Survival of hollow-bearing jarrah *(Eucalyptus marginata Sm)* and marri *(Corymbia calophylla)* trees in the south-west forest region of WA

K.R. Whitford[1] and M. R. Williams[2]

[1] Department of Conservation and Land Management, Science and Information Division, Dwellingup, WA 6213, Australia

[2] Department of Conservation and Land Management, Science and Information Division, Como, WA 6152, Australia

December 1997

Survival of hollow-bearing jarrah *(Eucalyptus marginata Sm)* and marri *(Corymbia calophylla)* trees in the south-west forest region of WA

K.R. Whitford[1] and M.R. Williams[2]

[1] Department of Conservation and Land Management, Science and Information Division, Dwellingup, WA 6213, Australia

[2] Department of Conservation and Land Management, Science and Information Division, Como, WA 6152, Australia

December 1997

This project was funded by the Commonwealth Government and the Western Australian Department of Conservation and Land Management as part of the Regional Forest Agreement for the south-west forest region of WA.

ACKNOWLEDGMENTS

We wish to acknowledge the substantial contribution of field work made by C. Anthony, C. Bathgate, J. Edwards, and J. Gale. P. Baalman, assisted with the planning and management of field work, selected all the field sites, and identified unlogged sites. J. Meharry, I Lee, and I. Jacobs assisted in locating the inventory plots and identifying tagged trees, and P. Blankendaal and R. Clifton undertook site surveys. C. English, C. Downes, D. Blechynden, and M. Smith advised on logging dates and the locations of unlogged sites. We thank staff of the Department of Conservation and Land Management's CALMfire unit for assisting with information on fire history.

G. Strelein, G. Stoneman, J. Bradshaw, M. Rayner, and P. Biggs of CALM, and J. Henstridge of Data Analysis Australia, provided valuable advice and information that assisted with the establishment and completion of this project.

CONTENTS

ABSTRACT

Habitat trees are retained after logging of the jarrah forest to moderate the effects of logging on animal species that use hollows in standing trees. As the forest regrows these large habitat trees will continue to fall from causes other than logging. The rate of fall of 1,880 habitat type trees was observed over periods ranging from 5 to 77 years (mean, 46 years) on 61 logged sites and 18 sites that had never been logged. Only 8.9% of the trees fell; a mean rate of tree fall of 0.020 trees per decade. There was no significant difference between the rate of marri tree fall (0.016 trees per decade) and the rate of jarrah tree fall (0.020 trees per decade). Hollowing out of the tree butt by fire, and breakage at this point was the most frequent mode of tree fall (approximately 72% of cases). Fire frequency and evidence of substantial termite infestation was associated with increased probability of tree fall. Considering only those trees with diameters of 70 cm or greater, the mean rate of tree fall was 0.024 trees per decade. Based on this estimate, 96 of the 400 habitat trees retained after logging of 100 hectares will fall within a 100 year period. This loss of some retained habitat trees is unlikely to have a major impact on hollow availability in this period.

INTRODUCTION

In the forests of WA there are 42 animal species that use hollows in standing trees; 21 are birds, 16 are mammals, and 5 are reptiles (Abbott, pers comm). Twenty-four of these species are considered totally dependant on tree hollows for breeding. Logging of the jarrah forest since the 1860's has preferentially removed the larger trees that are most likely to provide hollows suited to the larger of these animal species. To lessen this impact CALM marks and retains habitat trees when logging jarrah forest. The current prescription specifies the retention of an average of 4 habitat trees per hectare on all forest logged under shelterwood and thinning prescriptions, and the retention of an additional 6 to 8 potential habitat trees on areas logged to gap (CALM, 1995).

The specification of the type of trees to retain is based on the research of Inions (1985), Faunt (1992), and Whitford and Williams (in prep.). While the relationship between tree age and the probability of hollow occurrence is known, (Whitford and Williams in prep.), the fate of trees retained as habitat after logging is not quantitatively known. In the longer term, suitable trees must be available for recruitment as habitat trees, to replace those that are lost in storms, through decay and fire, or other natural processes. To manage for this eventuality it is necessary to know the longevity of habitat trees retained after logging, to understand the processes of tree loss and decline, and to combine this with knowledge of the age to hollow formation.

In addition, models developed to predict hollow occurrence (Whitford and Williams in prep.) show that, in the jarrah forest, marri trees that have hollows contain more hollows than hollow-bearing jarrah trees. This may be related to the relatively higher susceptibility of marri to decay (DaCosta, 1979, Brown et al., 1996). It is hypothesised that this same susceptibility may result in the more frequent and rapid decline of marri (in comparison to jarrah) once the processes of degeneration begins. In selecting trees to retain, the greater probability of a marri tree containing a number of useful hollows, must be balanced against the assumed greater longevity of jarrah trees. This can only be done when quantitative data on comparative longevity is available for these tree species, and this understanding is combined with our knowledge of the factors that influence the occurrence of hollows.

Factors likely to affect the longevity of retained trees are either site factors, or tree characteristics. Site factors are logging treatment type (or post logging stand structure and basal area), soil type and depth, topography, fire history and site slope and aspect. Tree characteristics include the tree species, tree diameter and height, crown size, the extent of hollowing of the tree butt, termite presence, rot occurrence, and crown condition. This project is a retrospective study that examines how long habitat type trees remain standing after logging, and identifies how the probability of habitat tree fall (ie. the falling of the tree due to natural causes) is related to these tree and site characteristics. The objective is to determine the rate of tree fall, and the major factors affecting the fall of these retained jarrah and marri habitat trees. The survey design considers those factors which can be managed and aims to sample across the range of tree characteristics.

METHODS

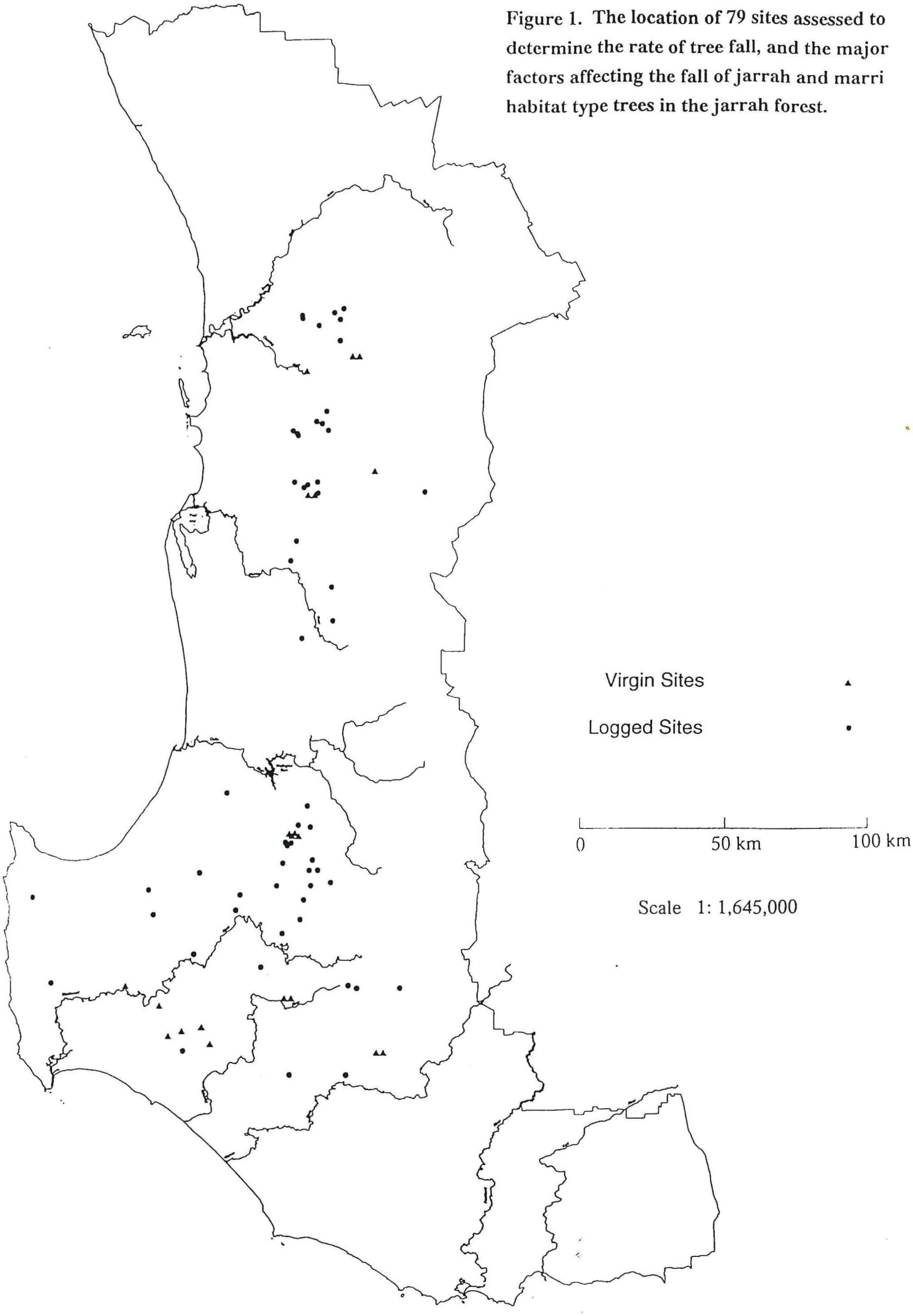
The data on tree fall came from two sources: Hardwood Permanent Increment Plots (HPIP's), and transects of the forest immediately adjacent to these plots. HPIP's were established in the 1930's and 1940's to measure tree and stand growth in the native hardwood forests of the south-west forest region and have been measured repeatedly since establishment. CALM has approximately 1000 of these plots spread evenly over the Northern, Central and Southern Forest Regions of CALM's forest estate. We selected 79 of these plots (see figure 1). The aim of the selection process was to maximize the period of repeated measurement, to cover a range of logging types, and to cover the geographical extent of the jarrah forest.

Initially data was collected from HPIP's. These plots have a long history of repeated measurement (from 5 to 54 years with a mean of 31 years) which provides an approximate date of tree fall. Preliminary analysis showed that tree fall on the 100 m x 40 m plots was rare over the historical period of measurement, so the survey was extended to transects around the boundary of the plots. These transects increased the number of trees observed, and enabled a longer period of observation. The observation period is that period of time over which individual tree falls can be determined. For the transects, assessing the degree of log decomposition enabled us to estimate the date of tree fall, and to include all tree falls since the last logging event. The method used on the HPIP's limited the period of observation to the historical period of measurement, which was often shorter than the time since the last logging event.

Plot history and site assessment

HPIP's are subject to the same management practices as the surrounding forest. Logging history for each HPIP was extracted from CALM's Forest Management Information System (FMIS) data base. The history of fire frequency for each plot was assembled from CALM records. Soil type and dieback status were obtained from a field review of HPIP's undertaken in 1987 and 1997. Detailed soil descriptions where used to group the sites into broad soil types: sandy loams, sandy gravels, sandy clays, clayey sands, loamy sands, gravels and loamy gravels, loams and clayey loams, or gravelly loams. Stand basal area was measured with a basal area prism. Sites were classified into 5 basal area (BA) classes based on the estimated stand density after

Figure 1. The location of 79 sites assessed to determine the rate of tree fall, and the major factors affecting the fall of jarrah and marri habitat type trees in the jarrah forest.



logging: very low density; low; moderate; high density; and unlogged. In most cases the stand density of unlogged sites was equivalent to that of the high density sites after logging.

Log Decay and the date of tree fall

Assessments of the degree of decomposition were used to determine the age of fallen logs. We called this group of assessments Log Decay (see Appendix 1). We assessed the following characteristics on an unburnt section of the log: the amount of bark present, the condition of the sapwood, the shape of the unburnt cross-section of the log, the amount of log contact with the ground, the depth of fissures in the log, the presence of moss, the heartwood strength, the presence of branches and the amount of understorey regeneration at the stump location.

Log Decay was assessed on all fallen trees and on a minimum of 4 crown logs from the most recent logging event at each site. The assessments of crown logs from 57 sites were regressed against the logging date to produce a linear relationship between Log Decay and log age for all sites. Because this relationship was clearly linear we then used each site assessment of crown logs to linearly scale Log Decay across the time period since logging for each individual site. As the site moisture environment affected the rate of log decomposition on each site (Brown et al., 1996), this latter technique was a more accurate means of estimating the age of logs when the date of logging was accurately known at a site.

The date of tree fall was determined in one of three ways. On HPIP's the date of tree fall was taken as the mid point between the assessment date when the tree was first recorded as fallen, and the previous assessment date. Where the scaled Log Decay assessment indicated a log age substantially greater or less than the mid-point between the two assessment dates, the date of tree fall was estimated by considering the Log Decay assessment. On the transects around HPIP's, the log age was determined by linearly scaling Log Decay over the period since logging. On unlogged sites, the regression relationship between Log Decay and log age was used to estimate the date of tree fall. In the majority of cases it was assumed that the tree was alive immediately prior to falling, and all decomposition had occurred after the tree fell. Where some aspect of the condition of the log indicated that this was not the case, only the most recent evidence of decomposition was used to determine the log age.

Tree selection

The February 1996 revision of CALM's current Habitat tree specification, (Appendix 5, Silviculture Specifications, CALM, 1995) specifies retained habitat trees be mature to senescent, > 70 cm in diameter, and be from intermediate crown senescence classes (selected from an 8 class pictorial scale, see Appendix 3). We sought to study the rate of fall of trees of this type: we examined trees down to 50 cm in diameter in order to more efficiently collect data for a large number of trees. In doing so we assumed that the mechanisms responsible for tree loss would operate similarly on these smaller trees and that this data would assist us in describing habitat tree fall. Trees of all crown senescence classes were included in the study as no records of crown senescence of the fallen trees, or of trees at the beginning of the observation period were available.

HPIP measurement

A map, drawn at the time of the initial HPIP assessment, was used to locate every tree on each plot and all trees and logs greater than 50 cm DBHOB were remeasured.

Transects around HPIP's

All trees, and logs that had fallen after the last logging event, were assessed along 20 m wide strip transects adjacent to the HPIP boundary. The length of the transect varied with stand density, with transects continuing until 25 trees, or logs that had fallen since the last logging event, were assessed.

Tree measurement

The following variables were recorded for each tree: tree status (standing/fallen, alive/dead), assessments of the causes of tree fall, tree diameter at 1.3 m (DBHOB), tree species, tree height, height to crown break, an estimate of the extent of hollow butt as a percentage of the original cross-sectional area, an assessment of the degree of termite infestation in the tree or log, an assessment of the crown senescence (SENESCENCE) and an assessment of the amount of decomposition of the fallen log (LOG DECAY, see Table 1, and Appendix 1; for SENESCENCE see Appendix 3).

Table 1. *Variables measured on 2526 trees and fallen logs on 79 sites in the jarrah forest.*

Variable	Variable name	Description
Tree and log attributes		
Log decomposition	LOG DECAY	10 stage categorical assessment of the degree of log decay. See Appendix 1 for detailed description.
Tree species	MARRI	Categorical variable; 1 if the tree or log is a marri, 0 for jarrah
Initial DBHOB	IDBHOB	Tree or log diameter at 1.3 m, over bark at the beginning of the observation period. (cm)
Final DBHOB	FDBHOB	Tree or log diameter at 1.3 m, over bark at the end of the observation period. (cm)
Crown senescence	SENESCENCE	An 11 class assessment of the stage of crown decline. See Appendix 3
Crown break height	CBREAK	Height to bottom of the crown break fork (m)
Termites	TERMITES	A classification of the type and degree of termite infestation 0: No termites 1: Superficial termite galleries in tree bark or log sapwood 3: Termite galleries in exposed wood of tree or log. 4: Yellowing at base of dead tree or galleries in log heartwood 5: Termites in scar at butt of standing tree or log on the ground 6: Termite mound on ground within 1 m of base of tree or log stump 7: Termite mound at base of tree or stump
Hollow butt	HOLBUTT	Amount of hollowing at the tree base, estimated as a percentage of the original sectional area.
Site attributes		
Stand density class	DENSITY	A classification of the stand density of the site after logging 1: Very low density after logging eg. clearfell; 2: Low stand density after logging, eg. heavy selection cuts 3: Moderate stand density after logging, eg. light selection cuts and shelterwoods 4: High stand density after logging, eg. light selection cuts and shelterwoods 5: Unlogged sites
No. of fires	NFIRES	A classification of the number of prescribed fires and wildfires since 1937 1: One to five fires 2: Six to eight fires 3: Nine or ten fires 4: Eleven or more fires
Soil type	SOIL	Broad classification of soil types 1: clayey sands 2: gravelly loams 3: loams 4: loamy gravels 5: loamy sands 6: sandy clays 7: sandy gravels 8: sandy loams
Slope	SLOPE	Coded into one of four categories: 1: < 3 2: 3 to 4 3: 4 to 7 4: 7+
Site aspect	ASPECT	The aspect of the site allocated to one of 5 classes 1: West to south-west 2: South to south-east 3: East to north-east 4: North to north-west
Dieback present	DIEBACK	Two categories; dieback present = 1, absent = 0
Observation length	OBSLENG	The length of time that the plot or transect was observed (years)
Years since logging	YRSLOGD	The number of year since the plot or transect was logged
Plot type	PLOT	Two categories, 0 for transects and 1 for plots

Calculating rate of fall, and DBHOB at the beginning of the observation period

As we sought to examine the longevity of trees currently being selected as habitat trees, and DBHOB is a major criteria for their selection, we estimated the DBHOB of trees at the beginning of the observation period. A simple model of jarrah diameter growth for average productivity jarrah forest (p 172. CALM 1992) was used to calculate the DBHOB of trees and logs at the beginning of the observation period for each site (IDBHOB). All trees that were then less than 50 cm DBHOB at the beginning of the observation period were removed from the data set.

We calculated the mean rate of tree fall for all trees, and for classes such as tree species, as the proportion of the observed trees falling per decade. These values are presented as summary values, and as a basis for discussion. Logistic regression was used for the analysis of the significance of site and tree attributes.

Statistical analysis

Those site and tree attributes related to tree fall were identified using logistic regression analysis, a maximum likelihood regression technique analogous to the more familiar linear regression model, but which is appropriate where the dependent variable follows a binomial rather than a normal distribution (see for example Hosmer and Lemeshow 1989, Myers 1990). Many earlier studies have used logistic regression to examine the factors affecting tree fall (Lohmander and Helles, 1987; Lindenmayer et al. 1990c), whether fallen trees have hollows (Williams and Faunt 1997), or whether tree hollows are occupied by fauna (Lindenmayer et al. 1990b, Lindenmayer et al. 1991, Lindenmayer et al. 1994). Logistic regression analysis provides a method of determining those attributes that are related to the tree status (standing or fallen), and the direction and extent of that relationship. The analysis was applied using the SAS software package (procedure LOGISTIC, SAS Institute Inc., 1989).

To include categorical variables such as soil type in the regression model, each was recoded as a set of design or "dummy" variables: each of n categories was replaced with n-1 binary design variables, and named with a combination of the parent variable and the category number (for example, "SOIL3", Table 1). This method of coding means that the estimated regression coefficient for each design variable represents the deviation of that category from the first category. For example, a significant, positive regression coefficient associated with the design variable SOIL3, would indicate a higher chance of trees falling for trees on those sites with loam soils, when compared to sites with clayey sand soils. Similarly, binary categorical variables, such as presence of dieback disease, were coded 1 if present and 0 if absent. For these variables, a significant, positive regression coefficient would indicate a higher incidence of tree fall for trees or sites having the feature present. Because there were a substantial number of missing values for some attributes, univariate models were calculated for the maximum possible number of records in each case.

We used standard methods expounded by Hosmer and Lemeshow (1989) to fit the regression model: first, the relationship between tree status and each variable alone was examined (univariate models), and any variable with $p<0.25$ was included in a pool of potentially important variables for further examination. A multivariate model was then estimated, using forward stepwise selection of variables from this pool with $p<0.15$, with backward elimination of variables deemed non-significant at $p>0.25$. The critical values 0.15 and 0.25 are those suggested by Hosmer and Lemeshow (1989), and are chosen to ensure that no potentially important variables are excluded.

RESULTS

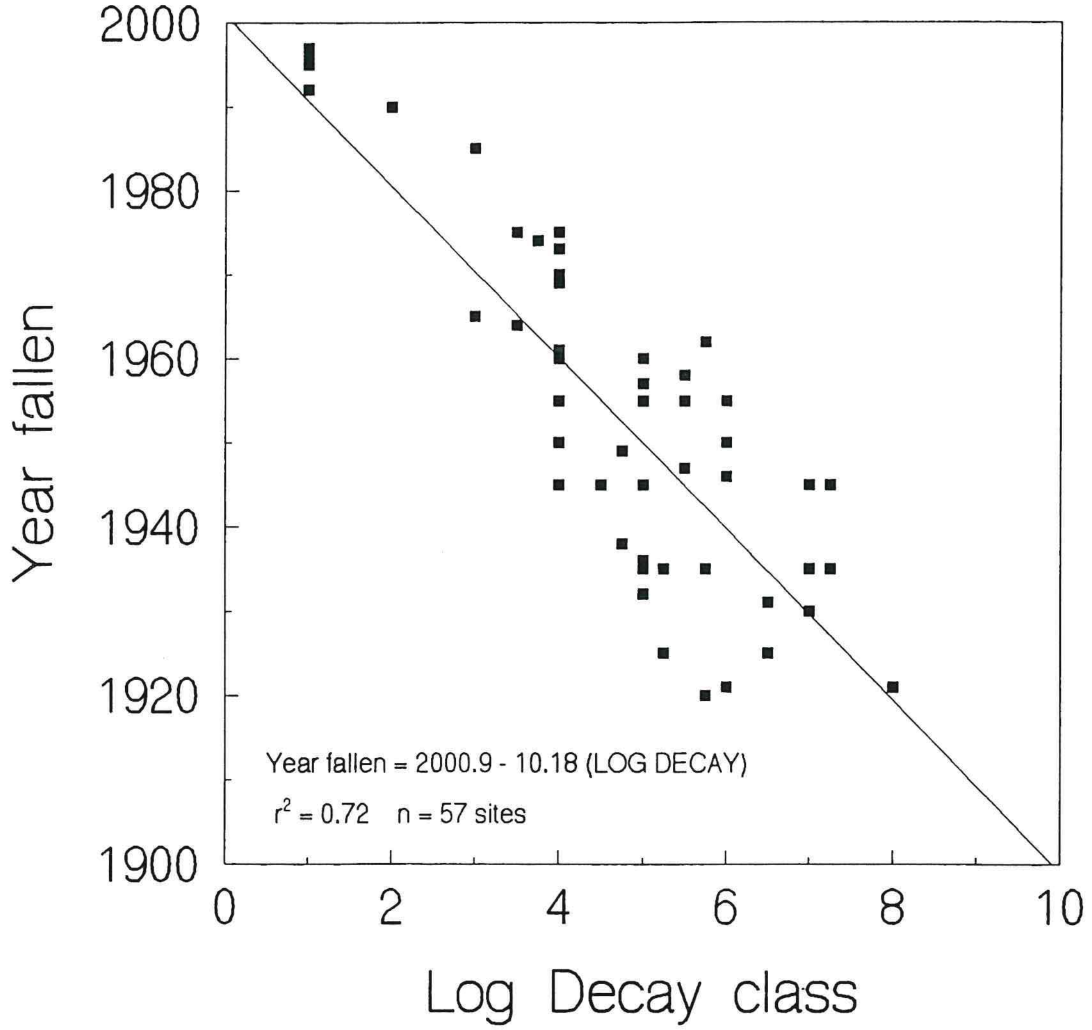
Log Decay and log age

The mean Log Decay of crown logs at each site (a minimum of 4 logs per site) was regressed against the year of logging for 57 sites (Fig. 2). This produced the relationship;

Year fallen = 2000.9 - 10.18 (Log Decay) $r^2 = 0.72$, $n = 57$

where;
Year fallen = Calender year that the tree fell, and
Log Decay = Log decomposition assessment.

Figure 2. Log Decay assessment vs year fallen for crown logs felled during logging



Data sources and sets

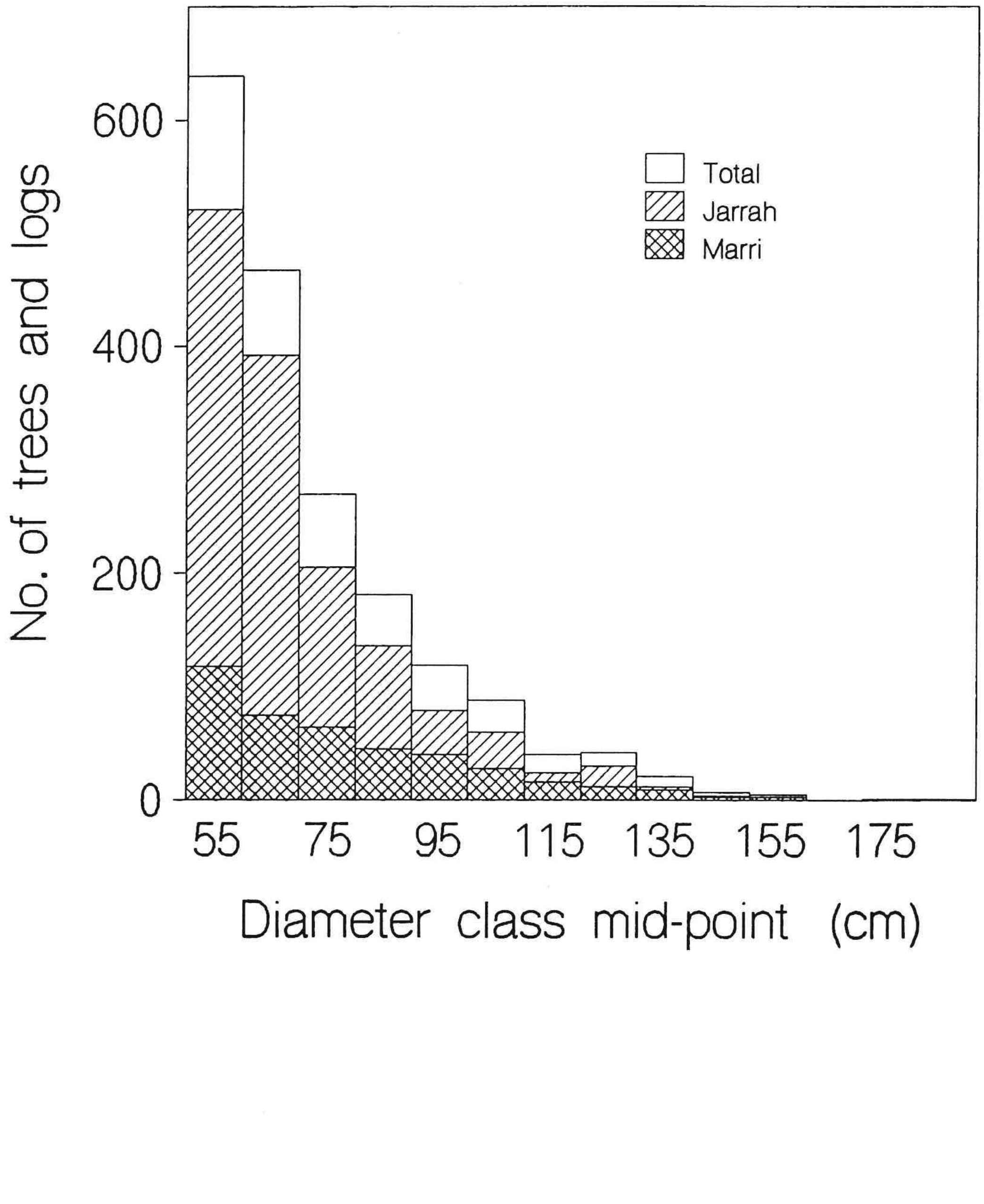
The base data set consisted of 2,526 trees (2006 jarrah and 520 marri) observed on 79 sites. Once the DBHOB of trees at the beginning of the observation period was calculated, and the trees with an initial DBHOB less than 50 cm were removed, 1880 trees remained (1466 jarrah and 414 marri). Figure 3 shows the diameter distribution of trees observed in this study, and Table 2 shows the source and status of these jarrah and marri trees.

The univariate logistic regressions and mean rates of tree fall were derived from this data set of 1880 trees. Complete site assessments were available for only 58 sites and only 38 sites had data for soil and fire, so the multivariate analysis of site and tree attributes was completed on 1405 trees.

Table 2. *Source, species and status of 2,526 trees observed on 79 sites and the resulting distribution of 1880 trees that remained once the initial DBHOB was calculated and trees with an initial DBHOB less than 50 cm were removed.*

Source	Jarrah Standing	Jarrah Fallen	Marri Standing	Marri Fallen	All trees Totals
All 2526 trees					
HPIP's	612	17	150	6	785
Transects around HPIP's	1232	145	338	26	1741
Totals	1844	162	488	32	2526
Final 1880 trees					
HPIP's	465	16	119	6	606
Transects around HPIP's	863	122	266	23	1274
Totals	1328	138	385	29	1880

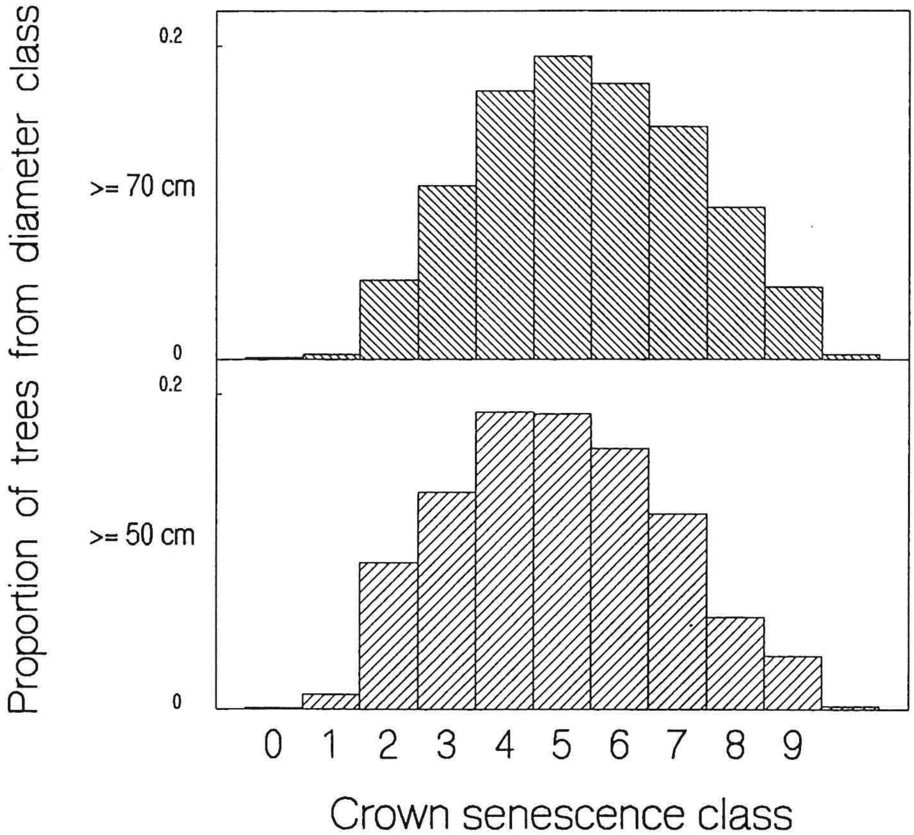
Figure 3. Diameter distribution of 1880 trees and logs assessed to determine the rate of tree fall



Crown senescence

Figure 4 shows the distribution of the crown condition assessment, SENESCENCE, for 2,328 of the standing trees observed in this study. Distributions are shown for both: trees with a final diameter of 50 cm or more, and for trees with a final diameter of 70 cm or more. 68% of trees with diameters of 50 cm or more are in crown senescence classes 2 to 5, compared to 65% of trees with diameters of 70 cm or more. 90% of trees with diameters of 50 cm or more have a crown senescence of 2 or greater, compared with 95% for trees with diameters of 70 cm or more.

Figure 4. Distribution of crown senescence for 2,328 jarrah and marri trees from 2 diameter classes



Rate of tree fall

Over the study period of approximately 46 years, very few (8.9 %) of the 1880 trees fell. The mean rate of tree fall for all trees greater than 50 cm DBHOB was 0.020 trees per decade. For trees greater than 70 cm DBHOB this rose to 0.024 trees per decade (see Table 3).

The rate of tree fall on the transects (0.022 per decade) was significantly greater than on the plots (0.012 per decade) ($\chi^2 = 35.19$ on 1 d.f., P = 0.0001) (Table 7).

There was no significant difference between the rate of marri tree fall (0.016 per decade) and the rate of jarrah tree fall (0.020 per decade) ($\chi^2 = 2.43$ on 1 d.f., P = 0.1187) (Tables 4 and 7).

Figure 5 shows the rate of tree fall in each diameter class. The rate of tree fall generally increases as the diameter of the trees increase, from 0.012 trees per decade for trees of 50 to 60 cm, to 0.030 trees per decade for trees of 120 to 130 cm.

Table 3. *The rate of tree fall per decade for 61 logged sites and 18 sites that had never been logged observed over a mean period of 46 years.*

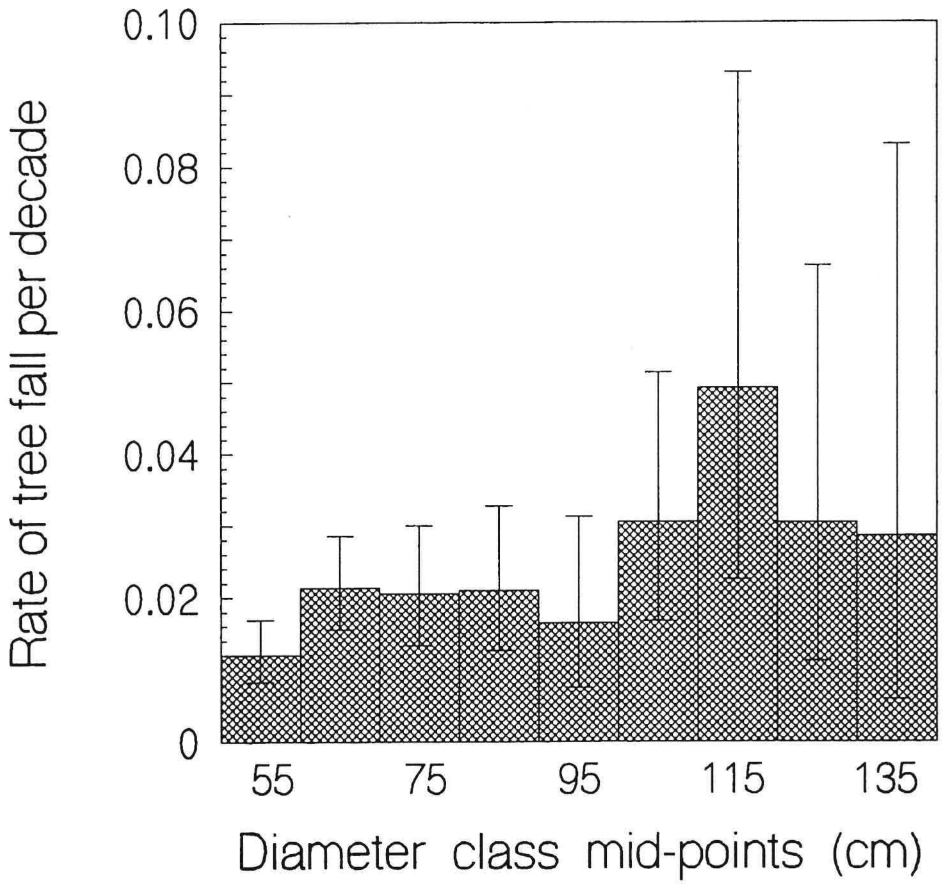
DBH range	Logged sites	Unlogged sites	All sites
>=50	0.017	0.026	0.020
>=60	0.021	0.028	0.023
>=70	0.021	0.031	0.024
>=80	0.023	0.030	0.026
>=90	0.025	0.035	0.028
>=100	0.029	0.045	0.034
>=110	0.028	0.063	0.038
>=120	0.021	0.063	0.032

Table 4. *Rate of tree fall per decade for jarrah and marri trees drawn from Hardwood Permanent Increment Plots (HPIP's) and transects around these plots.*

Jarrah HPIP's	Jarrah Transects	Marri HPIP's	Marri Transects	All Jarrah	All Marri	All trees
0.011	0.023	0.015	0.016	0.020	0.016	0.020

Figure 5. Rate of tree fall per decade by diameter class

Error bars are 95% confidence intervals



Comparing logged and unlogged stands

The rate of tree fall on sites that had never been logged (0.026 trees per decade, n = 18 sites) was greater than the rate of tree fall on logged sites (0.017 trees per decade n = 61 sites). When only trees greater than 70 cm IDBHOB or greater than 80, 90 and 100 cm are considered, the higher rate of fall on unlogged sites remained (see Table 3). Table 5 shows that the diameter distributions for logged and unlogged sites are similar.

Table 5. *The diameter distribution of trees on 61 logged (1500 trees) and 18 unlogged sites (380 trees).*

DBHOB	Logged sites		Unlogged sites	
Class	n	Proportion	n	Proportion
55	514	0.343	125	0.329
65	378	0.252	89	0.234
75	222	0.148	47	0.124
85	132	0.088	49	0.129
95	94	0.063	25	0.066
105	65	0.043	23	0.061
115	31	0.021	9	0.024
125	34	0.023	8	0.021
135	18	0.012	3	0.008
145	6	0.004	1	0.003
155	4	0.003	1	0.003
165	0	0.000	0	0.000
175	1	0.001	0	0.000
185	1	0.001	0	0.000

Direct causes of tree fall

Hollow butt and fire

The major direct cause of tree fall was hollowing out of the base of the tree (hollow butt), and the subsequent failure of the tree at this point. The mean amount of hollow butt of the fallen trees was 62% while the mean amount of hollow butt of standing trees was 8%. 72% of all fallen trees had hollow butts of 50% or greater compared to only 7% of standing trees. Fire was assessed as a major cause of tree fall in 63% of cases (Table 6).

Wind, Termites, and Rot

The effects of wind alone, or wind in association with causes other than fire, was assessed as a direct cause of tree fall for 37% of fallen trees. These trees were either blown over with their root plate intact, or the stem was broken, frequently in association with termite damage or rot (74% of these wind blown cases).

Termite infestation was assessed as a direct cause of tree fall in only 16% of cases. It was predominantly a contributing cause weakening the bole or roots, or aiding the development of hollow butt, and thus leading to wind damage. Similarly, significant weakening of the stem or roots by rot was rarely identified as a major cause of tree fall. Logging activities were a direct cause of the loss of 4 of the 2526 trees.

Table 6. *The direct causes of tree fall assessed on 194 fallen trees observed on 79 sites in the jarrah forest.*

Causes of tree fall	% of cases
Fire and wind	39
Fire and termites	4
Fire and rot	1
Fire alone	19
Wind alone	10
Wind and rot	16
Wind and termites	11
Termites alone	1

Regression analysis

Univariate analysis

Table 7 shows the results of the univariate logistic regression analysis. This analysis indicates that the percentage of hollowing of the tree base, was the factor most significantly related to tree fall. Development of hollow butt and breakage at this point was most frequently the mode of tree fall. Because hollow butt was always measured at the end of the observation period, ie. after trees had fallen in the case of fallen trees, we considered our assessments of hollow butt to be a series of observations as trees progressed toward tree fall, and unsuitable as predictors of tree fall. To be used as predictors of tree fall, they would need to be measured at the beginning of the observation period. HOLBUTT was excluded from the multiple regression.

Table 7. Estimated coefficients for univariate logistic regression of probability of tree fall on tree and site attributes. For the "Class" column: "yes", indicates there are 2 classes, a blank indicates a continuous variable and an integer indicates the class number.

Variable	n	df	χ^2	Overall p	Class	Coefficient	Individual p
MARRI	1880	1	2.43	0.1187	yes	-0.3218	
IDBHOB	1880	1	20.56	0.0001		0.0160	
FDBHOB	1880	1	10.58	0.0011		0.0124	
HEIGHT	1861	1	14.36	0.0002		-0.0519	
CBREAK	1867	1	6.43	0.0112		-0.0214	
TERMITES	1878	6	57.13	0.0001	0	0	
					1	-1.3662	0.0019
					2	0.0813	0.7491
					3	1.0156	0.0001
					4	0.5385	0.0883
					5	0.9659	0.0004
					6	0.7452	0.0144
HOLBUTT	1880	1	433.15	0.0001		0.0512	
DENSITY	1880	4	39.01	0.0001	1	0	
					2	0.2662	0.4170
					3	-0.3484	0.2867
					4	-0.4783	0.1553
					5	0.7942	0.0087
NFIRES	1406	3	17.95	0.0005	1	0	
					2	0.5047	0.0492
					3	-0.4860	0.0786
					4	-0.8864	0.1022
No. of wildfires	1406	2	3.63	0.1627	0	0	
					1	-0.0456	0.8529
					2	-0.8057	0.0879
SOIL	1339	7	70.00	0.0001	1	0	
					2	0.2342	0.5768
					3	1.0737	0.0077
					4	1.8057	0.0001
					5	-0.2099	0.5709
					6	-0.7531	0.1727
					7	0.8672	0.0259
					8	-0.1849	0.7591
Topography	1381	4	18.53	0.0010	1	0	
					2	-0.2701	0.3826
					3	-0.1002	0.8008
					4	0.9764	0.0072
					5	0.2215	0.4943
SLOPE	1371	3	28.76	0.0001	1	0	
					2	0.3611	0.1462
					3	0.0860	0.7470
					4	1.2565	0.0001
ASPECT	1331	3	4.74	0.1919	1	0	
					2	-0.0862	0.7758
					3	0.2909	0.3133
					4	0.3912	0.1843
DIEBACK	1318	1	5.22	0.0223	yes	-0.7111	
OBSLENG	1880	1	69.69	0.0001		0.0336	
YRSLOGD	1880	1	39.96	0.0001		0.0281	
PLOT	1880	1	35.19	0.0001	yes	-1.2665	

Soil type was the next most significant predictor of tree fall, with tree fall being most likely in loamy gravels, loams, and sandy gravels, in that order, and least likely in sandy clays. Gravelly loams, clayey sands, sandy loams and loamy sands, all had intermediate probabilities of tree fall.

The length of time that the tree was observed was the next most significant predictor. Though an obvious effect, this variable is included in the multivariate analysis to account for the differences between the length of observation at different sites.

Termite infestation was the next most significant variable, with low levels of termite infestation (classes 0, 1 and 2) associated with low probability of tree fall. Major termite infestations, evidenced by yellowing of the wood at the base of the tree or termite mounds within a metre of the tree, are associated with increased probability of tree fall.

Sixty-two of the sites were assessed for the presence of jarrah dieback disease. Nine of these sites were affected, with 53 sites unaffected. The presence of jarrah dieback did not increase the probability of tree fall for 1318 trees on these 62 sites (Table 7).

Multiple regression

All variables with $p<0.25$ in the univariate analysis were used to develop the multiple regression. The stepwise process selected observation length, termites, soil type, initial DBHOB, and number of fires, but eliminated soil type from the final model to produce the following expression for the probability of a tree falling (details, Table 8);

$$P = 1/(1+ \exp(4.5449 - 0.0235 \times OBSLENG + 1.7222 \times TERMITES1 + 0.4941 \times TERMITES2 - 0.4279 \times TERMITES3 - 0.7410 \times TERMITES4 - 0.1978 \times TERMITES5 - 0.6539 \times TERMITES6 - 0.0111 \times IDBHOB - 0.5772 \times NFIRES2 + 0.2630 \times NFIRES3 + 0.6648 \times NFIRES4))$$

where P is the probability of a tree falling and
OBSLENG is the number of years the tree is observed.
See Table 1 for a description of other variables.

Table 8. Results from the multivariate logistic regression of site and tree attributes affecting the probability of tree fall.

Variable	DF	Parameter Estimate	Standard Error	Wald Chi-Square	p > Chi-Square
INTERCEPT	1	-4.5449	0.5018	82.0450	0.0001
OBSLENG	1	0.0235	0.0063	14.0438	0.0002
TERMITES1	1	-1.7222	0.6179	7.7676	0.0053
TERMITES2	1	-0.4941	0.3730	1.7547	0.1853
TERMITES3	1	0.4279	0.3470	1.5208	0.2175
TERMITES4	1	0.7410	0.3558	4.3381	0.0373
TERMITES5	1	0.1978	0.4028	0.2412	0.6234
TERMITES6	1	0.6539	0.3729	3.0739	0.0796
overall	6				0.00004
IDBHOB	1	0.0111	0.0048	5.2494	0.0220
NFIRES2	1	0.5772	0.2716	4.5157	0.0336
NFIRES3	1	-0.2630	0.2893	0.8263	0.3634
NFIRES4	1	-0.6648	0.5615	1.4021	0.2364
overall	3				0.0072

DISCUSSION

Crown senescence

The crown senescence of trees at the beginning of the observation period was not known, and we could not determine crown senescence on fallen trees. Consequently we cannot examine how crown senescence is related to tree fall. Presumably crown senescence reflects the overall state of the tree and is related to the extent of internal stem piping, termite infestation, and stem decline such as hollow butt. We expect that more senescent trees are more likely to fall. Our estimates of rate of fall, and of the factors affecting tree fall, cover all crown senescence classes rather than just those retained as habitat trees (classes 2 to 5). We also examined the factors affecting tree fall on trees with diameters 50 cm and greater, when trees retained as habitat trees are 70 cm and greater. Figure 4 shows that there is a slight movement of crown senescence toward the high end of the scale when only trees greater than 70 cm are considered. The majority of trees with diameters of 50 cm and greater are within the prescribed habitat tree range of 2 to 5 (68% of trees, compared to 65% of trees >= 70 cm). After they are retained, trees will slowly progress upward through the crown senescence classes, and the distribution of retained trees should not be dissimilar from the distribution of trees with senescence classes greater than 2, ie. 90% of the trees that we studied. Consequently the rates of fall calculated in this study and the examination of factors affecting tree fall should accurately reflect the case for retained habitat trees.

Multiple regression selection process

The multiple regression model provides a rational basis for interpreting the relationship between tree fall and the large number of significant site and tree variables. The exclusion or removal of some variable in the stepwise process indicates that, although individually significant, the variation in tree fall was either better described by another single variable, or group of variables. This elimination does not always indicate that a variable is inconsequential, as surveys such as this suffer from poor control of covariation which may lead to the removal of a meaningful variable during the stepwise regression process. We selected sites primarily to cover the geographical range of the jarrah forest and some site variables may be correlated on a sufficiently large group of sites to reduce their significance in a multivariate analysis. Variables not included in the multiple regression model, such as soil type, stand density after logging, slope, years since logging and plot type, may still have value in explaining tree fall.

The predictive ability of model was not tested, as the main purpose of the model was to identify factors affecting longevity.

Included and excluded variables

The length of the observation period, OBSLENG, was included in the model as a simple means of dealing with the variation in length of observation period that occurred in our data. Burgman et al. (1994) discussed this problem and proposed the Cox proportional hazards model as a solution. We chose a logistic procedure and the inclusion of observation length as a simpler means of identifying significant variables.

Other variables in the model are termites, initial tree diameter and the number of fires. The selection of initial diameter concords with the pattern of tree growth and aging; increased tree size, and increased probability of structural damage leading to tree fall. As diameter is highly correlated with both tree height and crown break height, its use in the model precludes the inclusion of the latter variables.

The inclusion of the termites and number of fires is most likely related to their role in the formation and enlargement of hollow butt. The behaviour of the TERMITESx coefficients in the model is as expected, with major termite infestations, associated with increased probability of tree fall. However the behaviour of the NFIRESx coefficients is not so simple. Increases in the numbers of fires up to NFIRES2 (6 - 8 controlled burns since 1937) increases the probability of tree fall, but beyond this number of fires the probability of tree fall decreases. As frequent burning is usually associated with reduced fire intensity, it is possible that trees on sites which are infrequently burnt experience hotter fires and are more likely to develop hollow butt. Our arbitrary selection of the class limits for NFIRESx may have obscured this trend. However fire is difficult to describe simply, and these counts of the frequency of controlled burns since 1937 may poorly reflect fire intensity or duration at specific sites, (factors that are probably related to hollow butt formation).

We also considered the number of wildfires and non CALM fires in this period. These were much less significant descriptors of tree fall than the number of controlled burns (Table 7).

Fire, termites, and fungi

Fire and the many factors that affect its intensity, fungi, and termites, are all probably interrelated in the process of hollow butt formation and development. Scars caused by fire in the jarrah forest provide a site for decay organisms such as fungi to enter the tree (McCaw, 1983), termite infestation follows fungal attack (Perry et al. 1985), both fungal decay (Wilkes, 1982) and termite activity can produce the internal pipes in eucalypts that encourage hollow butt enlargement, and fire scars provide dead wood for future ignition.

The factors that affect fire intensity include, fuel load and moisture content, fire frequency, site aspect and slope, vegetation type and structure, and local weather conditions. The formation and development of fire scars at the tree base is related to fuel proximity and volume, and consistency of wind direction (with fire scars tending to form on the downwind side of a tree). Clearly, combining all these effects and interrelations and explaining their effect on hollow butt development is complex. Consequently both the inclusion of NFIRESx in the model and the unusual behaviour of the coefficients is not inconsistent.

Soil

The soil type variable was highly significant but was eliminated from the multiple regression model. We assessed soil type as a possible indicator of tree root anchorage, internal stem piping, and termite infestation. Few trees fell with their root plate intact. In the case of jarrah this is probably attributable to the combination of a dense lateral root system and a well developed sinker root system that penetrates to considerable depth (Kimber, 1974). It is unlikely that differences in how well trees were anchored in the soil are responsible for the significance of soil type. Greaves and Florence (1966) suggest that the potential for termite infestation is reduced in soils that restrict termite gallery formation, and field observations suggest that internal piping is more common in soil types that support slower growing forest. These factors may be the reason for the univariate significance of SOILx and its exclusion from the multiple regression model.

Differences between plots and transects, and logged and unlogged sites

Table 4 shows a higher rate of tree fall on transects compared to plots, and the univariate analysis similarly shows a significantly higher probability of tree fall on transects. However, when the effects of observation length and termites were accounted for in the multiple regression, the source of the data (ie. plot or transect) was no longer a significant effect.

The rate of tree fall on unlogged sites was higher than on logged sites (Table 3). We assumed that this effect would be due to the greater number of large trees on the unlogged sites and examined the diameter distributions (Table 5) of logged and unlogged sites. The slight difference between these distributions, is insufficient to explain the difference in rates of tree fall. We conclude that higher rates of tree fall observed on these unlogged sites are attributable to site factors such as fire history and occurrence of termites.

Tree species differences

It was expected that the lower decay resistance of marri compared with that of jarrah (Da Costa, 1979) would result in marri trees falling more frequently than jarrah. This was not observed. This may be due to the small number of marri trees observed in this study, to the disappearance of all evidence of older fallen marri logs on the transected areas, or due to incorrectly identifying fallen marri logs as jarrah.

To examine the latter proposal we compared the marri tree falls that had occurred on transects with observation periods up to the last 40 years, with all tree falls over the total period of observation (periods up to 77 years). If marri logs burnt or decayed away over time on the transects, we would expect that reducing the length of the observation period would increase the proportion of fallen marri trees identified, and hence increase the rate of marri tree fall on the transects. The rate of marri tree fall increased very slightly from 0.016 to 0.017 when the observation period was decreased from 77 to 40 years.

Incorrect identification appears unlikely, as data from the HPIP's, where the tree species was determined prior to tree fall, also shows little difference between the rate of fall of jarrah (0.011) and marri (0.015).

The assumption that marri will decay more readily than jarrah is possibly incorrect as the decay resistance of dead timber is not correlated with the resistance of the living tree (Manion and Zabel, 1979; cited in Wilkes, 1982). Hence living marri, with its capacity to resist and wall off fungal invasion (Tippett et al., 1985), may well oppose the processes of fungal and termite attack that aid the development of hollow butt in jarrah trees. This would not be the case for dead marri or for dead wood that resulted from fire scaring.

Assessment of hollow butt at the beginning of the observation period

As hollowing at the tree base and breakage at this point was the most frequent mode of tree fall, measurements of fire scaring or the extent of hollow butt at the beginning of the observation period would have been valuable as predictors of tree fall. As we did not have these measurements we were unable to consider directly how the rate of hollow butt formation and development varies directly with logging and fire. In the absence of data that integrates fire intensity and frequency, our result indicate that the presence of a major termite infestation is the best indication of how readily hollow butt will develop in a tree.

CONCLUSIONS

The rates of fall of jarrah and marri trees greater than 70 cm in diameter (2.4 % per decade) are an order of magnitude below those observed by Lindenmayer et al. (1990a) in ash-type forest (36 % per decade). Based on our estimate, 96 of the 400 habitat trees retained after logging of 100 hectares of jarrah forest will fall in a 100 year period. This comparatively low rate of loss of habitat trees is unlikely to have a major impact on hollow availability in this period as many of the smaller trees retained on logged areas will grow into the hollow-bearing size and condition over this period. The focus of greater concern should be on the correct specification and selection of habitat trees that contain useable hollows.

The majority of fallen trees were broken off at the stump and showed a large percentage of hollow butt. Fall due to this weakening at the base of the tree was most commonly the direct cause of fall. Tree markers should avoid selecting trees with hollow butt to retain as habitat trees where other suitable trees are available. Similarly, trees that show evidence of substantial termite infestations are more likely to fall. As evidence of termite infestation is not associated with increased probability of hollow occurrence (Whitford and Williams, in prep.) tree markers should avoid selecting habitat trees with such evidence. However, this consideration should not predominate when selecting trees that are most likely to bear hollows.

CALM's current habitat tree prescription specifies minimum tree size and crown condition but does not indicate a tree species preference. This survey indicates that a significant difference between the rate of fall of jarrah and marri is unlikely. Changing this aspect of the current prescription is unlikely to improve the longevity of habitat trees.

REFERENCES

Brown, S., Mo, J., McPherson, J. K., and Bell, D. T. (1996). Decomposition of woody debris in Western Australian forests. *Canadian Journal of Forest Research,* 26:954 - 966

Burgman, M. A. Incoll, W., Ades, P., Ferguson, I., Fletcher, T., and Wohlers, A. (1994) Mortality models for Mountain Ash and Alpine Ash. *Forest Ecology and Management.* 67: 319-327.

CALM (1992) *Management strategies for the South-West forests of Western Australia; A review.* CALM, W.A.

CALM (1995) Silvicultural practices in the jarrah forest. *Silvicultural Guidelines 1/95.* CALM, W.A.

Da Costa, E.W.B. (1979) Comparative decay resistance of Australian timbers in accelerated laboratory tests. *Australian Journal of Forest Research.* 9:119 - 135.

Faunt, K. (1992). Formation, frequency and longevity of hollows in jarrah. Unpublished report. CALM. WA.

Greaves, T. and Florence, R.G. (1966) Incidence of termites in Blackbutt regrowth. *Australian Forestry,* 30: 153-161

Hosmer, D.W. Jr. and Lemeshow, S. (1989). Applied Logistic Regression. Wiley and Sons, New York, 301 pp.

Inions (1985). The interactions between possums, habitat trees and fire. BSc (Hons) thesis, Australian National University.

Jacobs, M. R. (1955) *The growth habits of eucalypts.* Commonwealth Forestry and Timber Bureau, Canberra.

Kimber, P.C. (1974) *The root system of jarrah.* Research Paper, No. 10. Forests Department Western Australia.

Lindenmayer, D. B., Cunningham, R.B., Tanton, M.T., Smith, A.P., Nix, H.A.(1990a). The conservation of arboreal marsupials in the montane ash forests of the Central Highlands of Victoria, south-eastern Australia: II. The loss of trees with hollows and its implications for the conservation of Leadbeater's Possum Gymnobelideus leadbeateri McCoy (Marsupialia: Petauridae). *Biological Conservation* 54:133-145.

Lindenmayer, D.B., Cunningham, R.B., Tanton, M.T., Smith, A.P. and Nix, H.A., (1990b). The conservation of arboreal marsupials in the montane ash forests of the central highlands of Victoria, south-east Australia: I. Factors influencing the occupancy of trees with hollows. *Biological Conservation*, 54: 111-131.

Lindenmayer, D.B., Cunningham, R.B., Tanton, M.T. and Smith, A.P., (1990c) The conservation of arboreal marsupials in the montane ash forests of the central highlands of Victoria, south-east Australia: II. The loss of trees with hollows and its implications for the conservation of Leadbeater's possum *Gymnobelideus leadbeateri* McCoy (Marsupalia: Petauridae). *Biological Conservation*, 54: 133-145.

Lindenmayer, D.B., Cunningham, R.B., Tanton, M.T., Smith, A.P. and Nix, H.A., (1991). Characteristics of hollow-bearing trees occupied by arboreal marsupials in the montane ash forests of the central highlands of Victoria, south east Australia. *Forest Ecology and Managemant*, 40: 289-308.

Lindenmayer, D.B., Cunningham, R.B. and Donnelly, C.F., (1994) The conservation of arboreal marsupials in the montane ash forests of the central highlands of Victoria, south-east Australia, VI. The performance of statistical models of the nest tree and habitat requirements of arboreal marsupials applied to new survey data. *Biological Conservation*, 70:43-147.

Lindenmayer, D.B., Cunningham, R.B., and Donnelly, C.F. (1997) Decay and collapse of trees with hollows in Eastern Australian forests: Impacts on arboreal marsupials. *Ecological Applications*, 7(2) 625 - 641.

Lohmander, P. and Helles, F. (1987). Windthrow probability as a function of stand characteristics and shelter. *Scandinavian Journal of Forest Research*. 2:227 - 238.

McCaw, W. L. (1983) Wood defect associated with fire scars on jarrah (*Eucalyptus marginata* Sm.). *Australian Journal of Forest Research*, 13:261-266

Myers, R.H., (1990) *Classical and Modern Regression with Applications*. 2nd ed. PWS-KENT, Boston, 420 pp.

Perry, D.H., Lenz, M., and Watson, J.A.L. (1985) Relationship between fire fungal rots and termite damage in Australian forest trees. *Australian Forestry* 48(1), 46 - 53.

SAS Institute Inc. (1989) SAS/STAT User's Guide, Version 6, 4th ed. SAS Institute Inc., Cary NC, USA.

Tippet, J. T., Hill, T. C. and Shearer, B. L. (1985) Resistance of Eucalyptus spp. to invasion by *Phytophthora cinnamomi*. *Australian Journal of Botany*. 33:409 - 18.

Whitford and Williams (in prep.). Tree hollows for selected fauna species in jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*): the effects of tree age, tree size, crown condition, fire scarring, and termites.

Williams, M.R. & Faunt, K. (1997) Factors affecting the abundance of hollows in logs in jarrah forest of south-western Australia. *Forest Ecology and Management* 95:153-160.

Wilkes 1982. Stem decay in deciduous hardwoods - an overview. *Australian Forestry* 45:1: 42-50

Appendix 1. The Log Decay assessment. An assessment of how long the log has been on the ground. Assess an unburnt section of the log close to the butt. The assessment of regeneration at stump takes precedence over assessment of the condition of the log. Do not assess the effects of fire.

Log Characteristic	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Bark	intact	trace	absent	absent	absent	absent	absent	absent	absent	absent
Sapwood	hard, and brown	hard, grey to light brown	grey, surface can't be scuffed off with boot	grey, surface scuffed by boot, but ends hard to break off	surface of sapwood is crumbly	sapwood easily broken away by hand	sapwood missing on parts of log	sapwood gone	sapwood gone	sapwood gone
Shape of unburnt cross-section	round	round	round	round	95% of round	90%	75%	50%	< 25%	10%
Log contact with the ground	Log free of ground	Log free of ground	Log in contact with ground	Log in contact with ground	Log in contact with ground for full length	Log in contact with ground for full length	Sitting in ground	Sitting in ground	merging with ground	Only trace evidence of log remains
Fissures	absent	cracks possible	cracks	cracks present, slight fissuring, 1-2 cm deep, 8 - 10 cm apart	2 cm deep about 10 cm apart		3 - 4 cm deep	5 - 7 cm deep furrows in log surface	Deep furrows in log surface	
Moss	absent	absent	absent	some moss possible	present	present	present	May be absent	May be absent	May be absent
Heartwood strength	hard	hard	Jarrah hard Marri may be starting to collapse	Jarrah hard, Marri collapsing	Jarrah hard but decay is present, Marri collapsing	heartwood can be broken away by hand	heartwood easily broken away and crumbled by hand	heartwood easily kicked away	heartwood rotten and easily kicked away	heartwood rotten and easily kicked away
Branches	Minor branches intact	Minor branches intact	Major branches still intact if not burnt away	Major branch stubs or none	Major branch stubs or none	none	none	none	none	none
Regeneration at stump	None, bare ground	Some litter, small weeds	Some litter, small weeds	Litter cover, small acacias	Litter cover, bracken or larger plants	Litter cover, bracken or larger plants	Litter cover, bracken or larger plants	Similar to surrounding ground cover	Similar to surrounding ground cover	Similar to surrounding ground cover
Score	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

Notes; Assess the log as close to the butt as possible. Do not assess the effects of fire, try to ignore them. Assess cross sectional shape at an unburnt location on the log. Assessment of "Log contact with the ground" assumes that the log is not sitting on another log.

Appendix 2. Field instruction sheet for plot and transect assessment.

Block	CALM forest block name for plot location. eg. Holyoake, Lowden, Kingston
Plot	Plot identifier
Tree	Tree or log number used in previous assessment.
Condition	Tree or log condition 1. Standing alive 2. Standing dying 3. Standing dead 4. Fallen alive 5. Fallen dying 6. Fallen dead 7. Log, shows signs of log removal or cutting
DBHOB	Tree or log diameter 1.3 m above ground. Measured to one decimal place, eg. 62.3 cm. Trees with hollow butts or logs with butt missing - Estimate the diameter of the tree as if it was still round or as if the butt was still present.
Species	Tree species, jarrah = J, marri = M, blackbutt = B, Wandoo = W, Rudis = R
% hollow	Percentage hollow butt. Estimate this as a percentage of the original sectional area
Tree height	The height of the tree from the ground to the top of the highest limb or leaf. Measured in metres to one decimal place.
Crown break	The height of the tree from the ground to crown break - see definitions.
Termites	Type of termite infestation. 6 Termite mound at base of tree or stump. 5 Mound on ground within 1 m of base of tree or stump, or exposed log heart full of termite dirt. 4 Yellowing at base scar. Termites in scar at butt of standing tree or log on the ground. 3 Yellowing at base of dead tree or termite galleries in rotting heartwood of log. 2 Termite dirt in crack of dead tree, or exposed wood on live tree, (eg. scar) or termite galleries in sapwood 1 Termite dirt in bark of live tree or superficial galleries in sapwood on log. Trails seen but termites may be absent. 0 No termites
Log Decay	10 stage ordinal assessment of the length of time the log has been on the ground. Not required for logged trees. The assessment is based on rot and deterioration of the part of the bole closest to the stump (Ignore fire damage) and the amount of understorey regeneration at the stump location.
Senescence	Score from 1 - 10 rating the decline of the tree crown. See pictorial scale.
Cause	Causes of tree fall, 3 columns for codes in order of importance. Coded F = fire, W = wind, T = termites, R = rot, L = logging, T = termites.
Logging type	Shelterwood, Selection, Thinning, Gap, Uncut
Topography	Classification of topography at tree location. Valley = V, Midslope = M, Hilltop = H
Basal area	4 counts from factor 2 basal area prism, spread across the plot, or counts taken at each tree > 50 cm DBHOB
Comments	Any additional information, eg. stump type, info relevant to log age, log condition. Notes on logging history. Number of times logged.

Appendix 3. The pictorial scale used to determine crown senescence. Assessment of crowns as better (class 0) or worse (class 10) than those shown is permitted. Developed from Figure 59 of Jacobs (1955).