reduction in acceptable impact from the 50 per cent standard of six people per group to meet the 75 per cent group size standard of four people per group. The resources required to meet far more restrictive 75 per cent standards, especially if acceptable impact levels have already exceeded the 50 per cent standard as they have in many North American wilderness areas, explains why most managers prefer using 50 per cent rather than 75 per cent standards. It is unknown, for Nuyts, whether management to achieve or maintain 50 per cent standards is feasible. And, there is currently no monitoring program to assess changes against standards.

The last feature warranting discussion was the different responses evoked when respondents were asked to provide a percentage rather than a number for trees damaged and vegetation loss. For both indicators many more people answered the question when it asked for a percentage rather than a number, probably because for many it was easier to visualize a percentage of trees or vegetated area damaged rather than the numbers of trees damaged or square metres of bare ground. However, from a manager's perspective, it is much easier to record numbers of damaged trees rather than percentage of the total number of trees damaged and area of bare ground in square metres rather than percentage of bare ground. The challenge lies in researchers and managers being able to help survey respondents visualize impacts in terms of numbers and areas rather than percentages as this is how they will be measured.

Potential Management Actions

Understanding visitor attitudes towards management actions can assist in predicting the consequences of specific actions on the experience (McCool *et al.* 1990). The majority of respondents supported all potential management actions including those usually regarded as unpopular such as limiting the length of stay and use (e.g. type and level), temporarily closing areas, providing more rangers to enforce existing regulations and signs for direction, and introduction of a voluntary user fee (Table 5).

In comparison, the BC study found that the strongest support of potential management actions lay in the areas of increased education and rehabilitation (BC Forest Service 1995). When asked their attitude towards potential management actions, the BC survey found that respondents most strongly supported educating users more about minimum impact use and rehabilitating over-used areas, followed by discouraging or prohibiting the use of over-used areas and providing more patrols to enforce regulations. In contrast to Nuyts visitors, limiting the number of people per group and limiting use (e.g. type, location and amount) were generally less well supported by the BC survey respondents (BC Forest Service 1995). It is of interest to note that in both countries there was a reasonable level of support for increased enforcement. This support is possibly linked to the strong belief that damage is caused by others and enforcement will deal with others' misdemeanours. This fits with the comments from the BC survey that the main concern associated with social conditions was the poor behaviour by people in other groups.

CONCLUSION AND RECOMMENDATIONS

General Comments

Visitors were generally happy with the biophysical and social aspects of their most recent visit in Nuyts. Like Canadian wilderness visitors, people visiting Nuyts were more concerned about biophysical rather than social impacts. Overcrowding was not a significant issue for Nuyts visitors whereas it was an unpalatable feature of visits to US wilderness areas. However, for all wilderness visitors, litter was a sensitive issue. Given these broad comments, we conclude our paper with the following management and research recommendations.

Management Recommendations

(1) Developing a monitoring program

The environmental conditions and indicators outlined and discussed in the preceding sections - number of trees damaged, area of bare ground, number and size of groups encountered, pieces of litter and number of signs - provide a suite of indicators and associated standards (Table 4) and the basis of a monitoring program for Nuyts. For several reasons it is not necessary to monitor the whole suite especially in these times of limited resources. At Nuyts, visitors were most concerned about biophysical impacts, the only notable exception being littering. Of the biophysical impacts, the one of greatest interest was human damage to trees. Therefore, a monitoring program could initially focus on litter and tree damage and to a lesser extent vegetation loss. Sites where impacts are close to being exceeded or where management actions have been taken to deal with 'unacceptable' impacts have the highest priority for monitoring.

A range of monitoring techniques could be used. LAC applications in North America have relied on site-based measurements, usually recorded as numbers and less often as percentages. Other possibilities include ground-based or aerial photography taken at fixed points over time.

(2) Management actions to minimize or ameliorate impacts

Visitors were supportive of a broad range of management actions, from education through closure of areas and other limits on use, to charging fees (Table 5). This provides a broad choice of management strategies for managers. The two conditions of most concern were littering and inadequate disposal of human waste. Education through signs and pamphlets should decrease these impacts without having to provide facilities requiring capital resources and maintenance and impinging on the area's wilderness qualities. The management sub-unit where impacts most concerned visitors was the Coves and their biophysical condition. Erosion and vegetation loss were regarded as problems, making the provision of structures such as stairs and boards (supported by 79 per cent of visitors) a potential management solution.

Recommendations for Further Research

(1) Gaining a better understanding of cause-effect relationships in Nuyts and elsewhere

This study identified impacts and visitors' preferences regarding the level of impact and mitigating management actions. The next essential step is understanding the relationship between different types and levels of use and the resulting impacts. Such research is an essential stage of the VIM process (Step 6, Table 1). Also, a better understanding of cause and effect is needed to determine which management actions to take and then to subsequently assess the effectiveness of such actions.

(2) Developing indicators and standards for recreational use of the CALM Estate

This study has provided indicators and standards potentially relevant to other coastal parts of the south-west of Western Australia used by bushwalkers and accessible on foot. Similar indicators and standards are also needed for other forms of recreational use and landscapes across the CALM estate, from the small picnic areas on granite rocks in the wheatbelt to the waterholes and waterfalls of the Kimberley. Such indicators, through allowing the recognition of impacts of concern to visitors and managers, mean management priorities can be set and management actions taken as required. The effectiveness of such actions can also be determined over time through monitoring these key indicators.

(3) Placing recreation-use monitoring in a broader context

Monitoring recreation impacts eventually needs placing in a broader monitoring program directed toward ecological 'health' or sustainability. Recreation monitoring alone is insufficient given that impacts acceptable to visitors may not be ecologically sustainable in the longer term. Also, areas such as Nuyts are managed for nature conservation values as well as recreational use. A broader monitoring program, including the recreation framework developed from this study and directed toward ecological concerns, warrants investigation and development.

(4) Determining visitor tolerance to various forms of management intervention

An essential component of both the LAC and VIM planning frameworks is implementing strategies. However, some strategies may be widely supported by users while others may prove unpopular. For example, it is generally assumed that educational strategies in natural environments will be widely supported while strategies based on limiting use may be met with opposition. Research is needed to determine visitor tolerance, in Western Australian national parks and associated wilderness areas, to various forms of management intervention including more educational materials, site rehabilitation, limiting use either by restricting visitor numbers or closing selected areas, more staff either for enforcement or educational purposes, more infrastructure such as stairs and boarding to protect fragile areas, and introducing fees.

ACKNOWLEDGEMENTS

Contributions by Cliff Winfield and Bruce Bond to the development and execution of this study are gratefully acknowledged, as are the useful suggestions and input of reviewers Jackie Alder and Ross Dowling.

REFERENCES

Absher, J. (1994). Beyond carrying capacity. *Ranger*, Spring edn, pp. 30-32.

Anon. (n.d.). Zoning for national parks in Western Australia: discussion paper. Department of Conservation and Land Management, Como, Western Australia.

BC Forest Service (1995). The 1993 Northeastern British Columbia recreation survey. Recreation Section, Range, Recreation and Forest Practices Branch, Ministry of BC Forests, British Columbia, Canada.

Bohrnstedt, G.W. and Knoke, D. (1988). *Statistics for Social Data Analysis*. F.E. Peacock, Itasca, Illinois.

Bury, R.L. (1976). Recreation carrying capacity - hypothesis or reality? *Parks and Recreation* **11**(1), 22-25, 56-57.

CALM (1991). Fitzgerald River National Park management plan 1991-2001. Department of Conservation and Land Management for the National Parks and Nature Conservation Authority, Como, Western Australia. *Management Plan* No. 15.

CALM (1992). Walpole-Nornalup National Park management plan 1992-2002. Department of Conservation and Land Management for the National Parks and Nature Conservation Authority, Como, Western Australia. *Management Plan* No. 20.

Clark, R.N. and Stankey, G.H. (1979). The recreation opportunity spectrum: a framework for planning, management, and research. United States Department of Agriculture Forest Service, Pacific Northwest Forest and Range Experiment Station, Seattle, Washington. *General Technical Report* PNW-98.

Cole, D.W. (1985). Management of ecological impacts in wilderness areas in the United States. *In* Bayfield, N.G. and Barrow, G.C. (eds), *The Ecological Impacts of Outdoor Recreation on Mountain Areas in Europe and North America. R.E.R.G. Report No. 9.* Wye, England.

Cole, D.W. and Hammitt, W.E. (1987). *Wildland Recreation*. John Wiley and Sons, New York.

Graefe, A.R. (1989). Visitor impact management. In *Towards Serving Visitors and Managing Our Resources - Proceedings of a North American Workshop on Visitor Management in Parks and Protected Areas.* Feb. 4-17, 1989. Tourism Research and Education Centre, University of Waterloo and Parks Canada, Environment Canada, Waterloo, Ontario.

Graefe, A.R., Kuss, F.R. and Vaske, J.J. (1990). *Recreation Impacts and Carrying Capacity: A Visitor Impact Management Framework*. National Parks and Conservation Association, Washington D.C.

Knopf, R.C. (1989). The limits of acceptable change (LAC) planning process: potentials and limitations. In *Towards Serving Visitors and Managing Our Resources - Proceedings of a North American Workshop on Visitor Management in Parks and Protected Areas.* Feb. 14-17, 1989. Tourism Research and Education Centre, University of Waterloo and Parks Canada, Environment Canada, Waterloo, Ontario.

Kuss, F.R. and Graefe, A.R. (1985). Effects of recreation trampling on natural area vegetation. *Journal of Leisure Research* **17**(3), 165-183.

Lucas, R.C. (1973). Wilderness: a management framework. *Journal of Soil and Water Conservation* **28**(4), 150-154.

Lucas, R.C. (1990). Wilderness use and users: trends and projections and wilderness recreation management: an overview. *In* Hendee, J.C., Stankey, G.H. and Lucas, R.C. (eds), *Wilderness Management*. North American Press (Fulcrum Publishing), Golden, Colorado.

Mandis Roberts Consultants (1995). Determining an environmental and social carrying capacity for Jenolan Caves Reserve: applying a visitor impact management system. Unpublished report, Mandis Roberts Consultants, Sydney, NSW.

McCool, S.F. (1989). Limits of acceptable change: evolution and future. In *Towards Serving Visitors and Managing Our Resources - Proceedings of a North American Workshop on Visitor Management in Parks and Protected Areas*. Feb. 14-17, 1989. Tourism Research and Education Centre, University of Waterloo and Parks Canada, Environment Canada, Waterloo, Ontario.

McCool, S.F., Martin, S.R. and Yuan, M. (1990). The 1989 Bear Trap Canyon visitor study. Institute for Tourism and Recreation Research, School of Forestry, Missoula, Montana. *Research Report* 13.

Prosser, G. (1986). The limits of acceptable change: an introduction to a framework for natural area planning. *Australian Parks and Recreation* **22**(2), 5-10.

Roggenbuck, J.W. and Lucas, R.C. (1987). Wilderness use and user characteristics: a state-of-knowledge review. *In* Lucas, R.C. (compiler), *Proceedings - National Wilderness Research Conference: Issues, State-Of-Knowledge, Future Directions*. July 23-26, 1985. United States Department of Agriculture Forest Service, Intermountain Research Station, Ogden, Utah. *General Technical Report* INT-220.

Roggenbuck, J.W., Williams, D.R. and Watson, A.E. (1993). Defining acceptable conditions in wilderness. *Environmental Management* **17**(2), 187-197.

Shelby, B. and Heberlein, T. (1986). *Carrying Capacities in Recreational Settings*. Oregon State University Press, Corvallis, Oregon.

Stankey, G.H. and Lucas, R.C. (1985). Role of research in applying the limits of acceptable change system. In *Proceedings of the Southeastern Recreation Research Conference 1985,* Department of Recreation and Leisure Services, Georgian Southern College, Georgia.

Stankey, G.H., Cole, D.N., Lucas, R.C., Petersen, M.E. and Frissell, S.S. (1985). The limits of acceptable change (LAC) system for wilderness planning. United States Department of Agriculture Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah. *General Technical Report* INT-176.

Stankey, G.H., McCool, S.F. and Stokes, G.L. (1990). Managing for appropriate wilderness conditions: the carrying capacity issue. *In* Hendee, J.C., Stankey, G.H. and Lucas, R.C. (eds), *Wilderness Management*. North American Press (Fulcrum Publishing), Golden, Colorado.

Wagar, J.A. (1964). The carrying capacity of wildlands for recreation. Society of American Foresters, Washington, D.C. *Forest Science Monograph 7.*

Watson, A.E., Williams, D.R., Roggenbuck, J.W. and Daigle, J.J. (1992). Visitor characteristics and preferences for three national forest wildernesses in the south. United States Department of Agriculture Forest Service, Intermountain Research Station, Ogden, Utah. *Research Paper* INT-455.

CALMScience 2(3): 267-274 (1997)

Predicting canopy scorch height in jarrah forests

N.D. BURROWS

Science and Information Division, Department of Conservation and Land Management, 50 Hayman Road, Como, Western Australia 6152.

ABSTRACT

The height to which foliage is killed by fire (scorch height) is one of the criteria for prescribing control burns and for evaluating the impacts of wildfires in jarrah (*Eucalyptus marginata* Donn ex Smith) forests of Western Australia. Therefore it is important that scorch height can be predicted within limits acceptable to fire managers. This paper reports on the experimental determination of models for making such predictions. Scorch height was found to be a function of fire intensity, flame height and of the season in which the fire burnt. Under cool, moist, spring weather conditions, scorch height was about five times the height of the flames and under dry, warm, summer/autumn weather conditions, scorch height was about nine times the height of flames.

INTRODUCTION

Forest fires kill or damage vegetation by either girdling or incinerating the stem or by incinerating or scorching foliage and buds. Crown or canopy scorch is usually considered to be an undesirable effect of fire, especially in coniferous forests where excessive crown scorch can lead to tree death (e.g. Van Wagner 1970; de Ronde 1983; Johnson 1992) or loss of wood production (Hodgson and Hieslers 1972). For fire-sensitive North American coniferous forests, the degree of crown scorch is widely used to predict mortality (Peterson 1985; Peterson and Ryan 1986; Reinhardt and Ryan 1989; Saveland and Neuenschwander 1990; Swezy and Agee 1991). However, mature jarrah (*Eucalyptus marginata* Donn ex Smith) and marri (*E. calophylla* Lindl.) trees, like many species of *Eucalyptus*, have evolved adaptive traits to recover or regenerate following fire-caused injury (Jacobs 1955; Gill 1975) and quickly replace scorched crowns from epicormic shoots.

In the management of jarrah forests, scorch height, or the height to which foliage and fine branches have experienced a lethal temperature regime, is often used as a criterion for implementing prescribed burns (Sneeuwjagt and Peet 1985). When precribing low intensity fires to reduce fuel levels in uneven-aged forests (trees of mixed ages), the aim is to minimize crown damage by keeping scorch height to less than about 6 m. Scorch above this level can cause long-term crown and stem damage, especially to small saplings where growing tips can be killed back and stem deformities induced. Full crown scorch can cause a temporary reduction of amenity value. Fires of sufficient intensity to cause canopy scorch can temporarily disrupt breeding of birds and arboreal mammals which utilize hollows or feed in the green canopy (Christensen *et al.* 1988; Inions *et al.* 1989). The protection benefits derived from fuel reduction burning can be reduced if the forest canopy is fully scorched. Scorch induces leaf fall which can add up to 5 t ha^{-1} of additional fuel to the forest floor (Luke and McArthur 1978).

In some circumstances, however, the objective of prescribed burning is to fully scorch the forest canopy. This may be required to maximize regeneration by creating 'ashbed' and by stimulating a massive and synchronized release of canopy stored seed (Cremer 1965; Henry and Florence 1966; Christensen 1971; Burrows *et al.* 1989), to induce a positive growth response from established trees following crown replacement (Kimber 1978), or to interrupt the life cycle of forest pests such as jarrah leaf miner (Abbott *et al.* 1993). Prescribed burns to regenerate or eradicate specific understorey species usually require fires of sufficient intensity to cause full crown scorch (Shea *et al.* 1979; Christensen 1982; Burrows 1985).

Whatever the purpose of prescribed burning, it is essential that jarrah forest fire managers be able to predict the extent of crown scorch. Sneeuwjagt and Peet (1985) present a table for predicting the maximum scorch height to jarrah during low intensity spring fires from predicted rates of spread and total available fuel quantities. During autumn conditions, scorch height is estimated to be 1.8 times greater than the predicted spring scorch height. The table presented by Sneeuwjagt and Peet (1985) applies to a narrow range of burning conditions which is adequate for low intensity fuel reduction fires where rates of spread are less than about 70 m h^{-1} and scorch heights are less than about 12 m. A rule of thumb used in south-eastern Australian eucalypt forests is that scorch height is about six times flame height (Luke and McArthur 1978). Hoare (1985) used flame height to assess and predict the biological effects of fire in tropical eucalypt woodland and found scorch height to be about 4 times flame height.

During a forest fire, vegetation above the flames is affected by a rising plume of hot air, and live leaves and fine twigs are scorched and killed when heated above temperatures of about 60-70 °C for very short durations (Kayll 1968; Methven 1971; Ryan 1982; Cheney *et al.* 1992; Gill 1995). Thomas (1963), using dimensional analysis, derived a relationship between temperature rise above ambient, fire intensity and the height above ground for no-wind situations and Van Wagner (1973) used this relationship as a basis for determining the height at which lethal temperatures were experienced (scorch height). He also introduced the idea that, under the influence of wind, the plume follows an angled path up into the vegetation. His relationship between scorch height and fire intensity was developed from 13 small experimental fires in Canadian forest types with theoretical adjustments to scorch for ambient temperature and wind speed; the theory being that scorch height is directly related to ambient temperature and inversely related to wind speed, other things being equal. Thus the acute physical impact of fire is a function of the amount and rate of heat release (intensity) and of factors affecting heat transfer (ambient temperature and wind speed). Van Wagner's (1973) equations are shown below (in the units of this study).

$$h_s = 0.148(I)^{2/3}$$

$$h_s = [4.4713(I)^{2/3}]/(60-T)$$

$$h_s = \frac{0.742(I)^{7/6}}{[0.0256(I) + (0.278U)^3]^{1/2}\,(60-T)} \quad \text{(van Wagner 1973)}$$

Where:
h_s = scorch height (m),
I = fire intensity (kW m^{-1}) (Byram 1959),
U = wind speed (km h^{-1} in the forest at 1-2 m),
T = ambient temperature (°C).

Van Wagner's models have been widely used to predict crown scorch and tree mortality in North American conifer forests (e.g., Rothermel and Deeming 1980; Kercher and Axelrod 1984). Cheney *et al.* (1992) developed a semi-physical model based on Van Wagner's model to predict scorch height from low intensity fires in *E. sieberi* regrowth forests in New South Wales. They found that most variation in scorch height (55 per cent) could be explained by flame height, followed by intensity and rate of spread. As fuel quantity was considered to be more or less constant during their experimental fires, they presented another model for predicting scorch height from rate of spread (R), and ambient temperature (T):

$$S_h = 2.9263(R^{0.5})(e^{0.0537T})$$

R^2 = 0.63 (Cheney *et al.* 1992)

To develop a physical model of scorch height, Cheney *et al.* (1992) measured radiation and air temperature in the crown scorch zone above low intensity prescribed fires in *Eucalyptus sieberi* regrowth forests. They used these measurements and Van Wagner's plume theory to model plume temperatures above fire and combined this with a model describing the thermal response of *E. sieberi* leaves to produce a model to predict scorch height.

None of the physical models described have been validated for jarrah forests and the scorch tables presented by Sneeuwjagt and Peet (1985) are limited in that they apply only to low intensity fires. This study evaluates these models for use in jarrah forests and develops specific empirical models for predicting scorch height in jarrah forests over a wide range of burning conditions.

METHODS

The study was carried out in conjunction with jarrah forest fire behaviour experiments conducted over summer and early autumn (January, February and March) in 1979 and 1980. Details of these experiments are described by Burrows (1994). Experimental fires were set in forty 2 ha plots which were last burnt 7 years prior to this experiment. The quantity of dead leaves, twigs, bark and floral parts < 6 mm in diameter on the forest floor (litter fuel) was measured before and after each experimental fire in a series of 20 m x 4 m sub-plots (30-40 per 2 ha plot). Litter fuel depth was measured at ten locations within each sub-plot and a relationship between litter depth and fuel quantity was used to determine litter fuel quantity (Burrows 1994). Fire rate of spread was measured by timing the spread of flames through the sub-plots, and visual estimates of flame height and length were made by experienced observers. Calibrated wooden pegs situated in the plots aided the visual assessment of flame dimensions. A portable weather station set at 1.5 m above the forest floor in an adjacent plot some 50 m from the plot to be burnt recorded ambient air temperature, relative humidity and wind speed and direction during each experimental fire.

Mean scorch heights within the sub-plots were measured about 5-6 weeks after fire using either a height stick for scorch ≤2 m or a clinometer for scorch >2 m. Mean scorch heights were regressed with mean fire behaviour parameters (rate of spread, flame height, flame length and fire intensity) obtained for each sub-plot. Scorch height measurement was limited by the maximum height of the vegetation at each sample point. In many cases, the entire vegetation profile was scorched indicating that the potential scorch height exceeded the height of the vegetation used to measure scorch height. Therefore, only data where scorch height was less than canopy height were used in analysis.

Additional scorch height data were acquired from Peet (1966 unpublished data archived at the CALM Manjimup Research Station Archive File 22/06.2). Peet's data were obtained during small, low intensity fires set in jarrah forests in spring 1966 when conditions were cool and moist. Unfortunately, we were unable to reliably match Peet's historical scorch height and fire behaviour records with the weather records. Therefore, seasonal data (spring and summer/autumn) were analysed separately because of seasonal differences in weather conditions during the fires, fuel moisture content and tree physiology.

RESULTS AND DISCUSSION

Scorch Height and Semi-physical Models

Observed scorch heights are graphed, with scorch heights predicted by Van Wagner's (1973) model using fire intensity, ambient air temperature and wind speed, in Figure 1. When applied to jarrah forests, Van Wagner's model consistently under predicted scorch height. The scorch model derived by Cheney *et al.* (1992) using fire intensity, wind speed and ambient temperature, also under predicted at low scorch levels and showed poor predictive capacity at high fire intensities. Differences in forest type, fuel characteristics and methods of calculating fire intensity probably explain the poor performance of these models. Cheney (1990) has discussed the limitations of using Byram's (1959) fire intensity to compare fires burning in different fuel types. Correction factors to improve the predictability of the Van Wagner model were generated by regressing observed scorch height with predictions, as shown in Figure 1. Regression analysis solving for coefficient values ('k' values) using Van Wagner's equation form did not improve the R^2 values or the error statistics. The best-fit equation using the form given by Van Wagner (1973) is:

$$S_h = 1.49 \frac{0.742(I)^{7/6}}{(60-T)[0.0256(I) + (0.278U)^3]^{1/2}} + 1.06 \quad R^2=0.65$$

Where:

S_h = scorch height in jarrah forests (m),

I = fire intensity (kW m^{-1}),

T = ambient air temperature (°C),

U = wind speed in the forest and at 1.5 m (km h^{-1}).

Scorch Height and Fire Behaviour Variables

Of the fire behaviour variables, flame height, flame length and Byram's (1959) fire intensity showed strongest correlation with scorch height. This is not surprising as these descriptors reflect the amount and rate of heat release for a given fuel type (Cheney 1990). There is considerable variation in scorch height not explained by the relationships in Table 1, reflecting the inherent variability and difficulty of measurement of scorch height, the behaviour of fire, fuels and meteorological conditions. In some instances, tilting of the convection column would have resulted in inaccuracies when matching scorch height with the appropriate fuel and fire behaviour variables which gave rise to the scorch, further adding to the unexplained variation in scorch height.

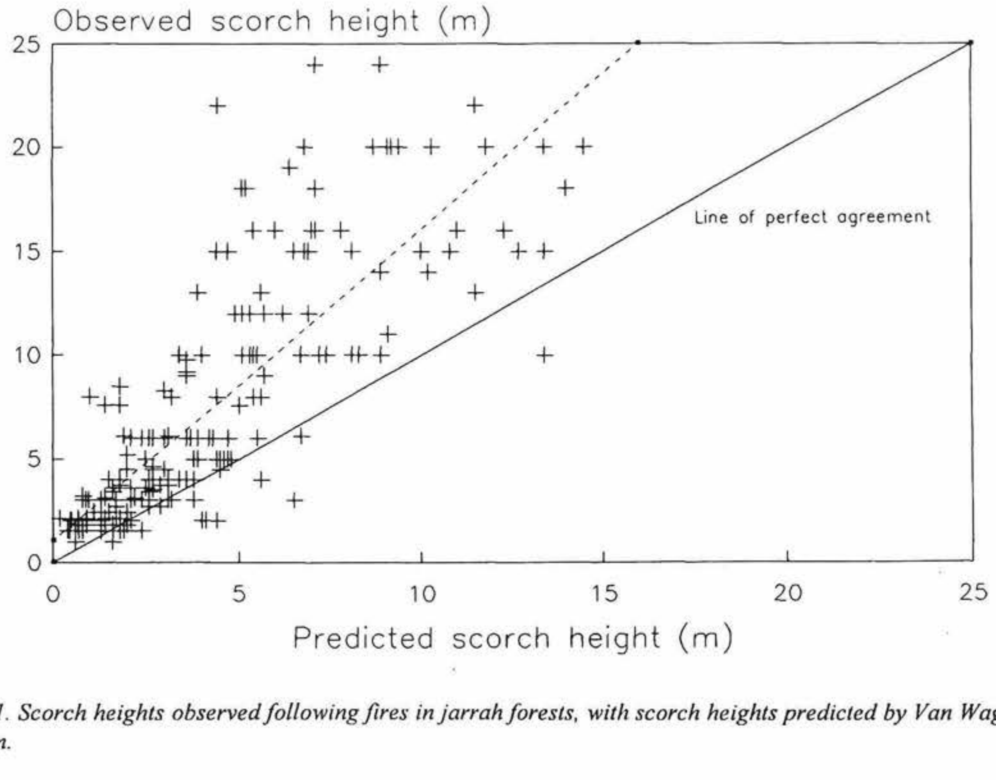


Figure 1. Scorch heights observed following fires in jarrah forests, with scorch heights predicted by Van Wagner's (1973) equation.

There were also clear seasonal influences as described by the linear regressions below (Fig. 2). Scorch height during warm, dry summer/autumn conditions was about nine times flame height, and during spring conditions was about five times flame height, as determined from regressions through the origin. The important effect of ambient air temperature on scorch height has been theorized and demonstrated experimentally by other workers (e.g., Van Wagner 1973; Cheney *et al.* 1992; Gill 1995). However, I was unable to isolate or determine the effect of ambient temperature on scorch height, mainly because I could not match Peet's historical weather data (including ambient temperature) with fire behaviour and scorch height data, as discussed above. Analysis of the summer/autumn data set failed to show any significant effect of ambient temperature on scorch height.

An example of the seasonal variation in the moisture content of dead outer bark on jarrah trees is graphed in Figure 3. During early spring fires the moist bark rarely ignites or chars beyond flame height, however, in summer and early autumn when the bark is dry, combustion of bark along parts of, and in some instances the entire length of, the bole were observed, especially during higher intensity summer fires. As well as augmenting spot fires (fires which start ahead of the main fire from firebrands), heat released from bark burning on the stem and branches in or near the canopy contributed to crown scorching. The combustion of coarse surface fuels (logs and limbs) and of

TABLE 1

Empirical equations and associated statistics for predicting scorch heights (S_h) (m) from flame height (F_h) (m), flame length (F_l) (m), and Byram's (1959) fire intensity (I) (kW m^{-1}). Fire seasons are variable and indiscrete but generally apply over the periods shown in Figure 3. Spring burning conditions normally apply when the Soil Dryness Index (SDI) is less than about 750 and rising (Burrows 1987) and summer/autumn burning conditions apply when the SDI is greater than about 1200. The spring equations were derived from Peet's (1966) unpublished data. Standard errors are shown in parentheses.

EQUATION	SEASON OF FIRE	N	R^2
$S_h = 4.92(F_h) + 0.49$ (0.29) (0.15)	Spring	50	0.61
$S_h = 8.53(F_h) + 2.03$ (0.49) (0.55)	Summer/autumn	114	0.72
$S_h = 5.87(F_l) + 2.81$ (0.33) (0.53)	Summer/autumn	114	0.71
$S_h = 0.28(I)^{0.58}$ (0.09) (0.06)	Spring	50	0.59
$S_h = 0.36(I)^{0.59}$ (0.12) (0.05)	Summer/autumn	114	0.58

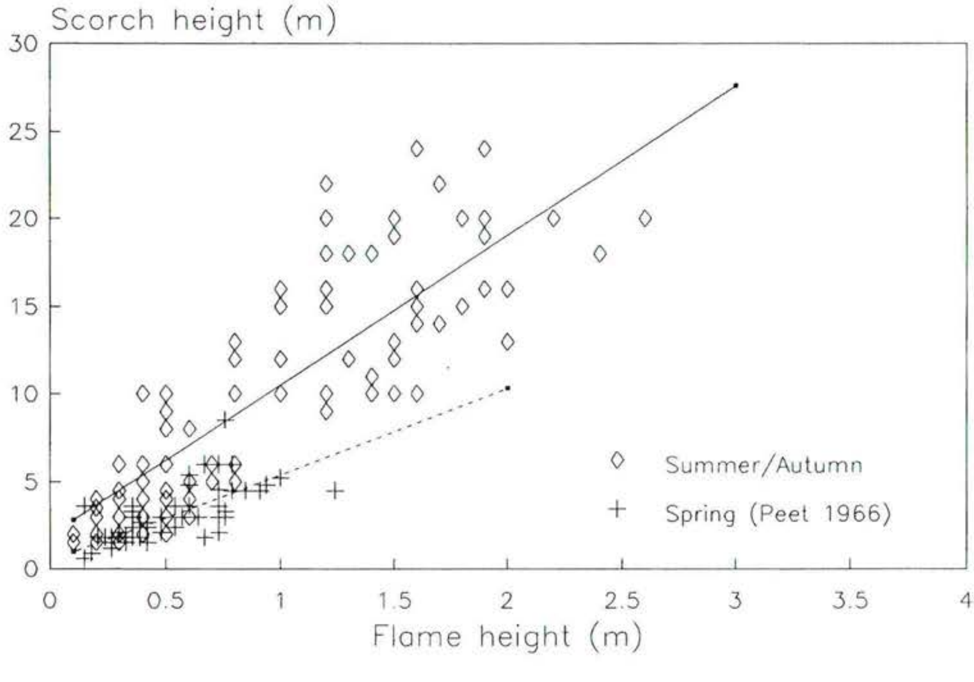


Figure 2. Relationship between scorch height and flame height for jarrah forest fires burning in different fire seasons; spring scorch data are from Peet (1966) and summer/autumn regression equations are shown in Table 1.

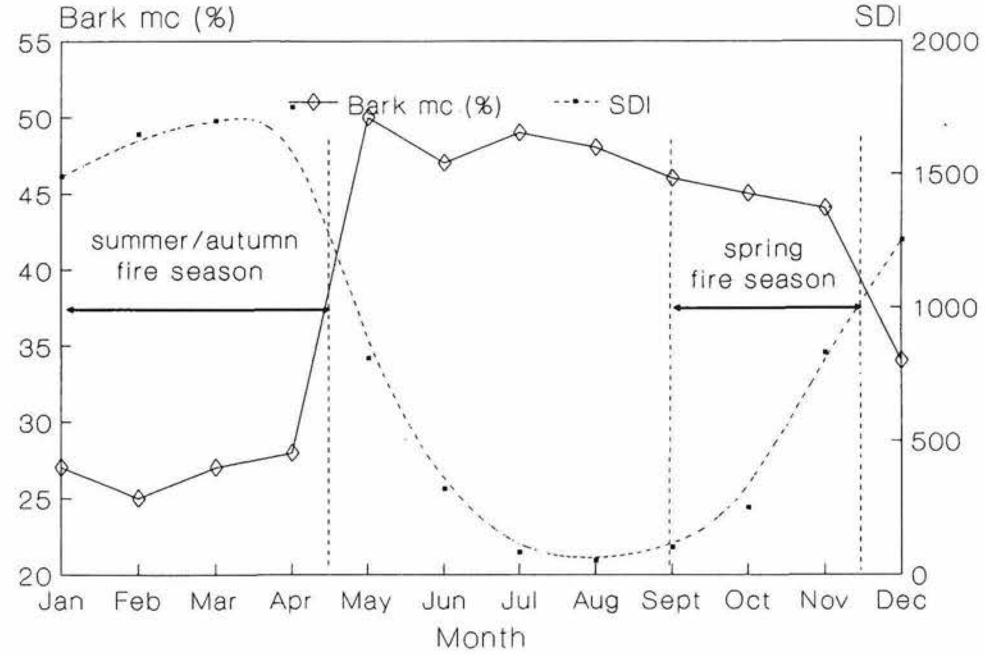


Figure 3. Mean monthly moisture content (percentage of oven dry weight) of the outer 5-10 mm of bark on 25 live, standing jarrah trees during 1980. The Soil Dryness Index (SDI) (Mount 1972; and Burrows 1987) is used to assist with the delineation of 'fire seasons'.

bark on standing trees is not included in the quantity of fuel burnt when calculating fire intensity. The quantity of bark burnt is difficult to measure and varies with fire history, but in high intensity jarrah forest fires it has been estimated to be as high as 6 t ha^{-1} (Peet and McCormick 1965; and Ward and Burrows 1985).

Therefore, the significantly higher scorch levels experienced during summer and early autumn jarrah forest fires for given measures of flame height and fire intensity (Fig. 2) are probably owing to:

(1) higher ambient air temperatures in summer and early autumn;
(2) increased susceptibility of plants to scorching owing to a significant water deficit over the hot, dry, summer months (see Crombie *et al.* 1988 for water deficit);
(3) combustion of additional fuels that do not normally burn under cool, moist, spring conditions. These include coarse dead fuels and bark on the boles and limbs of standing live trees. These fuel components are not normally included in the fire intensity calculation because they are not necessarily involved in flaming zone combustion of surface fuel. While there are data on the total quantity of bark consumed during jarrah forest fires, there are no data available on the proportion of bark consumed in the flaming zone.

Scorch heights experienced during summer and early autumn fires ('dry' conditions) were related to Byram's fire intensity by the equation shown in Table 1, above, which is graphed with Van Wagner's (1973) relationship in Figure 4. A similar equation was derived using Peet's unpublished data for spring fires ('moist' conditions). All equations are of the same form, but the equations derived for jarrah forest fires predict a higher scorch level than Van Wagner's equation, especially under summer/autumn conditions (Fig. 4). The explanation provided above for the discrepancy between the predictions made by Van Wagner's semi-physical model and observed data probably explains the under-prediction. For these reasons, scorch height predictive models developed under one set of forest and fuel conditions may not be transferable to other conditions (Cheney 1990) and unique equation coefficients may need to be generated for each forest/fuel type.

Management Implications

Flame height, flame length and fire intensity are convenient and meaningful fire behaviour descriptors for predicting scorch height. These variables are related to fire rate of spread (which is dependent on weather and fuel moisture conditions) and the quantity of fuel burnt, factors that can be controlled, or selected for, to some extent when prescribing fires. An important fire management objective in jarrah forests is to protect human life and property and forest values from the impacts of intense summer

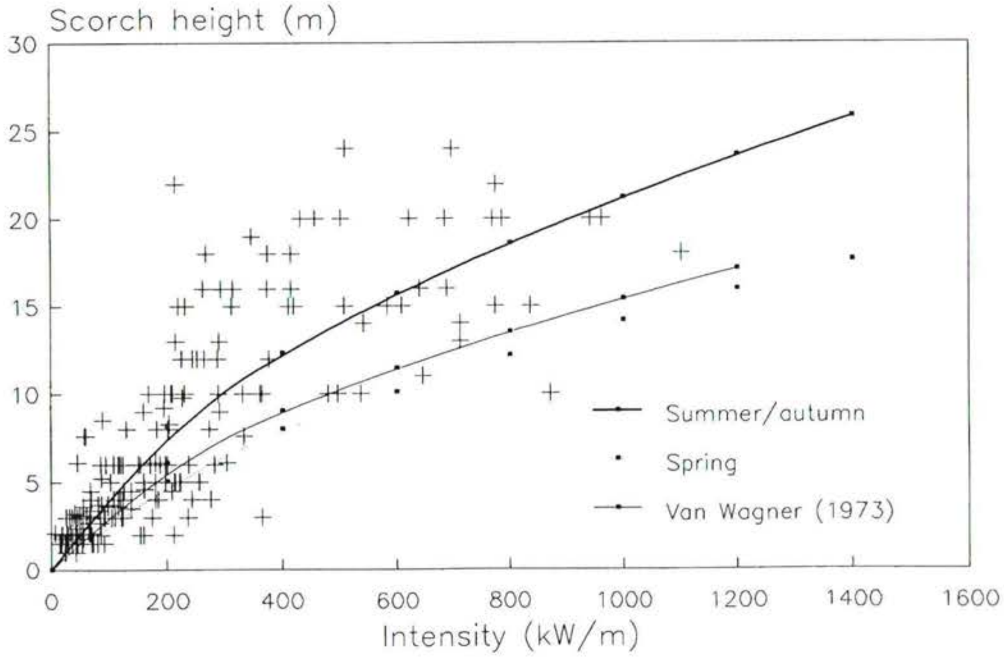


Figure 4. Scorch heights during jarrah forest fires in spring and summer/autumn are graphed with Byram's (1959) fire intensity. Scorch height predicted using Van Wagner's (1973) equation is also graphed for comparison. Regression equations are shown in Table 1.

wildfires. A strategy for achieving this is to implement low intensity fires in spring under cool weather conditions when fuels are moist. This operation successfully achieves fuel reduction while minimizing canopy damage, especially in regrowth forests. Current prescriptions require scorch height to be less than 6 m which also minimizes the impact on flora (especially small trees), fauna and visual qualities (e.g. see Burrows and Friend *in press*). Using the relationships contained in Table 1, this can be achieved by prescribing fires with flame heights less than about 1 m in spring (cool, moist conditions) and less than about 0.5 m in summer/autumn (warm, dry conditions), or maintaining fire intensities below about 250 kW m^{-1}. For a standard jarrah forest fuel with about 8.0 t ha^{-1} of available fine fuel, headfire rates of spread should not exceed about 65 m h^{-1}.

Fires burning under warm and dry conditions in summer or autumn cause significantly higher crown scorch than spring fires with similar flame heights. Where the aim is to fully scorch the forest canopy with prescribed fire, then this is best achieved with the minimum fire intensity needed to fully scorch the canopy to ensure that the fire can be controlled and does not cause excessive damage to other forest values. From the relationships in Table 1, the minimum flame height to achieve full canopy scorch to a mature jarrah forest (top height 20-25 m) under warm, dry summer/autumn conditions is about 2-3 m, which is equivalent to a fire intensity of about 1000-1200 kW m^{-1}.

CONCLUSIONS

Scorch height is a useful and meaningful criterion for setting limits to the intensity of prescribed burns and for assessing the potential severity of wildfires. An ability to predict scorch height is important for planning and implementing fire management activities.

None of the existing scorch models adequately predicts scorch height over the range of fire conditions likely to be experienced in the jarrah forest. This study developed new relationships enabling scorch height in jarrah forest fires to be predicted, within reasonable limits, from readily measured fire behaviour variables such as flame height, flame length and fire intensity. The strong seasonal differences between these relationships is probably owing to seasonal variation in (1) weather conditions, (2) plant physiology and (3) fuels available for burning.

ACKNOWLEDGEMENTS

I thank Bob Smith, Bob Voutier, Alex Robinson and Bruce Ward for their assistance in the field and George Peet for the use of his unpublished data. I also thank CALM staff at Dwellingup, Kirup and Nannup for controlling the experimental fires and Marty Alexander, Lachie McCaw, Malcolm Gill and Phil Cheney for comments on earlier drafts of this paper.

REFERENCES

Abbott, I., Van Heurck, P. and Burbidge, T. (1993). Ecology of the pest insect jarrah leaf miner (*Lepidoptera*) in relation to fire and timber harvesting in jarrah forest in Western Australia. *Australian Forestry* **56**, 264-275.

Burrows, N.D. (1985). Reducing the abundance of *Banksia grandis* in the jarrah forest by the use of controlled fire. *Australian Forestry* **48**, 63-70.

Burrows, N.D. (1987). The Soil Dryness Index for use in fire control in Western Australia. WA Department of Conservation and Land Management *Technical Report* 17.

Burrows, N.D. (1994). Experimental development of a fire management model for jarrah (*Eucalyptus marginata* Donn ex Sm.) forest. Ph.D. thesis, the Australian National University, Department of Forestry, Canberra.

Burrows, N.D., Woods, Y.C., Ward, B.G. and Robinson, A.D. (1989). Prescribing fire to kill wildings in *Pinus radiata* plantations in Western Australia. *Australian Forestry* **52**, 45-52.

Burrows, N.D. and Friend, G. (in press). Biological indicators of appropriate fire regimes in southwest Australian ecosystems. *In* Leonard A. Brennan and Teresa L. Pruden (eds), Fire in ecosystem management: shifting the paradigm from suppression to prescription. Proceedings of the Tall Timbers Fire Ecology Conference No. 20. Tall Timbers Research Station, Tallahassee, FL.

Byram, G.M. (1959). Combustion of forest fuels. *In* K.P. Davis (ed.). *Forest Fire: Control and Use*. pp. 61-89. McGraw-Hill, New York.

Cheney, (1990). Quantifying bushfires. *Mathematical and Computer Modelling* **13**, 9-15.

Cheney, N.P., Gould, J.S. and Knight, I. (1992). A prescribed burning guide for young regrowth forests of silvertop ash. CSIRO Division of Forestry, Bushfire Research Unit, Report to the Forestry Commission of New South Wales.

Christensen, P.S. (1971). Stimulation of seedfall in karri. *Australian Forestry* **35**, 182-190.

Christensen, P.E.S. (1982). Using prescribed fire to manage forest fauna. Forests Department of Western Australia *Forest Focus* **25**, 8-21.

Christensen, P.E.S., Wardell-Johnson, G. and Kimber, P. (1988). Birds and fire in southwestern forests. *In* A. Keast, H.G. Recher, J. Ford and D. Saunders (eds). *Birds of Eucalypt Forests and Woodlands: Ecology, Conservation and Management.* pp. 291-299. Surrey Beatty and Sons, Sydney.

Cremer, K.W. (1965). How eucalypt fruits release their seed. *Australian Journal of Botany* **13**, 11-16.

Crombie, D.S., Tippett, J.T. and Hill, T.C. (1988). Dawn water potential and root depth of trees and understorey species in south-western Australia. *Australian Journal of Botany* **36**, 621-631.

de Ronde, C. (1983). Controlled burning in pine stands in the Cape. The influence of crown scorch on tree growth and litterfall. *South African Forestry Journal* December 1983, 39-41.

Gill, A.M. (1975). Fire and the Australian flora: A review. *Australian Forestry* **38**, 4-25.

Gill, A. (1995). Stems and Fires. *In* B. Gartner (ed.). *Physiology and Functional Morphology*. pp. 323-342. Academic Press, San Diego.

Henry, N.B. and Florence, R.G. (1966). Establishment and regeneration in spotted gum-iron bark (*Eucalyptus maculata/E. drepanophylla/E. siderophloia*) forests. *Australian Forestry* **30**, 304-316.

Hoare, J. (1985). A model of fire behaviour and resulting damage to vegetation for predicting the biological effects of fire on plant communities at Kakadu National Park. *In* J. Walker, J.R. Davis and A.M. Gill (eds). Towards an Expert System for Fire Management at Kakadu National Park. CSIRO Division of Water and Land Resources, *Technical Memorandum* **2**, 138-152.

Hodgson, A. and Hieslers, A. (1972). Some aspects of the role of fire in south eastern Australia. Forests Commission of Victoria *Bulletin* 21.

Inions, G.B., Tanton, M.B. and Davey, S.M. (1989). The effect of fire on the availability of hollows in trees used by the common brushtail possum *Trichosurus vulpecula* Ker 1792, and the ringtail possum *Pseudocheirus peregrinus* Boddaerts 1785. *Australian Wildlife Res*earch **16**, 449-458.

Jacobs, M.R. (1955). *Growth Habits of the Eucalypts*. Forestry and Timber Bureau, Canberra.

Johnson, E.A. (1992). *Fire and Vegetation Dynamics: Studies From the North American Boreal Forest.* Cambridge University Press.

Kayll, A.J. (1968). Heat tolerance of tree seedlings. *Proceedings of the Tall Timbers Fire Ecology Conference* **8**, 89-105.

Kercher, J.R. and Axelrod, M.C. (1984). A process model of fire ecology and succession in a mixed conifer forest. *Ecology* **65**(6), 1725-1742.

Kimber, P.C. (1978). Increased girth increment associated with crown scorch in jarrah. Forests Department of Western Australia *Research Paper* 37.

Luke, R.H. and McArthur, A.G. (1978). *Bushfires in Australia*. Forestry and Timber Bureau and CSIRO Division of Forest Research, Canberra.

Methven, I.R. (1971). Prescribed fire, crown scorch and mortality: field and laboratory studies on red and white pine. Canadian Forestry Service Information Report PS-X-31. Petawawa Forest Experiment Station, Chalk River, Ontario, Canada.

Mount, A.B. (1972). The derivation and testing of a soil dryness index using run-off data. Tasmania Forestry Commission *Bulletin* 4.

Peet, G.B (1966). Department of Conservation and Land Management Archive File 22/06.2. Unpublished. (CALM,Manjimup, WA)

Peet, G.B. and McCormick, J. (1965). Bark reduction by intense fires in jarrah forest. Forests Department of Western Australia *Forest Notes* **3**(3), 26-29.

Peterson, D.L. (1985). Crown scorch volume and scorch height estimates of postfire tree condition. *Canadian Journal of Forest Res*earch **5**(3), 596-598.

Peterson, D.L. and Ryan K.C. (1986). Modelling postfire conifer mortality for long range planning. *Environmental Management* **10**(6), 797-808.

Reinhardt, E.D. and Ryan, K.C. (1989). How to estimate tree mortality from underburning. *Fire Management Notes* **49**(9), 28-36.

Rothermel, R.C, and Deeming, J.E. (1980). Measuring and interpreting fire behaviour for correlation with fire effects. USDA Forest Service *General Technical Report* INT-93.

Ryan, K.C. (1982). Techniques for assessing fire damage to trees. Proceedings of a Symposium on Fire - Its Field Effects. Jackson, Wyoming. Intermountain Fire Council and Rocky Mountain Fire Council.

Saveland, J.M. and Neuenschwander, L.F. (1990). A signal detection framework to evaluate models of tree mortality following fire damage. *Forest Science* **36**(1), 66-76.

Shea, S.R., McCormick, J, and Portlock, C.C. (1979). The effect of fire on the regeneration of leguminous species of the northern jarrah (*Eucalyptus marginata* Sm) forest of Western Australia. *Australian Journal of Ecology* **4**, 195-205.

Sneeuwjagt, R.J. and Peet, G.B. (1985). Forest Fire Behaviour Tables for Western Australia (3rd edn). Department of Conservation and Land Management, Western Australia.

Swezy, M.D. and Agee, J.A. (1991). Prescribed fire effects on fine roots and tree mortality in old-growth ponderosa pine. *Canadian Journal of Forest Research* **21**(5), 626-634.

Thomas, P.H. (1963). The size of flames from natural fires. *In* Ninth Symposium (International) on Combustion. pp. 844-859. Pittsburgh, The Combustion Institute.

Van Wagner, C.E. (1970). Fire and red pine. *Proceedings of Tall Timbers Fire Ecology Conference* **10**, 211-219.

Van Wagner, C.E. (1973). Height of crown scorch in forest fires. *Canadian Journal of Forest Res*earch **3**, 373-378.

Ward, B. and Burrows, N.D. (1985). The contribution of bark on standing trees to fuel weight in jarrah-marri forests. Unpublished Report, Western Australian Department of Conservation and Land Management. CALM Library (archives).

NOTES ON CONTRIBUTORS

Carmel Baggetta is a clerical officer based at CALM's Harvey office. She can be contacted on (08) 9729 1505 or fax (08) 9729 1868.

Gary Brennan is a Senior Research Scientist at CALM's Timber Technology Branch, Harvey. He can be contacted on (08) 9729 1913 or fax (08) 9729 2063.

Neil Burrows is Director of the Science and Information Division of CALM. He can be contacted at CALM's State Headquarters, Crawley on (08) 9442 0307, fax (08) 9386 6399 or email neilb@calm.wa.gov.au

Janet Farr is a Research Scientist at CALM's Science and Information Division, Manjimup. She can be contacted on (08) 97 717 996 or fax (08) 97 771 183.

Neil Gibson is a Senior Research Scientist in the Biodiversity Conservation group based at CALM's Wildlife Research Centre at Woodvale. He can be contacted on (08) 9405 5100 or fax (08) 9306 1641.

Greg Heberle is a forester currently involved in the auditing of CALM's operations. He can be contacted on (08) 9334 0337, fax (08) 9334 0458 or email gregh@calm.wa.gov.au

Brendan Lepschi is a consultant botanist based at CALM's WA Herbarium. He can be contacted on (08) 9334 0500 or fax (08) 9334 0515.

Mike Lyons is a Technical Officer in the Biodiversity Conservation group based at CALM's Wildlife Research Centre at Woodvale. He can be contacted on (08) 9405 5100 or fax (08) 9306 1641.

Susan Moore is a Lecturer in Environmental Science, Division of Science at Murdoch University. She can be contacted on (08) 9360 6484, fax (08) 9360 6787, and email smoore@essun1.murdoch.edu.au.

Shannon Morin completed her Master of Science (Environmental Science) at Murdoch University in 1995. She now works for the Major Project Review Unit, Habitat and Enhancement Branch, Department of Fisheries and Oceans, Vancouver, Canada. She can be contacted via the following email address: /R=VANHQ4/R=AM/U=morins/FFN=MORINS/@mr.pac.dfo.ca.

Sue Patrick is a senior Research Scientist in Biodiversity Conservation based at CALM's Western Australian Herbarium in Kensington. She can be contacted on (08) 9334 0500 or fax (08) 9334 0515.

Wayne Schmidt is Program Coordinator, Parks, Recreation, Planning and Tourism Division, based at CALM's State Operations Headquarters, Como. He can be contacted on (08) 9334 0575 and fax (08) 9334 0253.

Ian Wheeler is a Technical Officer at CALM's Science and Information Division, Manjimup. He can be contacted on (08) 97 717 994 or fax (08) 97 771 183.

INSTRUCTIONS TO AUTHORS

CALMScience publishes scientific research and technical investigations carried out by CALM or under the direction and authority of CALM. All papers are refereed outside the Department of Conservation and Land Management.

Editorial correspondence and submissions should be addressed to The Editor, *CALMScience*, Department of Conservation and Land Management, Locked Bag 29, Bentley Delivery Centre, Western Australia 6983.

All scientific and technical manuscripts submitted to the editor for publication must be accompanied by a completed *Science and Information Division Publications Submission Form.*

Papers must be of a high standard. Submission of a paper implies that the material has not been published or submitted elsewhere. The journal assumes that all authors of a multi-authored paper agree to its submission and accept intellectual responsibility for it.

Authors are required to forward three hard copies of the manuscript and all accompanying material to the editor, word processed and double spaced in draft format (single spacing may only be used where it is necessary to make a table fit a page). Word for Windows or MS WORD software should be used, and authors are required to provide floppy disks readable by IBM computer.

Manuscripts must NOT be desktop published.

Manuscripts must be on quality A4 white paper printed on one side of the paper only. The characters must be clear and black and all margins must be at least 3 cm. The pages of the manuscript must be numbered consecutively, throughout the entire paper, beginning at the title page, and including those pages containing references, appendices, tables, illustrations, captions, all of which are placed after the text.

Spelling should conform with the preferred (i.e. first-cited) spelling of the Oxford English Dictionary, with the single exception of the word 'program'.

SI units should be used for exact physical quantities and measurements. Authors who are unfamiliar with the SI units should consult AS 1000-1979 *The International System of units (SI) and its Application* issued by the Standards Association of Australia (1979).

Numbers referring to unit of measurement (e.g. 10 cm) are never spelt out unless forming the beginning of a sentence. All numbers under 10 not referring to units of measurement are spelt out.

Abbreviations should be identified the first time they are used.

The Harvard system (name and year in text, alphabetical listing) for the citation of references is to be used in all manuscripts. References must be cited in full – no abbreviations will be used in the Reference list. No editorial responsibility can be taken for the accuracy of the references: authors are requested to check these with special care.

References to personal communication in the text should be footnoted with the affiliation and location of the person. The words 'personal communication' should be spelt out in full.

Papers for publication must be mailed flat; do not bend or roll. Fasten with clips or clamps: do not staple or bind.

Manuscripts that do not meet submission requirements will be returned to the author.

Authors must retain a complete copy of the manuscript to ensure against loss in the mail, and for their own use. Prior to final publication and distribution, it is the author's responsibility to handle any requests or enquiries concerning the manuscript, other than those arising from the normal publishing procedure.

Manuscripts received by the editor are submitted to two referees for critical comment. If both referees consulted agree on whether the manuscript is acceptable or unacceptable this will be passed on to the senior author. If the referees disagree a third referee will be sought. If there is still doubt the Science Publications Committee will decide.

Following refereeing, the authors must return a revised manuscript within six months, otherwise it will be rejected or treated as a newly submitted manuscript requiring refereeing.

The editor may amend the text of a contribution in order to make it more generally comprehensible

Authors are required to proofread their papers. The set of proofs forwarded to the author must be corrected (not revised) and returned to the editor within 48 hours of receipt.

Twenty offprints will be forwarded free of charge to authors. No additional reprints will be available.

For more detailed information regarding submission requirements refer to *Guide to Authors* by M. Lewis.

4334 1097 300