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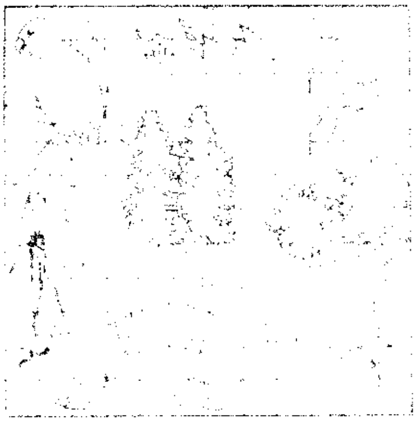

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Fire caused bole damage to Jarrah (*Eucalyptus marginata*) and Marri (*Eucalyptus calophylla*).

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SUMMARY

Fire is used in the forests of Western Australia to achieve a variety of objectives. Low intensity (<350 kW/m) fires set under carefully defined fuel and weather conditions are used to reduce levels of fuel build-up on the forest floor. Recently, moderate intensity fires (~1000 kW/m) burning under dry fuel conditions have been used for disease control and habitat management. Foresters need to know the nature and extent of timber loss resulting from these fires. In this study, the extent of bole damage to jarrah (*Eucalyptus marginata*) and marri (*Eucalyptus calophylla*) trees following low and moderate intensity experimental fires was measured in successive years.

Moderate intensity summer fires caused considerable bole damage to the smaller diameter trees (<35 cm) of both species. Jarrah boles were more resistant than marri to fire. The boles of large diameter (≥35 cm), single-stemmed jarrah trees which were undamaged prior to the study and which were more than 2 m away from logs were not damaged by moderate intensity summer fire.

INTRODUCTION

Controlled fire continues to be an important factor in the successful management of forests in Western Australia. Since the 1950s, the jarrah (*Eucalyptus marginata*) forests have been burnt periodically by low intensity (<350 kW/m) fires set under carefully selected fuel and weather conditions (Underwood and Christensen 1981). These periodic, low intensity fires maintain forest floor fuel levels below about 8 t/ha, and therefore contribute significantly to the control of wildfires (Underwood *et al.* 1985). Such fires have not caused measurable reductions in timber yield (Loneragan 1961; Podger and Peet 1964; Abbott and Loneragan 1983), nor have they caused any significant damage to large trees (Cheney 1981; Abbott and Loneragan 1983).

Recently, the possibility of using fire for disease control (Shea 1975; Burrows 1985) and for fauna habitat management (Christensen 1983) has been examined. In both instances, fires need to be of a higher intensity than fuel reduction fires and set under drier conditions. Although ground litter fuels in much of the jarrah forest are maintained at less than about 8 t/ha, intense summer fires can cause crown and bole damage (McArthur 1968; McCaw 1983).

In forests managed primarily for timber production, the effect of moderate intensity summer fires on timber values needs to be determined. Severe wildfires cause commercial timber value losses (Peet and Williamson 1968), but the effect of fire behaviour on the extent of bole damage is not well defined.

It is important, therefore, to examine the extent of fire scarring and tree mortality following low and moderate intensity summer fires in a jarrah forest, and to define fire behaviour and stand characteristics predisposing tree boles to fire injury.

METHODS

The study was carried out in 40 ha of jarrah forest in Young Block, 25 km south-east of Dwellingup, Western Australia. The surrounding forest for a distance of up to 3 km was burnt by low intensity fire in 1979 as part of the Forests Department's (now the Department of Conservation and Land Management) fuel reduction program. The study area had been logged in the 1930s and had experienced regular (5-7 years) low intensity fuel reduction burns since the mid 1950s, and prior to this study was last prescribed burnt in 1974. A rubber-tyred tractor was used to construct twenty plots, each about 2 ha (200 m x 100 m) and separated by a 3 m wide mineral earth break. Four parallel rows of quadrats running lengthwise in each plot were marked with pegs.

Each row consisted of six numbered, contiguous quadrats, each 4 m wide and 20 m long. There were 24 quadrats in each plot and 480 quadrats in all. Not all were used. Many quadrats were not burnt, were damaged by falling trees or were disturbed during fire control operations. Finally, only 163 quadrats were used.

Pre-burn measurements were made in November, 1979. All trees taller than 2 m in each of the quadrats (20 m x 4 m) were identified by attaching numbered metal tags around each stem at 1.8 m above the ground. Tree species (either jarrah or marri) was recorded and diameter at breast height over bark (dbhob) was measured (using a diameter tape). A knife-type bark gauge was used at four points around the stem to measure bark thickness at breast height. The average of these four readings was used to represent bark thickness. As the forest had been commercially cut over in the past, many stems were coppice off old stumps. A note was made of whether the stem was a coppice stem or was a single, original stem.

The bole of all tagged trees, up to 2 m above ground, was examined for previous fire damage. The first 2 m only was examined as this is the zone most likely to be fire damaged, and represents the most valuable section of log. There were also practical difficulties in attempting to measure fire damage higher up the stem.

Fire injury or drysiding occurs when a section of cambium on the bole is killed by heat (Gill 1974). The bark at the injury site later sloughs away, exposing the dry wood. In some cases, the wound occludes, and is only recognizable as a lump beneath the bark (McCaw 1983). In this study, an assessment of pre- and post-experimental burn bole damage was made by measuring the area of exposed wood (cm^2) where the extent of injury was visible, or by lightly tapping the outer bark where the bark had ruptured or was lumpy. Tapping the bark covering the cambial injuries produced a 'hollow' sound. (The latter technique was particularly useful when assessing damage 12 months after burning, as by this time the bark had not always sloughed away to expose the injury). Tapping the bark was preferred to tearing the bark away and exposing the wound. After calibrating this technique on a number of test trees, a reliable estimate of the extent and area of cambial kill was obtained. The total area of cambial damage on each tree was placed into one of the following categories:

1. <200 cm^2 of cambial kill (light or primary damage).

2. 200-800 cm^2 of cambial kill (moderate or secondary damage).

3. 800-1200 cm^2 of cambial kill (heavy or tertiary damage).

Two other categories were also used:

5. No bole damage.

6. Death of the original stem to ground level.

The distance of logs (>10 cm in diameter) from the base of trees was also measured.

The quantity of fine litter fuel burnt in each quadrat was determined by measuring the depth of the litter (Sneeuwjagt and Peet 1985) before and after burning. This measure was used, with fire rate of spread, to calculate fire intensity (Byram 1959). Fire rate of spread was calculated by timing the progress of flames through each of the 20 m long quadrats. At the same time, visual estimates were made of flame height and flame length.

A line intercept method (van Wagner 1968) was used to calculate the quantity of dead woody material (10 mm in diameter) on the forest floor before and after burning. Immediately prior to burning each plot, three litter samples, each of about 50 g were taken, and their moisture content was determined by oven drying.

Conditions of fuel, weather and fire behaviour are shown in Table 1 below. The plots were burnt under warm, dry conditions over the period January-March, 1980. An on site weather station measured air temperature, relative humidity and wind speed and direction throughout the experiment.

Post-burn assessment of bole damage was carried out in January, 1981; January, 1982; and finally in August, 1984 with techniques outlined above.

TABLE 1: Summary of the fire behaviour, fuel and weather conditions during experimental fires in jarrah forest near Dwellingup, W.A. The Soil Dryness Index (Mount 1972) ranged from 1256-1680.

	Fire rate of spread (m/h)	Flame height (m)	Fine fuel weight consumed (1) (t/ha)	Fine fuel moisture content (3) (% o.d.w.)	Coarse fuel (2) consumed (t/ha)	Air temp (°C)	Relative humidity (%)	Wind speed (4) (km/h)	Intensity (kW/m)	Scorch height (5) (m)
Mean	61	2.0	8.8	5.8	34	28	37	3.8	410	15.1
Minimum	12	0.4	4.2	4.0	0	21	20	2.2	52	8.0
Maximum	221	6.8	14.0	10.1	96	37	64	5.9	1497	25.0
Standard error	17	0.4	0.5	0.4		0.7	2.8	0.2	49	1.3

(1) Weight of leaf litter and dead material <10 mm in diameter.
(2) Coarse fuel is woody ground fuels (logs) ≥10 mm in diameter.
(3) % Oven dry weight and dried at 105°C.
(4) In the forest and at 1.5 m above the forest floor.
(5) Height to which leaves were killed but not consumed by fire. Maximum height of tree canopy was 25 m.

Data Analysis

Each quadrat was allocated a fire intensity class as follows (with the number of quadrats in brackets):

1.	50 - 150 kW/m	(24)	
2.	151 - 350 kW/m	(43)	low intensity
3.	351 - 600 kW/m	(38)	
4.	601 - 1000 kw/m	(39)	moderate intensity
5.	1001 - 1500 kW/m	(19)	
	TOTAL	163	

Fire damage data were analysed by stages in an attempt to isolate damage severity and causes. Initially, all trees were pooled and then sorted into stem diameter classes. The extent of bole damage before the experiment was then compared with damage 4.5 years after experimental burning. Similar comparison was also made, but for trees which were single stemmed (i.e. not coppice regrowth) and away from logs (>2 m away). In this instance, jarrah and marri were examined separately. A comparison of bole damage was then made between all trees which were near logs (<1 m and 1-2 m away) and all trees away from logs (>2 m away).

Pre-burn and post-burn levels of bole damage were compared for single-stemmed trees which were not damaged prior to the study, and which were further than 2 m from the nearest log.

Finally, damage levels in each stem diameter class and in each fire intensity class were examined in an attempt to determine whether or not fire intensity was an adequate measure of a fire's potential to damage standing trees.

RESULTS

Pre-burn damage

Low and moderate intensity summer fires caused a considerable increase in the level of bole damage to trees <20 cm dbhob (Figs 1 and 2). Almost all stems <5 cm dbhob were killed to ground level, so are not included in Figures 1 and 2. The level of pre-burn damage was high: 20-25 per cent of all stems in the smaller diameter classes displayed some degree of bole damage. The proportion of pre-burn damage was higher for the larger trees (Fig. 1). In the 80-100 cm class, only 26 per cent of all trees were undamaged prior to the experimental burns. A high proportion (64 per cent) of trees in this diameter class had been severely fire damaged (fire scarred) prior to this study (Fig. 1).

Of a total of 664 trees sampled, 550 were jarrah and 114 were marri (Fig. 3). Of the total, 67 trees were coppice stems growing off stumps. Most of these were jarrah.

Post experimental burn damage

Fire-caused bole damage to single-stemmed jarrah trees not affected by burning log material is shown in Figure 4. The full extent of bole damage was not apparent until measurements were made two years after the fires. When the final assessment was made, 4.5 years after the fires, the level of damage (including death of stems to ground level) had increased from the pre-burn assessment level by 42 per cent for trees in the 5-20 cm class, by 29 per cent in the 20-35 cm class and by 8 per cent in the 35-50 cm class. Trees larger than 50 cm showed little or no increase in numbers of stems with damage.

The proportion of undamaged jarrah trees in the 5-20 cm class fell from 80 per cent prior to the experimental fires to 21 per cent measured 4.5

FIGURE 1
Percentage of trees (jarrah and marri) and level of fire-caused bole damage before the experimental burns and by dbhob class.

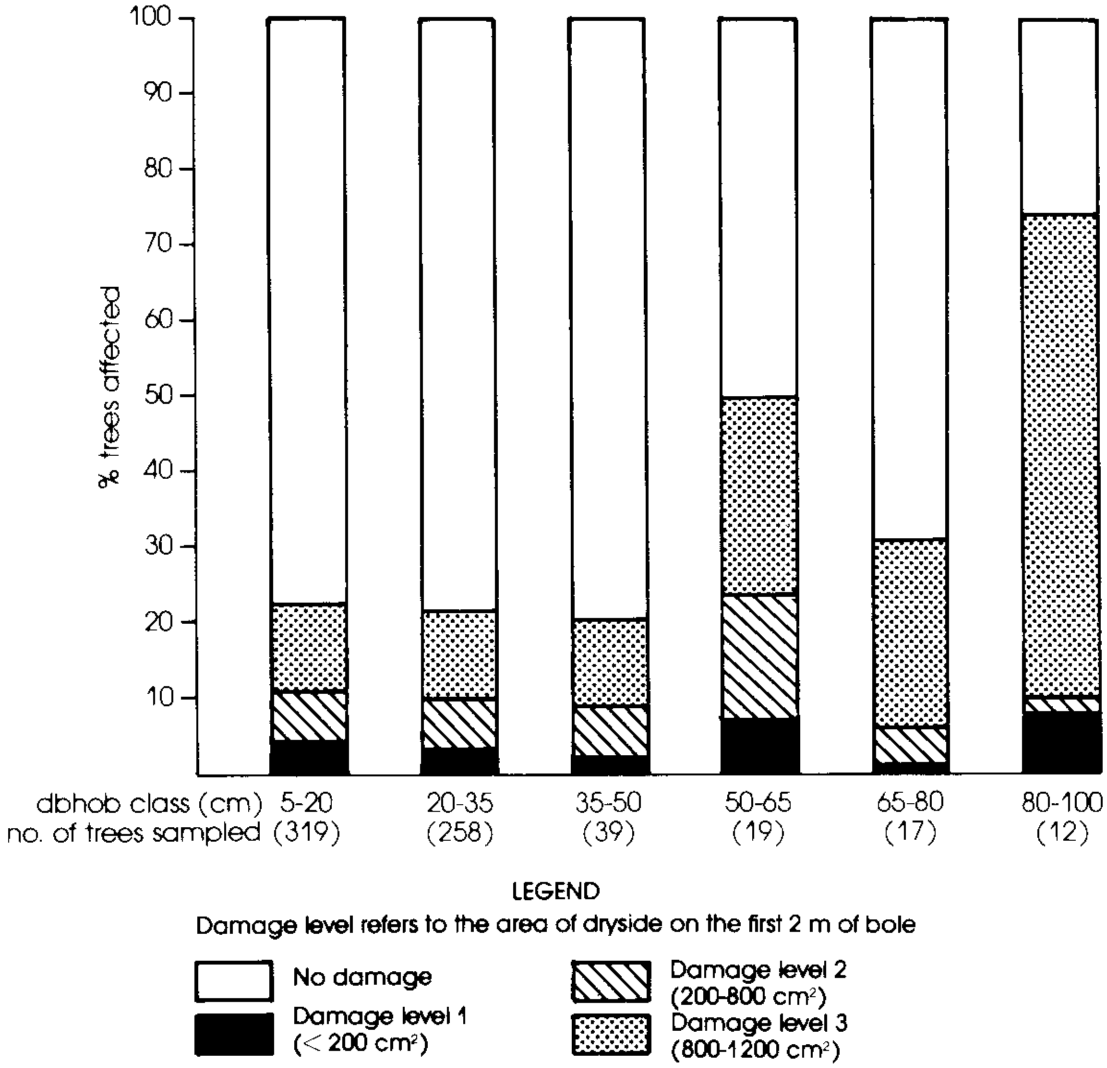


FIGURE 2
Level of fire-caused bole damage to all sample trees 4½ years after experimental summer burns.

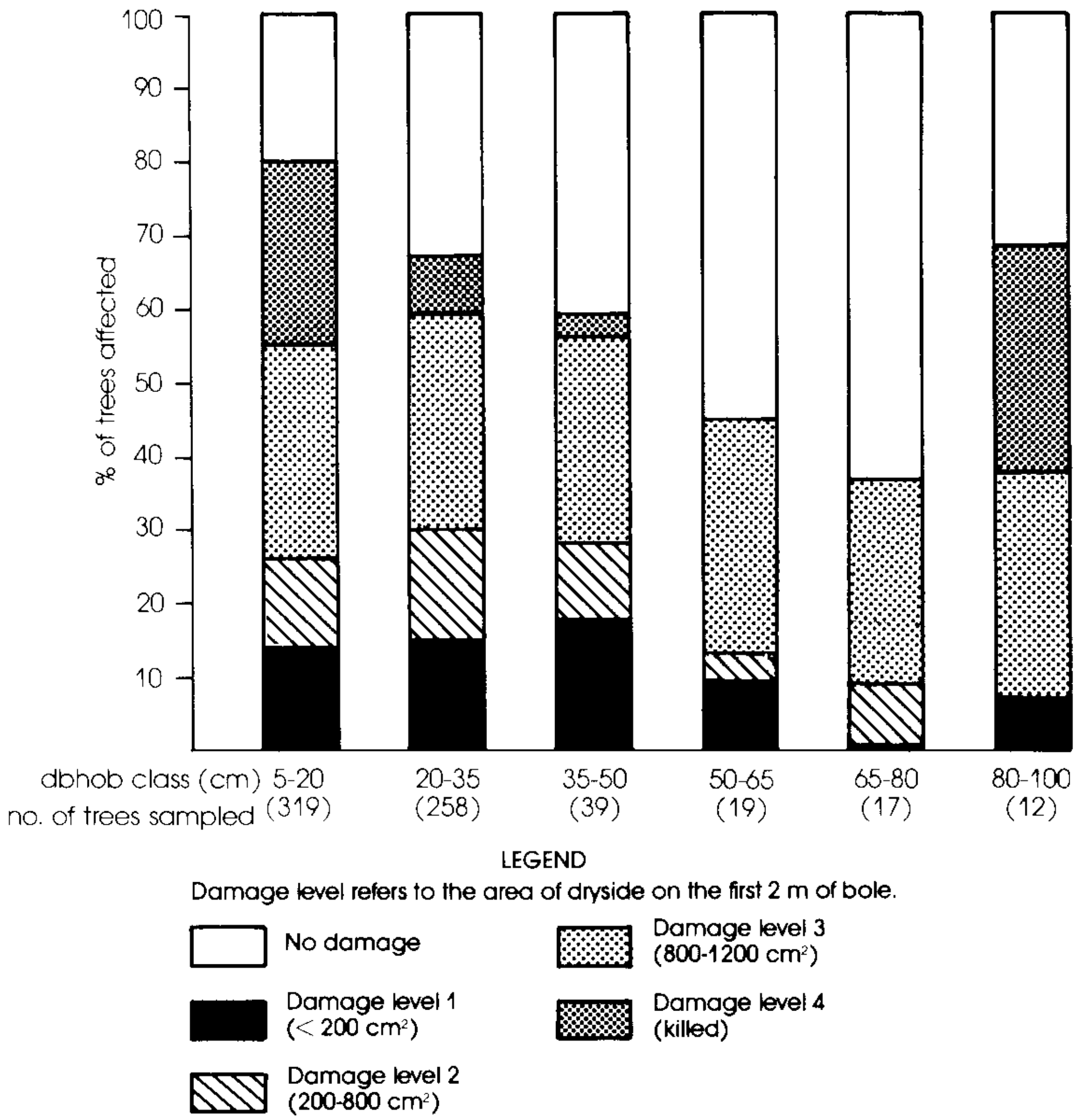


FIGURE 3
Stem size-class frequency distribution for jarrah (E. marginata) and marri (E. calophylla) studied at Young Block.

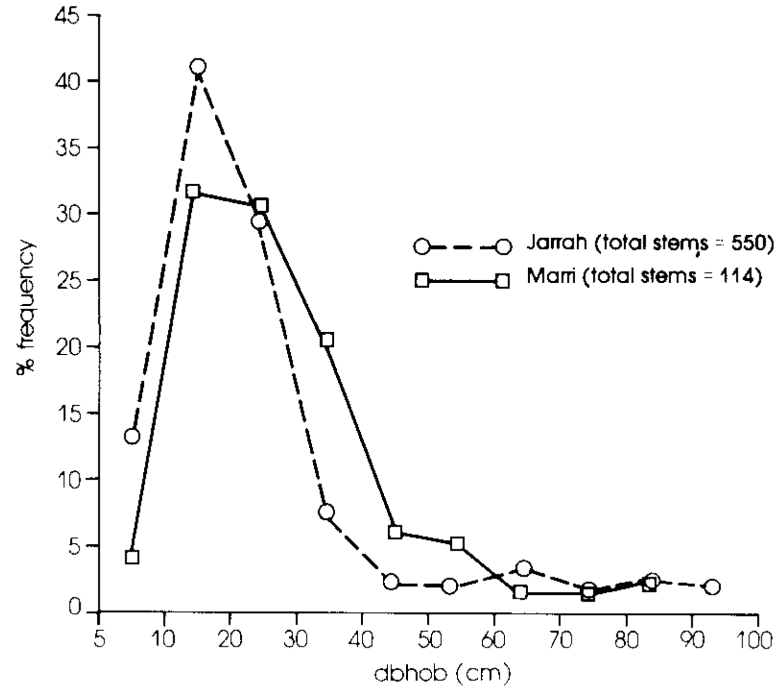
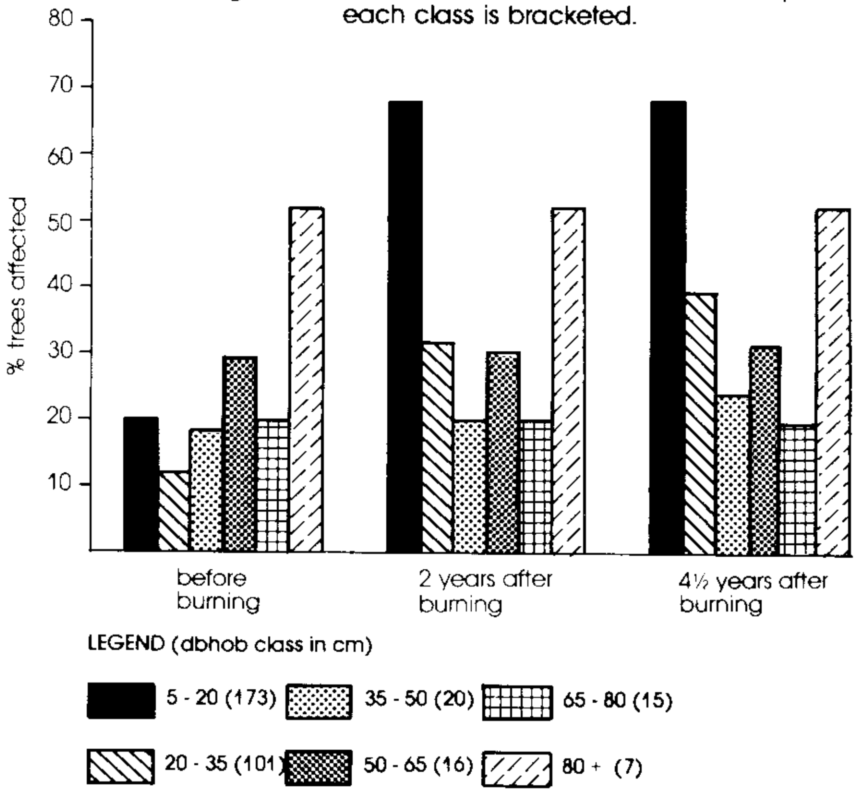


FIGURE 4
Total fire-caused bole damage to single-stemmed jarrah trees which were further than 2 m from smouldering logs. The number of trees damaged in each diameter size class is expressed as a percentage of all trees in that class. Number of trees sampled in each class is bracketed.



years after the fires (Fig. 5). Damage to marri trees in this size class was similar to jarrah. In the 20-35 cm class, the proportion of undamaged jarrah trees fell from 85 per cent to 50 per cent, and for marri from 85 per cent to 14 per cent. Larger jarrah trees showed only slight bole damage. Damage levels, however, remained high among marri trees, even in the larger diameter classes (Fig. 6).

The level of fire-caused bole damage was considerably lower among those trees which were:

1. single stemmed (i.e. not coppice stem);
2. away from logs;
3. undamaged prior to the study (Fig 7 and 8).

Of a total of 664 trees measured, only 283 (or 43 per cent) met these criteria. Of these, nearly all small diameter trees were extensively damaged, with 46 per cent of jarrah trees in the 5-20 cm class either killed to ground level or severely damaged (area of cambial kill exceeded 800 cm^2). Almost all trees killed to ground level later coppiced from rootstock.

Damage levels were similar for marri trees in the smallest diameter class. While 18 per cent of jarrah trees in the 20-35 cm class (meeting the above criteria) were killed or severely damaged, the proportion of marri trees damaged in this diameter class was double that for jarrah. A very low proportion (4 per cent) of jarrah trees larger than 35 cm were severely damaged (Fig. 7) but marri trees of similar size were extensively damaged (Fig. 8).

FIGURE 5
Proportion of visibly undamaged jarrah trees by dbhob class, at various intervals since burning. Only single stemmed trees away from logs are included. Number of trees is shown in brackets.

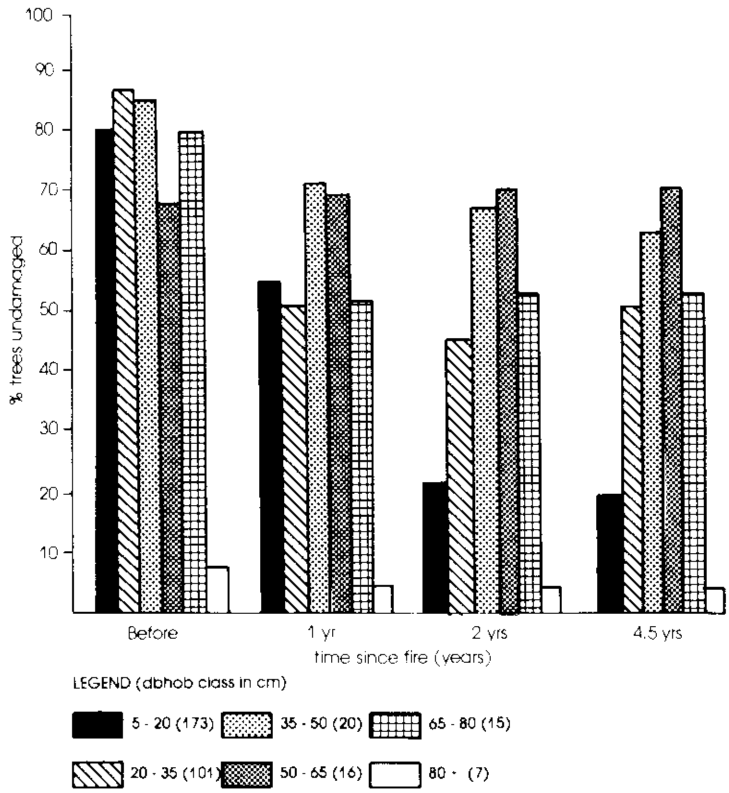


FIGURE 6
Proportion of visibly undamaged marri trees by dbhob class, at various intervals since burning. Only single-stemmed trees away from logs are included. Number of trees is shown in brackets.

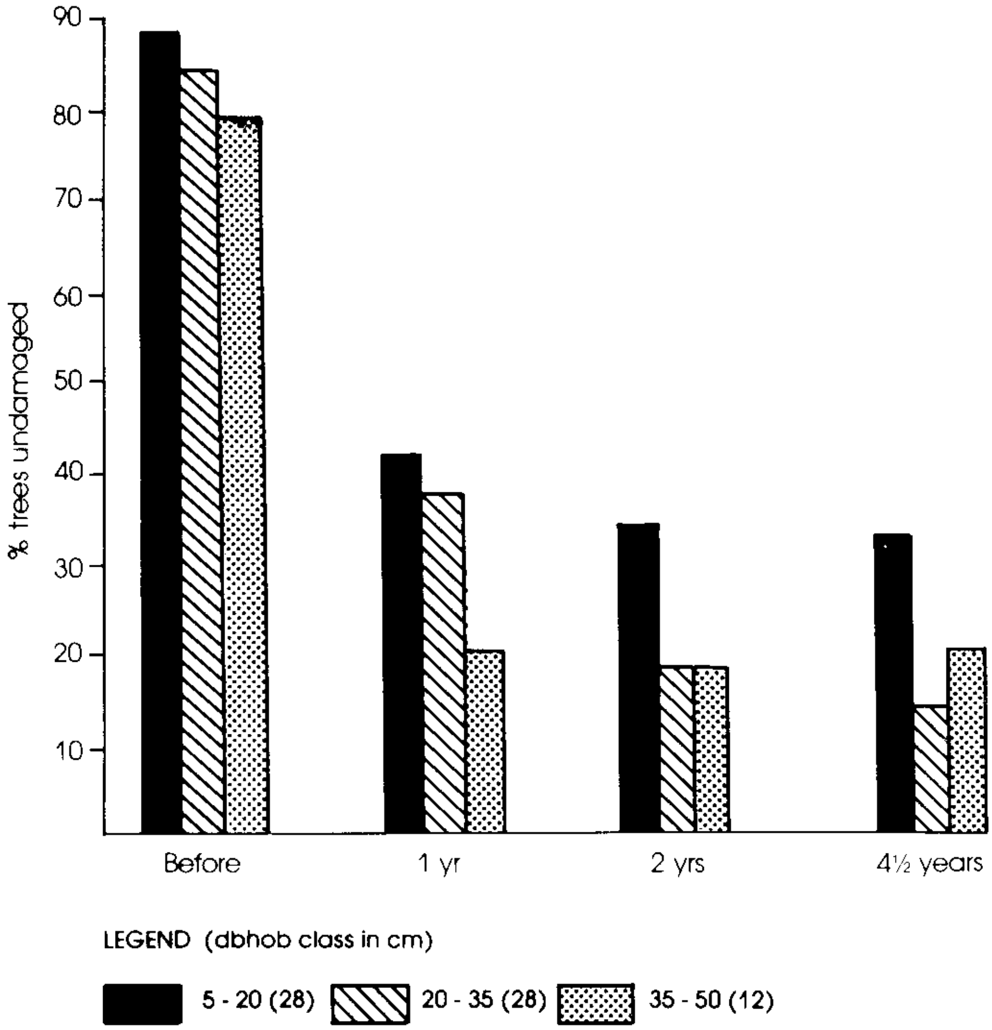


FIGURE 7
Damage levels to single-stemmed jarrah trees which had no bole damage prior to burning and which were further than 2 m from logs. Damage was measured 4½ years after burning.

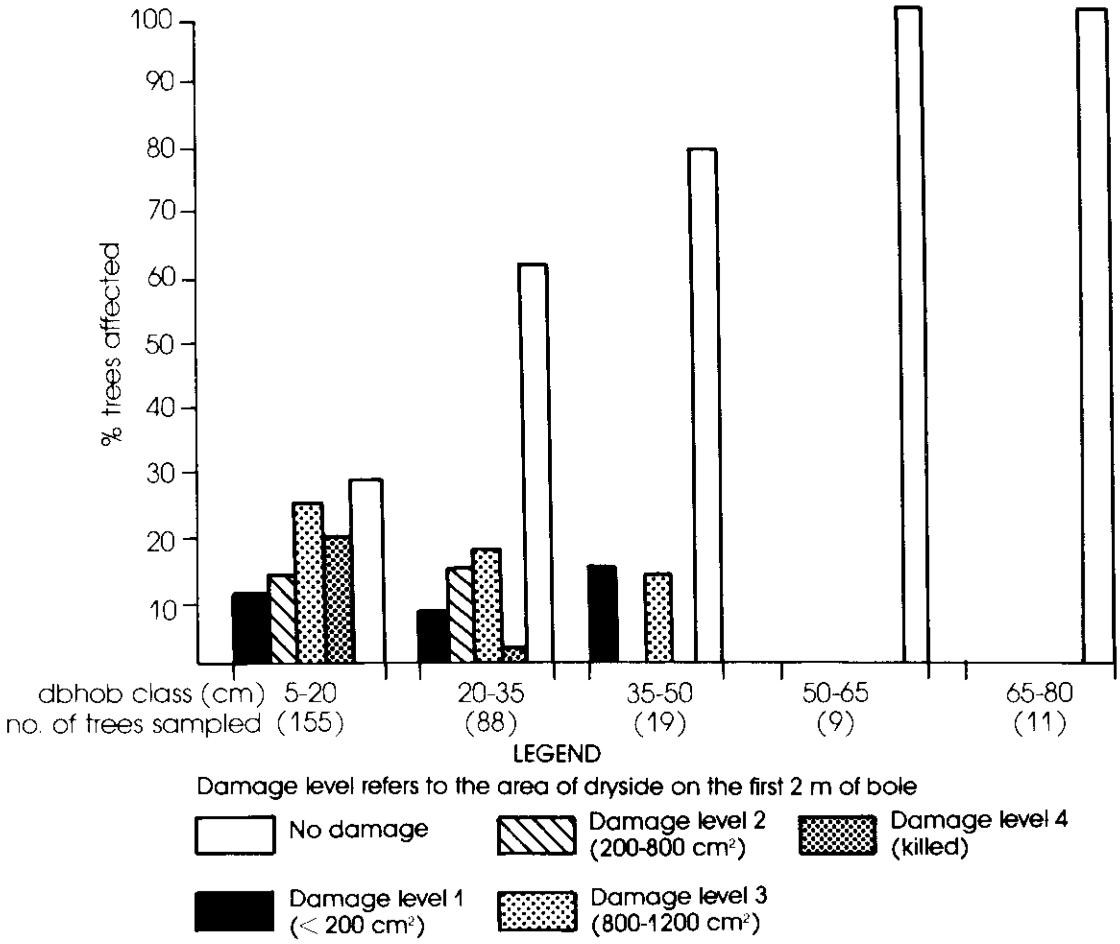
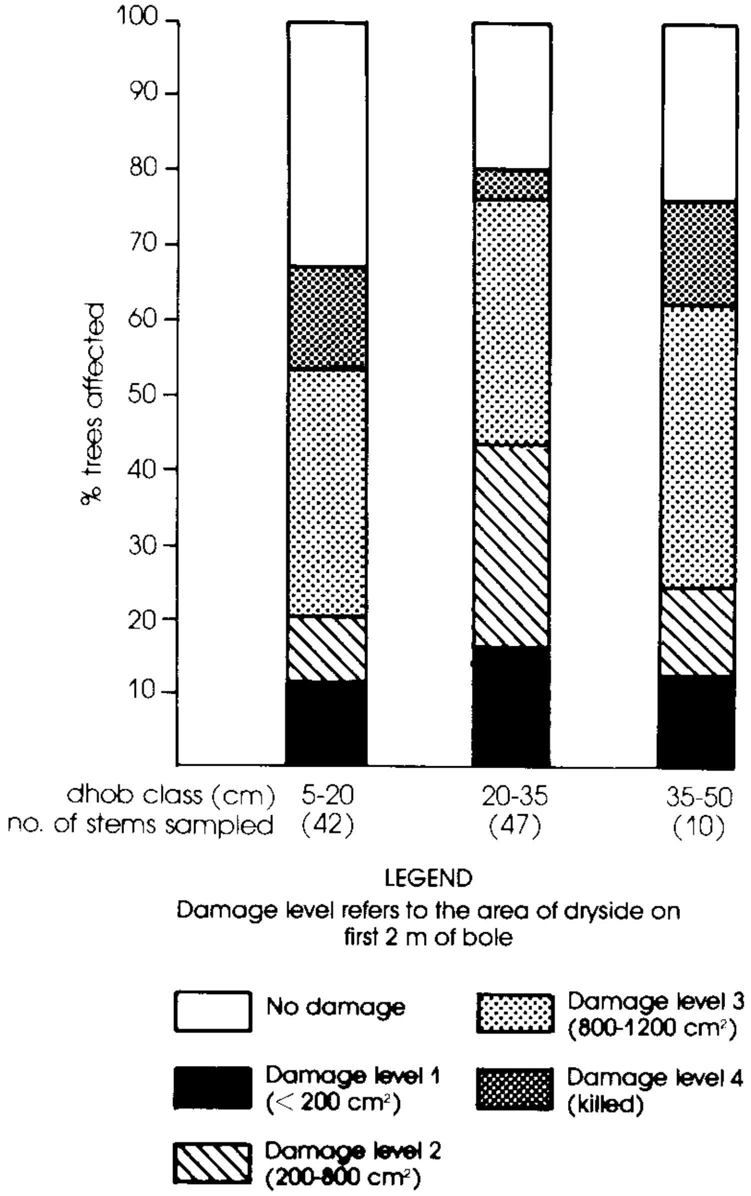


FIGURE 8

Damage levels to single-stemmed marri trees which had no bole damage prior to burning and which were further than 2 m from logs. Damage was measured 4½ years after burning.



Bole damage caused by smouldering logs

A comparison of bole damage to trees near logs and trees away from logs is shown in Table 2. Included in Table 2 are all single-stemmed jarrah and marri trees >5 cm dbhob. Trees less than 1 m from the nearest log showed a higher incidence of damage both before (33 per cent) and 4.5 years after the fires. About 24 per cent of all trees were within 1 m of a log. Almost all (92 per cent) trees less than 1 m from a log, were damaged by the long duration of heating produced by the burning log. The extent to which logs burnt varied, and there was no apparent reason why some logs burnt completely and other logs burnt partially.

Fire intensity and bole damage

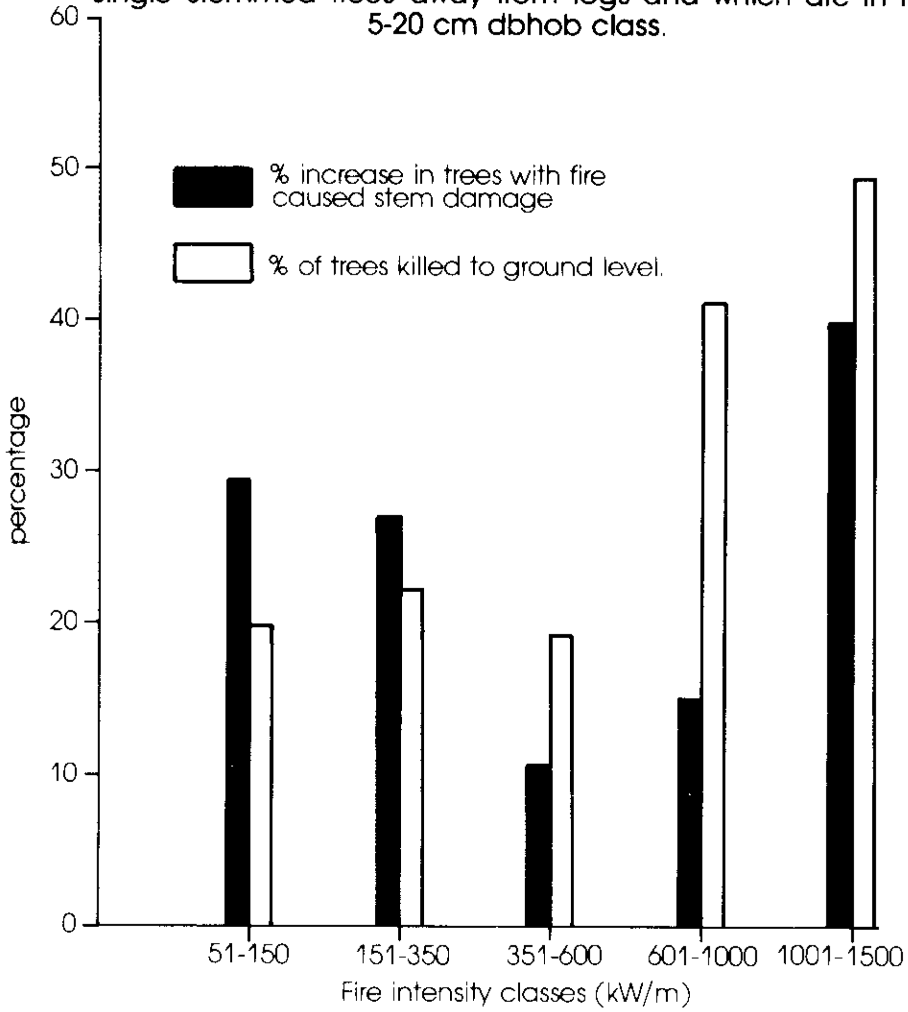
Fire intensity up to 600 kW/m was not a reliable measure of the level or severity of bole damage. When, however, intensity exceeded 600 kW/m there was an increase in the number of stems in the 5-20 cm class killed or severely damaged (area of cambial kill >800 cm^2). The percentage increases in numbers of trees displaying fire caused bole damage and the percentage of trees killed by fires of different intensity are shown in Figure 9. Fires of an intensity exceeding 1 000 kW/m either killed or severely damaged most trees in the 5-20 cm dbhob class.

When fire intensity exceeded 1000 kW/m, then all trees in the small diameter class were either killed to ground level or severely damaged. Increased fire intensity had little affect on the level of bole damage to jarrah trees larger than 20 cm dbhob over the narrow range of intensities studied here. The number of quadrats in which fire intensity exceeded 600 kW/m was too low to allow an assessment of damage to trees larger than 35 cm.

TABLE 2: Single-stemmed jarrah trees showing any signs of damage by burning logs. Damage was measured before and 4.5 years after low and moderate intensity summer burns (up to 1500 kW/m).

	Single stemmed trees >2 m from logs		Single stemmed trees 1-2 m from logs		Single stemmed trees less than 1 m from logs	
	Undamaged	Damaged	Undamaged	Damaged	Undamaged	Damaged
Before burning	314 (78%)	88 (22%)	19 (82%)	4 (18%)	107 (66%)	56 (33%)
4.5 years after burning	250 (62%)	152 (38%)	13 (56%)	10 (43%)	14 (8%)	149 (92%)

FIGURE 9
Percent increase in trees with fire caused stem damage and mortality levels following different intensity fires. Data are for all single stemmed trees away from logs and which are in the 5-20 cm dbhob class.

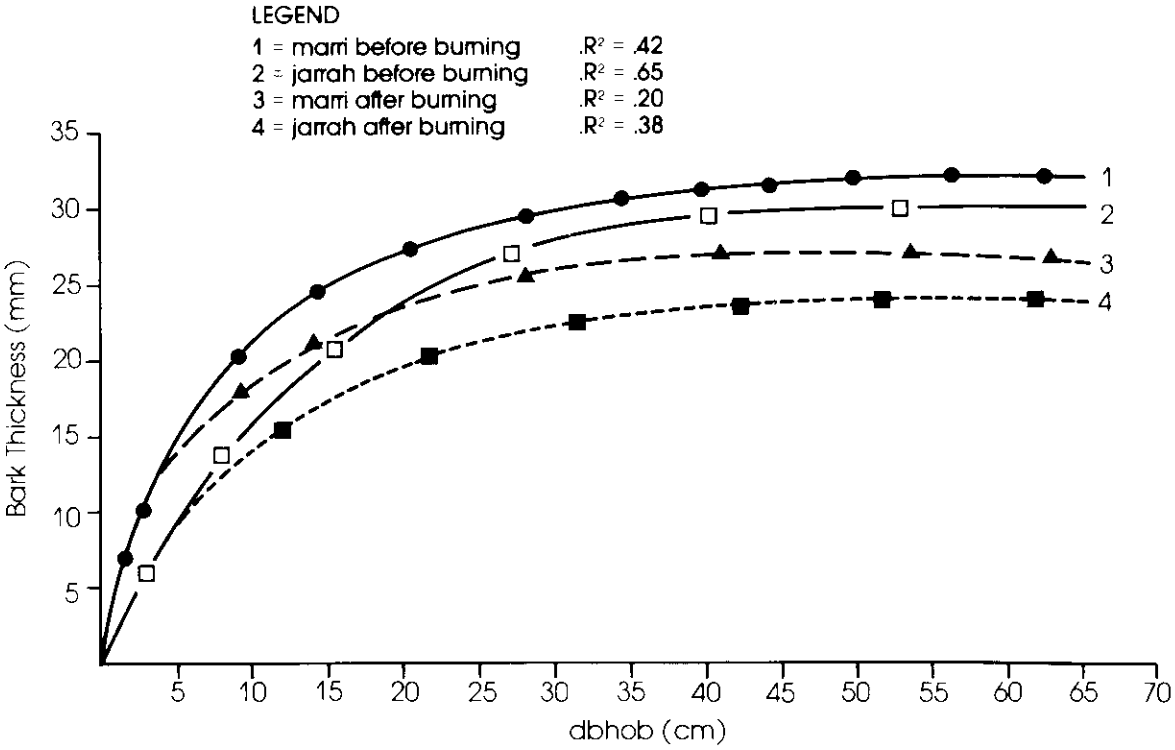


Bark thickness

Bark thickness is widely recognized as being an important factor affecting trees' resistance to fire (Spalt and Reifsynder 1961; Hare 1961). The thickness of bark on marri and jarrah trees initially increased with increasing stem diameter, and became more or less constant when stem diameter exceeded about 35 cm dbhob (Fig. 10). While both species are rough barked, the bark structure and texture differs. Jarrah has a rough stringy bark and marri has a short-fibred, tessellated, and typical bloodwood type bark. Before burning small marri trees (<20 cm dbhob) had thicker bark than equivalent size jarrah trees (Fig. 10). A considerable amount of bark was burnt off, with jarrah losing more than marri.

The depth of bark lost by burning was highly variable and was up to 10 mm in some cases. Burning strips of jarrah bark were carried aloft in the convection column, but marri bark appeared to mostly burn on the tree.

FIGURE 10
Bark thickness and dbhob relationship for marri and jarrah before and after experimental burns.



DISCUSSION

The incidence and severity of fire damage to boles was attributed to at least seven factors, acting independently or together. These were:

1. Stem diameter
2. Bark thickness
3. Tree species
4. Tree growth habit (single, original stem, or coppice off old stump)
5. Proximity to heavy fuels (logs)
6. Extent of past bole damage
7. Fire intensity (hence the weight of fuel burnt and factors affecting the rate of fire spread).

The boles of small diameter (<5 cm) trees of both species were killed or severely damaged following low to moderate intensity summer fires. Bark thickness was directly proportional to tree diameter (until diameter exceeded 35 cm). Vines (1968) and others have also found that fire resistance depends largely on bark thickness. Bark is an excellent insulator of heat (Martin 1963) so the amount of heat conducted across the bark from the flames to the cambial zone would decrease with increasing bark thickness. Tree diameter may also be important, not only because it relates to bark thickness, but also in the ability of the inner woody core of larger diameter trees to absorb and conduct heat. Wood has a higher thermal conductivity than bark (Martin 1963), so heat can be dissipated away from the cambial zone more effectively by larger diameter trees.

Bark thickness, bark moisture content, and the duration of heat input at the bark surface will determine the amount of heat received at the cambial zone (Vines 1968). Marri trees showed considerably more bole damage than jarrah, even though both species had similar bark thickness. Marri bark, however, is often deeply fissured and the minimum bark depth around the bole may be considerably less than the measured average. The technique used to measure bark depth was unsuitable for measuring the depth of bark in the narrow fissures. Under these dry conditions, there was a tendency for marri bark to catch alight and to combust on the tree. It is also likely that the more visually obvious response to cambial injury by marri (which included prolific exudation of kino and rupturing of the bark) caused bias towards over-estimating the extent of the injury. Of the marri trees in the 35-50 cm class which were single stemmed, away from logs and without historical damage 24 per cent were not damaged. By contrast, 80 per cent of jarrah trees in the same category were not damaged.

Species and stem diameter aside, other factors predisposing trees to bole injury were the tree's growth habit and the proximity of heavy, woody fuels (logs and stumps). Trees which were damaged prior to this study were further damaged by these fires. Previous injuries were extended when the dry wood at the old injury site ignited and continued to burn for up to several hours after the main fire had passed. Old trees with large hollowbutts resulting from past fires, often broke off at the base. Coppice stems growing off old dry stumps were severely damaged or killed as stumps ignited and burnt for long periods (Plate 1). Under these dry conditions, almost all stumps, logs and exposed, dead woody material on living stems (drysides) ignited readily. Normally, these fuels do not ignite during fuel reduction burns carried out in spring or late autumn when fuels are moist.

Plate 1: Typical jarrah coppice. The old dry stump readily ignites during summer fires and causes severe damage to coppice stems.

The distance of logs from tree boles had a marked effect on stem damage (Plate 2). Logs at the base of trees are often the cause of severe fire scarring and eventually hollowbutting (Jacobs 1955; Vines 1968). The extent to which a burning log caused damage was found to be dependent on its distance from the tree bole (Table 2). Although not measured here, log size and, probably more importantly, the quantity of log material burnt, are likely to affect the level of damage. When trees were more than 2 m from even large logs, then little or no damage was sustained.

The extent of previous injuries, the growth habit of stems and the quantity and location of log material on the forest floor critically affected the level of bole damage caused by fire. These factors can be controlled by short and long term management practices. Of the 664 trees examined, 304 trees were in situations predisposing them to bole damage, even following low intensity summer fires. A similar hypothetical forest of single stemmed trees (no coppice), without previous bole injuries, and with fewer logs lying on the forest floor may have incurred about 50 per cent less bole damage than the forest studied here (Plate 3).

Plate 2: Stem damage to jarrah caused by a log burning nearby. Subsequent fires will extend this injury until the tree is 'hollow butted'.

Plate 3: This single stemmed jarrah tree is clear of logs and heavy fuels and has no previous bole injury. Even after a moderate intensity (1200 kW/M) summer fire, this tree shows no signs of bole injury.

The effect of fire intensity on the level of bole damage was not clearly defined by this study. The results, however, do show an increase in stem mortality and bole damage when fire intensity exceeded 600 kW/m. This was most obvious in the smaller stem diameter classes.

Knight (1981) has shown the amount of heat energy absorbed by a billy-can calorimeter near ground level to be a function of the quantity of fuel consumed and not related to fire intensity *per se.* Burrows (1985) found a positive correlation between fire intensity and the death rate in populations of *Banksia grandis*, and suggested that both the quantity of fuel burnt and the rate of heat release were important factors. Fire intensity is a function of the quantity of fuel burnt and fire rate of spread (Byram 1959). Fire rate of spread is a function of the quantity of fuel available for burning, and other fuel, weather and topographical conditions. The single most important factor, then, is the quantity of fuel which is burnt. Fires which burn under warm, dry conditions burn a greater quantity of the total fuel complex (Byram 1959) and generally spread faster than fires burning under cool, moist conditions (McArthur 1967). When fuels and soils are dry, additional fuel types are burnt, including living vegetation, bark on standing trees, and larger, woody material on the forest floor. It is not normal for these fuels to burn under moist conditions in spring.

The usefulness of fire intensity to characterize the killing power and bole damage potential of fires could not be fully determined because the intensity range was narrow. Forest fires can generate up to 60 000 kW/m under extreme conditions (Cheney 1981). Such high intensity wildfires have caused extreme bole and crown damage in the jarrah forest (Peet and Williamson 1968).

Although not measured here, windspeed in the forest during a fire is also likely to affect the level of bole damage, not only by its affect on increasing spread rate (hence intensity), but also on the pronounced 'chimney' effect. Flames were observed to persist on the leeward side of trees and bole damage (except for that caused by burning logs) was mostly found here. Laboratory studies by Gill (1974) showed that the duration and length of flames on the leeward side of cylinders was affected by windspeed. The height, length and depth of the ground fire flames strongly affected the duration and length of flames on the leeward side of tree boles in this study. Flame structure integrates many factors of fuel, weather and topography and relates well to fire intensity (Byram 1959).

The level of timber loss as a result of these experimental fires would be exceedingly difficult to forecast. McCaw (1983) reported a significant positive correlation between the extent of fire-caused drysiding and the extent of subsequent timber degrade resulting from fungal and insect activity. He found a high incidence of fungal and termite attack in jarrah trees damaged by wildfire and suggested that the sawn recovery from fire-damaged trees would be influenced by the diameter of the tree at time of injury. Many small (5-20 cm) trees were severely damaged by fire in this study.

Secondary degrade through decay and insect activity is likely to increase the incidence of timber degrade and volume of timber loss in the centre of logs when these trees reach maturity in 50-70 years. Damage to small trees also predisposes these trees to further damage by subsequent fires. A considerable amount of timber can be lost as a result of repeated fire-caused lesion extension of a small (<200 cm^2) fire-caused injury to a young tree. Timber degrade due to gum veining is likely to increase following low-to-moderate intensity fires, particularly in marri.

CONCLUSION

Low and moderate intensity summer fires caused a considerable increase in the level of bole damage to both jarrah and marri trees. Trees most prone to bole injury were trees with a dbhob <20 cm, trees with old injuries, trees near logs and trees growing off stumps (coppice). The incidence and severity of bole damage was greatest in marri. Trees near logs were damaged, even when fire intensity was low (<350 kW/m). Under warm, dry summer conditions, considerably more fuel becomes available for burning and the quantity of fuel burnt was probably the single most important factor affecting the level of bole damage.

While not immediately quantifiable, there will undoubtedly be a significant loss of timber yield from forest fires either deliberately lit or unplanned, under dry conditions (fuel moisture content ≤8 per cent and S.D.I. ≤1200 Mounts (1972)). This loss may not be fully realized for many years until the trees are of millable size. Given this, foresters must carefully consider whether to forfeit some timber producing potential for equally unquantifiable gains in disease control or habitat diversity, in timber production forest. Damage levels, hence timber losses, will be dramatically reduced in mature forests (most trees >20 cm dbhob) of single-stemmed trees with little or no previous bole damage and which do not contain heavy ground fuels or logs. These factors can be controlled at a cost by forest management. Young re-growth forests should only be burnt by low intensity fires when most trees have reached a diameter of at least 10 cm and are clear of logs and other heavy fuels.

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