DRAFT AUGUST 1993

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Abstract

Although there is fossil evidence of fires in the jarrah (*Eucalyptus marginata*) forest and numerous historical references to the widespread and frequent use of fire by Aborigines in the south-west of Western Australia, there is little definitive evidence of the frequency of fire prior to European settlement. This research attempted to compare fire frequency before and after European settlement by studying stem sections from large, old jarrah trees for fire injury and by comparing this with the documented historical evidence.

The resilience of jarrah to injury by fire and the limitations of ring counting as an ageing technique, prevented an accurate and definitive reconstruction of the fire frequency prior to European settlement. However, the chronological pattern of fire-caused bole injury supports historical descriptions of fire history and can be explained by broad eras of human activity in the forest. Prior to European settlement, the incidence of fire injury was very low with the average interval between injurious fires being about 81 years. Following European settlement, the

frequency of fire injuries increased and the average interval between injuries decreased to about 17 years.

Our interpretation of the temporal pattern of stem injury is that the pre-European fire regime in the drier jarrah forest and the forest margin was probably one of frequent, therefore non-injurious, low intensity fires set mainly in summer and autumn, with occasional long intervals between fires ending in high intensity, injurious fires. The increase in fire injury to trees immediately following European settlement and up to the 1950s is probably due to the higher frequency of intense wildfires associated with increased fuel levels resulting from logging and long periods of fire exclusion.

1. Introduction

There is considerable fossil evidence of the long association between climate, vegetation and fire on the Australian continent (e.g., Lundelius 1960, Merrilees 1968, Kemp 1981 and Singh *et al.* 1981). Long periods of warm, dry weather and abundant flammable vegetation have ensured that fire is a major natural disturbance factor which has influenced the development and maintenance of forest ecosystems in the south-west of Western Australia (see Gardner 1957, Christensen and Kimber 1975, Gill 1975, Gill *et al.* (eds.) 1981).

Prior to European settlement, Aborigines and lightning were the main causes of forest fires. Hallam (1975, 1985) provides ample evidence of the extensive use of fire by Aborigines in south-west forests in her detailed review and summary of documents and journals of early explorers and settlers. She found numerous references to the firing of the vegetation by Aborigines for a variety of reasons. Nicholson (1981) and Pyne (1991) also provide descriptive accounts of the widespread Aboriginal practice of burning the vegetation. Other authors have speculated about the traditional use of fire by Aborigines and most agree that much of the jarrah forest was burnt frequently by low intensity fires (e.g., Wallace 1966, Abbott and Loneragan 1983, Abbott and Van Heurck 1988). However, there is no quantitative evidence of the frequency of fire prior to European settlement, which occurred first at Albany in 1827 and on the Swan River (near Perth) in 1829. Within 40 years of settlement, Aborigines and their culture had virtually been displaced (Hammond 1933, Berndt and Berndt 1964, Hallam 1975, Frost 1979).

Today, prescribed fire is applied to jarrah (*Eucalyptus marginata*) forests for many purposes (see Shea *et al.* 1981, Underwood and Christensen 1981, McCaw and Burrows 1989). Since its introduction in the 1960s, fuel reduction burning on a 5-10 year cycle with low intensity fires set in spring or autumn has been very effective at reducing the wildfire threat to human life and property but has been controversial (Underwood *et al.* 1985). Opponents claim that such a regime is "unnatural" and is harming the forest ecosystem, although there is no scientific evidence of this (Christensen and Abbott 1989). Knowledge of the fire regime prior to European settlement would assist fire ecologists and forest fire managers in interpreting fire ecology and with developing appropriate fire management strategies.

Trees are among the oldest surviving individual organisms from the pre-European settlement era, and are a potential source of information about the pre-historical frequency of fire. This study aimed to compare forest fire frequency before and after European settlement by ageing fire injuries embedded in stem sections taken from stumps of large, old jarrah trees and by comparing this with the largely descriptive historical evidence of fire.

2. Methods

Dendrochronology has been a useful technique for reconstructing the history of climate, of disturbances such as fire, frost and insect defoliation, and of forest dynamics (e.g., Studhalter 1955, Stokes and Smiley 1968, Koerber and Wickman 1970, Fritts 1976, Dunwiddie and LaMarche 1980a, Taylor 1981, Bowman and Kirkpatrick 1984 and Means 1989). Dendrochronology as a method for estimating the age of Australian forest trees has been reviewed by Ogden (1981), and recently by Banks (1990a). The growth rings of many Australian eucalypts are indistinct and not always annual, but where the climate is such that trees experience a regular and defined annual growing season, eucalypts (and other species) tend to produce clear annual growth rings (Ogden 1978, Mucha 1979, Dunwiddie and LaMarche 1980b, Ogden 1981, Banks 1982, Rayner 1992).

The jarrah forest region experiences a strong Mediterranean-type climate, with warm dry summers and cool wet winters, limiting tree stem growth to a single growing season each year. Dunwiddie and LaMarche (1980b) reported that ring counting and cross dating of *Callitris* sampled near Perth was relatively straightforward because of the strong seasonal climate. Rayner (1992) successfully used growth rings to estimate the age of karri (*Eucalyptus diversicolor*), a forest tree species endemic to the south-west of Western Australia. Stem growth of jarrah is determined by seasonal soil moisture (Abbott and Loneragan 1986) and commences with the opening rains in autumn. The soil is relatively dry so growth is slow at first, then increases with increasing soil moisture over the cool (but not freezing) winter months and early spring. Growth ceases over the warm dry summer months. The slow growth at the end of autumn and beginning of winter produces a narrow band of dark wood, followed by a wider band of faster grown lighter coloured wood.

Jarrah is a rough-barked eucalypt which is very tolerant of fire. The susceptibility of tree boles to fire-caused injury is a function of fuel and fire behaviour characteristics and of tree size (e.g., Vines 1960, Hare 1961, Martin 1963, McArthur 1968, Gill 1974 and Burrows 1987). Fire intensity (Byram 1959) is a function of the quantity of fine fuel burnt, which is proportional to time since last fire and fire rate of spread. Long intervals between fires normally result in heavy fuel accumulation and intense fires when the forest eventually burns. The type of fuel burnt and its dryness will also influence the extent of bole injury. Fine fuels such as leaves and twigs which accumulate on the forest floor burn away quickly whereas large fuel particles such as logs and limbs, burn slowly. Where large fuels are near trees, or when the fine fuel load is high, fire-caused bole injury is likely to be severe, especially under warm, dry conditions (Burrows 1987).

Young and very small jarrah (< 10 cm diameter at breast height) with thin juvenile bark may be killed to ground level by low intensity (<500 kw m^{-1}) fire but resprout readily from a subterranean lignotuber. Larger, established trees with thick fibrous bark may be injured by fire but are rarely, if ever, killed (Abbott and Loneragan 1986 and Burrows 1987). Scorched canopies are quickly replaced by epicormic shoots. Injuries resulting from fires in the fine litter bed fuels most often occur on the leeward side of the tree bole (see Gill 1974) and some 0.5 m - 1.5 m above ground level. A strip of cambium 5-10 cm wide and up to 1.5 m long may be killed by moderate and high intensity fire (> about 500 kW m^{-1}), resulting in a "fire scar". Providing the area affected is not extensive, and there is a sufficient interval between intense fires (3-5 years), new occlusion wood will usually encase the damaged site making it invisible externally but obvious when the stem is sectioned. Usually a single fire causes a single injury. Cambial death due to prolonged heating, such as occurs with the slow combustion of a nearby log, may be extensive and may not completely heal.

If the cambium is injured but not killed, then a kino vein may form in the sapwood immediately behind the injured cambium. Kino, an exudate rich in polyphenols, forms veins in many eucalypt species following the formation of a tangential layer of traumatic parenchyma, a process described in detail by other workers (e.g., Day 1959 and Skene 1965). Traumatic parenchyma can form through mechanical injury to the cambium, heating by fire, fungal and insect attack and drought stress. Marri (*Eucalyptus calophylla*), a tree species which sometimes grows in association with jarrah, is highly prone to kino vein formation.

During this study, a total of 107 jarrah tree stem sections were sampled from 14 sites within State forest, covering the climatic range of the main jarrah forest belt (see Figure 1). At each site, a cluster of 5-10 trees were sampled and the combined fire injury record used to determine the likely fire history for that site. Individual tree stems often had more than one encased fire scar, each corresponding to a separate fire. Sample details are contained in Table 1. At each site, cross sections were cut from the largest jarrah stumps of trees recently felled during commercial logging operations. The 10 cm thick sections were cut from the stumps at about 0.5 m above ground as this was above the root buttress and in the fire injury zone. All stumps sampled from a site came from within an area of several hectares. Each section was labelled and returned to the laboratory for analysis.

The known histories of logging and fire were obtained from records held by the Western Australian Department of Conservation and Land Management (CALM) and are summarised in Table 2. Reliable fire records have been maintained at CALM district offices since about 1937. Logging records date from the 1920s.

FIGURE 1, TABLE 1 AND TABLE 2 NEAR HERE

The diameter under bark (dub) and bark thickness of each sample were measured and recorded. Samples were prepared in the laboratory by first planing and then sanding the sections along 4 radii. The clarity of the growth rings was variable but generally good, ranging from distinct bands of light and dark wood, to less distinct rings. Wood defect associated with fungal and insect activity was prevalent on some sections. Pipe, a longitudinal cavity along the growth centre or heart of tree stems (Clarke and Ellis 1989) was found in about 20% of the sample trees. To make allowances for pipe in ageing the samples, it was assumed that the tree growth rate was constant for the period affected by pipe and was the same as the growth rate in surrounding wood. The number of growth rings allowed for pipe was then estimated by measuring the radius of the pipe, which was usually less than 10 cm. Clearly, the fire history over this period could not be determined for trees with centre pipe.

A ring counting technique described by Banks (1982 and 1990b) was used to estimate the age of trees and to date fire injuries. This involved visually counting the growth rings along each of the 4 prepared radii. Tree age (establishment year) was estimated by averaging the counts. All defects were noted and mapped onto a stem section diagram. Defects were categorized as being caused either by fire, insect borers or fungi. The position and size (length and width) of kino veins was also recorded. The cause of all kino vein formation could not be determined with certainty. Fire-caused kino veins were able to be verified only when they could be cross-matched with known fire records or with trees showing obvious fire scars due to complete cambial death. Encased fire-caused cambial injury was distinguished from other forms of defect by the presence of a band of bleached wood immediately behind the killed or injured cambium. This was the sap wood at the time of the fire and with the death or injury of the cambium, was not impregnated with extractives. On very old injuries, this band of bleached wood was often badly decayed or had disintegrated, leaving a cavity. Distinctive occlusion wood was also evident. Old fire injuries had, in most cases, fully occluded and were embedded in the bole. Fire injury and other defects were planed and sanded and the age of each defect was estimated by ring counting.

Marker rings (Banks 1990b) (or "signature years" Ogden 1978, Dunwiddie and LaMarche 1980a) and fire injuries were cross referenced between trees to improve the reliability of dating. It was unusual for all 10 trees sampled from a site to be injured by the same fire, but common to find near-synchronous injuries to more than one tree. When fire injuries to trees from the same site were dated to within 4 years of each other, we assumed that the same fire event caused the injuries and that the discrepancy was due to the imprecision of ring counting. It is unlikely that an area would re-burn with sufficient intensity to injure trees at less than a four year interval and most unlikely that small fires would burn beneath individual trees. The actual date of the fire was fixed from fire records where they were available, or estimated from the mean of the ring counts. In addition, the date of fires determined from ring counting was regressed against the known date of recorded fires to provide an estimate of the accuracy of the ring counting technique (Figure 2). Reliable records of fires in State forest exist for the last 55 years. Prior to this, records are sketchy, with only severe bushfires in settled areas being recorded in local newspapers.

FIGURE 2 NEAR HERE

Data were analysed in relation to four cultural eras based broadly on patterns of human usage of the jarrah forest over the last 390 years or so. Banks (1982 and 1988) found this approach to be useful when interpreting fire history in the Australian alps based on fire scar dating from trees. The four cultural eras identified for the jarrah forest were:

i) Aboriginal era - 1613 to 1855.

Tree ring data extended from about 1613 (based on ring counting) and we have assumed that traditional Aboriginal burning practices had ceased in most of the jarrah forest by about 1855 since the 1847 Bushfires Ordinance provided for "minors and Aborigines to be flogged for lighting fires". This era represented a period of a "natural" fire regime when forest fires were ignited by lightning and by Aborigines.

ii) First European era - 1855 to 1920.

This period was marked by European settlement and the cessation of traditional Aboriginal burning practices. The northern portion of the forest and the western and eastern margins were heavily cut for timber, grazed by domestic stock and cleared for farms, towns, roads and railways (see Wallace 1965, Mills 1989, and Havel 1989). These activities spread into the central and southern portion of the forest towards the end of this era.

iii) Second European era - 1920 to 1965.

This period marks the beginning of organized forest management. Most of the remaining jarrah forest was incorporated as State forest, the sawmilling industry was brought under some form of control and there was an attempt at controlling wildfires. The fire management policy during most of this era was essentially one of fire suppression and fire exclusion with the exception of strategic buffers which were burnt frequently. The gradual introduction of broad area fuel reduction burning commenced in about 1953.

iv) Third European era - 1965 to present.

This is the period of multiple use forest management, of improved timber utilization, and of sophisticated fire management, including aerial fire detection, well equipped and trained fire fighters and broad area fuel reduction burning. Each year, about 200,000 ha (about 12%) of south-west forests are prescribed burnt by low intensity (<350 kW m^{-1}) fire on a 5-10 year cycle to reduce the litter fuel load.

3. Results and Discussion

The age class frequency distribution based on ring counts of jarrah stems sampled from all sites is shown in Figure 3. The oldest tree sampled was estimated to be 377 years (established in about 1613 in Chandler forest) with the mean age being 208 years. The under-bark diameter at 50 cm above ground ranged from 55-166 cm (Table 1). Bark thickness ranged from 15-30 mm.

Ring counting is an estimate of the age of the tree form of the plant and not necessarily the age of the plant. Jarrah has a capacity to persist on the forest floor as a low multi-stemmed bush for up to 40 years before establishing as a single stemmed tree (Abbott and Loneragan 1986). Fire, site conditions and stand dynamics are also likely to influence the production of growth rings, hence the accuracy of ageing trees. These data represent the oldest and largest trees felled during commercial logging operations and not necessarily the oldest trees in the forest. Very old, senescing trees are usually retained as habitat trees, or are badly fire-damaged and unsuitable for milling. Of the total of 107 trees sampled, 87 were established as trees prior to 1855.

Tree age estimates reported by this study are within the range reported for other Eucalypts. The oldest tree examined by Banks (1990) in old growth dry sclerophyll silvertop ash (*Eucalyptus sieberi*) forest in New South Wales was 210 years. By ring counting, Rayner (1992) found that the largest trees in virgin old growth karri forest were less than 350 years old. Tree age estimates based on ring counting and radiocarbon dating (e.g., Wellington *et al.* 1979, Turner 1984) reveal Australian mainland eucalypts to be relatively short lived when compared with Tasmanian tree species such as huon pine (*Dacrydium franklinii*) which have been estimated to be as old as 2,200 years (Ogden 1978).

The approximate date of establishment of the oldest tree sampled at each forest (site), and dates when one or more of the sample trees were injured by fire, are summarised for each forest in Figure 4. The frequency of fires of sufficient intensity to cause bole injury to sample trees is summarised for each forest and by cultural eras in Table 3.

FIGURE 3 AND FIGURE 4 AND TABLE 3 HERE

All sample sites have experienced an increase in the incidence of fire scars to trees since the 1850s. Banks (1982, 1988, 1990b) reported similar patterns for Australian alpine forests and for eucalypt forests in the south-east of New South Wales.

The lower rainfall forests (Dordagup, Centaur and Bell) had been only lightly logged, or, in the case of Dordagup and Bell, were virgin forest prior to cutting in 1990. These forests had the lowest incidences of fire injury. However, the pattern of increased incidence of fire injury since

European settlement is evident. The northern forests (Jarrahdale, Harvey and Collie districts) have a history of selection cutting virtually since European settlement. Generally, forests further south have a more recent history of cutting (Table 2).

The number of fires sufficiently intense to cause injury to jarrah trees is summarised for all forests and by cultural eras in Table 3. The data in Figure 4 and Table 3 show that prior to the 1850s, the interval between moderate to high intensity fires which caused bole injury, varied from 13-166 years. The mean interval between these fires decreased from 81.6 years for the Aboriginal era to 13.4 years for the second European era, increasing to 16.6 in the third, most recent European era.

From about 1937 when reliable fire records were kept, the known fire frequency, based on these records, was 5-15 years (Table 2). However, not all fires since 1937 caused bole injury and, without records, these fires would not have been detected by the stem sectioning technique. A limitation of ring counting as a technique for reconstructing fire history is that only moderate and high intensity fires are likely to injure the trees, thus leaving a permanent mark or defect in the wood. Lower intensity fires ($<1,500$ kW m^{-1}) are unlikely to injure mature jarrah trees >35 cm diameter at breast height over bark (dbhob) (Burrows 1987), so would not necessarily be detected by this procedure. The incidence of fire injury was extremely low during the Aboriginal era, even though many of the sample trees were obviously younger and smaller then, hence more susceptible to fire injury. Jarrah trees are extremely fire resistant. While they may be injured by fire, even young jarrah trees are rarely killed outright by fire.

Therefore, it is unlikely that the trees sampled were the uninjured survivors which may have escaped damage in earlier fires when the trees were young.

Trees sampled from the same area were not all injured by the same fire. Variability in fire intensity and in other factors predisposing trees to fire injury highlights the need for a large sample size. The sample size during this study was limited to some extent by the low number of very large, very old trees felled in a relatively small area during commercial logging operations.

The frequency of fire injury to jarrah trees and the number of trees in the sample is shown by decades and for all forests in Figure 5. The frequency of injury increased dramatically after the Aboriginal era which may be due in part to the concurrent increase in the number of trees in the sample. After about 1860, the sample number remained constant but the frequency of injury increased.

FIGURE 5 HERE

If the jarrah forest region has continued to experience a Mediterranean type climate over the last 400 years, and if the incidence of lightning-caused fires has been more or less constant over this time, then the pattern of fire injury can be attributed to human activity, both Aboriginal and European, and can be interpreted in terms of the four cultural eras described above.

3.2 The Aboriginal era

It is clear that the incidence of fire injury to jarrah trees was very low and that there were long intervals between fire scars, or between moderate and high intensity fires during this era. The mean interval (for all forests) between fire scars (or between moderate and high intensity fires) prior to European settlement was about 81 years, the longest interval being 166 years (Bell forest, Harvey district).

This can be interpreted as meaning either i) there were no fires in the intervening period or ii) there were fires but they were not intense enough to injure the young trees.

A regime of infrequent but intense fires is inconsistent with i) the historical evidence of the use of fire by Aborigines, ii) the incidence of lightning strikes and iii) the Mediterranean-type (fire-prone) climate of south-west Australia. The most plausible explanation is that the fire regime during this era was one of frequent, low intensity fires (<500 kW m^{-1}) with occasional intense fires. The following evidence is presented in support of this.

The jarrah forest region experiences a regular, annual "fire season", a period when fuel moisture and weather conditions are conducive to the start and spread of fire. The duration of the fire season varies across the range of the forest and from year to year, but is normally from about October to April. For example there are, on average, 141 days each year when the forests around Perth are dry enough to burn. The number of days decreases southward, but there are still many "fire days".

Lightning strikes occur somewhere in the forest every year when the forest is dry enough to burn. For example, in a fourteen year period from 1975 to 1989, a total of 274 lightning-caused wildfires were recorded in south-west forests (Underwood 1990).

As described in the introduction to this paper, south-west Aborigines used fire extensively, with the pattern of both season and size of fire varying in accordance with the patterns of Aboriginal social and ecological activity. Hallam (1975) cites many historical accounts of forest fires from October to June, with most fires recorded over the summer months (see Figure 6). For example, she cites from the journal of J.L. Stokes, on board H.M.S. Beagle in November 1840;

"We met a party of natives engaged in burning the bush, which they do in sections every year. The dexterity with which they manage so proverbially a dangerous agent as fire is indeed astonishing."

While fires could have occurred whenever the forest was dry enough to burn, the historical evidence indicates that most fires burnt during the warm, dry summer and early autumn months (Figure 6). If the normal interval between fires was longer than about 5 years in the higher rainfall jarrah forest (> 1,000 mm annum^{-1}) and about 7 years in the lower rainfall forest, then the expected result would have been a higher frequency of intense and injurious fires due to high accumulations of fuel burning under dry conditions. This is not reflected in the fire injury data. In addition, the overwhelming historical evidence compiled by Hallam (1975) led her to the conclusion that the low intensity of the fires must imply a low density of ground litter, and a high frequency of firing, especially in areas most frequented by Aborigines, namely the northern portion of the jarrah forest and the forest margins. Hallam (1975) is of the opinion that the wetter karri (*Eucalyptus diversicolor*) and adjacent wet jarrah forests were less frequented by Aborigines so burnt less frequently.

FIGURE 6 HERE

The fire injury data reported by this study are consistent with all the historical evidence (Hallam 1975, Pyne 1991) and support the speculative fire regime models presented by Abbott and Van Heurck (1988). The very low incidence of fire injury to jarrah was probably as a result of a fire regime of mostly frequent, low intensity fires with an occasional high intensity fires, perhaps once every 80 years or so on average. Fire will not spread if the litter fuel load is less than about 3.0 tonnes per hectare (t ha^{-1}). The rate of post-fire litter fuel accumulation varies throughout the range of the jarrah forest, depending on canopy cover and site productivity (Sneeuwjagt and Peet 1985) but is in the order of 1-2 t ha^{-1} $annum^{-1}$. Therefore, the minimum possible fire interval for most of the high rainfall jarrah forest is about 2-3 years. Fuel accumulation rate in eastern forests where the rainfall and canopy cover is lower is about 0.6-1.5 t ha^{-1}, so the minimum possible fire interval is about 2-5 years.

Prior to European settlement, much of the jarrah forest was most likely maintained as a mosaic of burnt patches varying in size and time since last fire, but with most of the patches being less than 6 years since last fire. Part of this mosaic would have included patches which would have remained unburnt for longer periods with the inevitable intense fires causing injuries to jarrah trees.

3.2. The First European era

During this era there were numerous reports of large forest fires, many deliberately lit by graziers who ran stock in the forest or which were escapes from clearing burns set to establish farmland.

The increase in the incidence of fire injury to trees was most likely due to the increased incidence of intense wildfires. With the cessation of the traditional Aboriginal practice of frequent burning, fires were intense due to the longer interval between fires and the consequent heavy accumulations of fuel. Early logging operations were wasteful and large quantities of debris remained in the forest. These factors, together with the setting of uncontrolled and intense fires by loggers, settlers and graziers, are the likely reasons for the high levels of tree injury recorded during this era.

3.4 The Second European era

In 1918, legislation established the Forests Department. The early European-trained foresters saw fire as a destructive agent and adopted a policy of keeping fire out of most of the forest using a system of strategic buffer burning and fire suppression. This was partially successful in that large areas of forest remained unburnt for 25-40 years.

Fires eventually started in these forests, either by lightning or human activity. During this era there was a spate of large and very intense wildfires which burnt in heavy fuels resulting from long periods of fire exclusion, and from logging debris. Notable wildfires occurred in the 1930s, 1940s, 1950s and the early 1960s (CALM archives, Fire Protection Branch). The severity of these fires is reflected in the dramatic increase in the incidence of fire injury to trees, which was the highest of the four eras. Trees sampled from virgin (unlogged) forests were also injured during this era, indicating that it was not logging debris alone which caused the escalation in the incidence of tree injury, but intense fires resulting from extended fire-free periods and high fuel loadings.

The extent of fire injury during this era did not go unnoticed and in 1938, Stoate and Helms (1938) reported that 30.5% of potential sawlog jarrah trees were damaged by fire. Burrows (1987) found that 70% of large (>80 cm dbhob) jarrah and marri trees in Young State forest near Dwellingup had some external sign of fire injury. The wildfires of 1961 were the most severe recorded over the last 400 years or so based on the incidence of tree injury. The combination of heavy fuels resulting from the long interval between fires, logging debris and severe weather conditions, resulted in substantial injury to trees (Peet and Williamson 1968). For many of the trees sampled during this study, the 1961 wildfires were the most intense ever experienced, with 200-300 year old trees being injured by fire for the first time.

3.5 The Third European era

The most recent period, that of fire management based on good detection and suppression systems and broad area fuel reduction burning on a 5-10 year cycle began to take effect in the mid 1960s. From then to present, the incidence of fire injury has decreased, but is considerably higher than the pre-European era. This can be attributed largely to logging debris which ignites during summer wildfires. Intense summer wildfires burning in 5-10 year old litter fuels also cause some injury to smaller trees. Burrows (1987) reported that moderate intensity summer fires (up to 1,500 kW m^{-1}) burning in 6 year old fuels in intermediate rainfall forest caused considerable bole damage to smaller (< 20 cm dbhob) jarrah and marri. The boles of larger trees were unaffected providing the trees were well away from logging debris and had no previous injury. Fire intensities of up to 10,000 kW m^{-1} have been observed in 6-7 year old fuels under severe weather conditions. These fires caused fire scars to large trees.

While modern logging practices are more efficient at utilising timber and in disposing of debris, residue from early logging operations persists on the forest floor and when it burns during intense summer wildfires, is a major cause of bole injury. It is partly for this reason that low intensity prescribed fires are implemented in spring when coarse woody debris is moist and non-combustible.

4. Conclusion

Re-constructing the fire history of jarrah forests solely by tree ring counting and by studying fire injuries to tree stems has several limitations. Firstly, a paucity of reliable chronological reference points prior to the 1930s means that fire injury dates determined from ring counting can not be cross checked. Secondly, Jarrah trees are well protected by their thick bark against low intensity fires, so fire scars only indicate occurrences of moderate and high intensity fires (injurious fires) or the combustion of a heavy fuel such as a logs, near the base of the tree. Marri is more sensitive to fire (Burrows 1987), with kino veins forming following low intensity fires so may be a better species to study. Finally, the spatial variation of fire occurrence and fire intensity requires that a large number (perhaps 30) of old trees be sampled from a site to obtain reliable estimates of fire injury years for that site. This is difficult to achieve without broad area destructive sampling.

However, stem analysis and tree ring counting used in conjunction with historical evidence, provides insight to the pre-European or "natural" fire regime. The combined evidence supports the hypothesis that, prior to European settlement, most of the jarrah forest was burnt by non-injurious, low intensity fires. Therefore, most of the forest probably carried low fuel quantities, an assumption further supported by historical descriptions of the forest floor. Low fuel quantities can only be maintained by frequent burning, probably at intervals less than about 6 years.

Fires occurred whenever fuels were dry enough to burn, but the period from January to March, coinciding with the hottest, driest time of year and with increased Aboriginal activity in and around forests, was undoubtedly the peak period of fire activity in jarrah forests. We surmise that seasonal and spatial variation in Aboriginal activity would have resulted in an interlocking mosaic of different ages since fire, from recently burnt to long unburnt patches of forest. The scale of this mosaic is important from an ecological viewpoint, but is unknown. Given the high incidence of ignitions and the seasonal rainfall pattern, burnt patches probably varied from a few hectares to several thousand hectares.

Acknowledgements

We thank Western Australian Department of Conservation and Land Management employees at Pemberton, Nannup, Kirup, Harvey, Collie and Jarrahdale for collecting the tree stem sections. We also thank John Banks, Ian Abbott, Rodger Underwood, Chris muller and Russell Smith for valuable comments on earlier drafts.

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Figure 1: Location of fire history study sites within the main jarrah forest belt in the south-west of Western Australia. Site numbers correspond to forest site numbers in Figure 4.

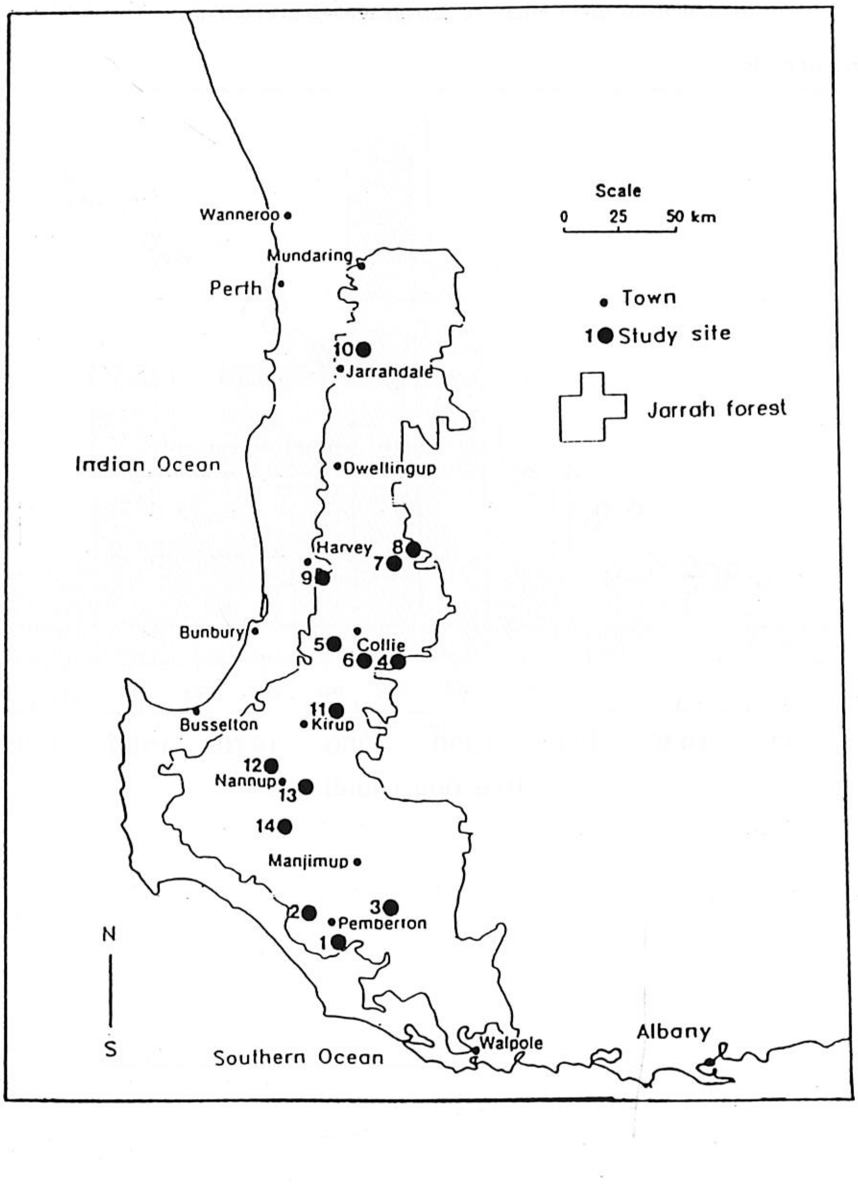

Figure 2: Actual fire year from known records with fire year estimated from stem injury to jarrah and ring counting.

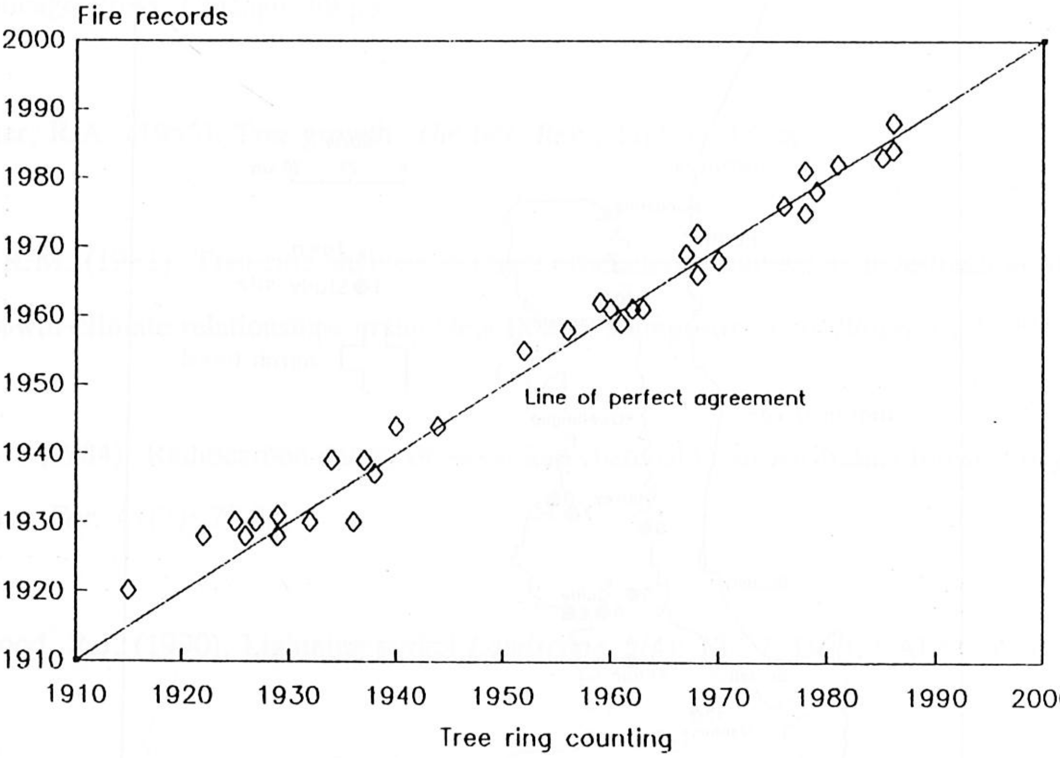

Figure 3: Age class frequency distribution of 107 jarrah trees sampled for fire injury analysis.

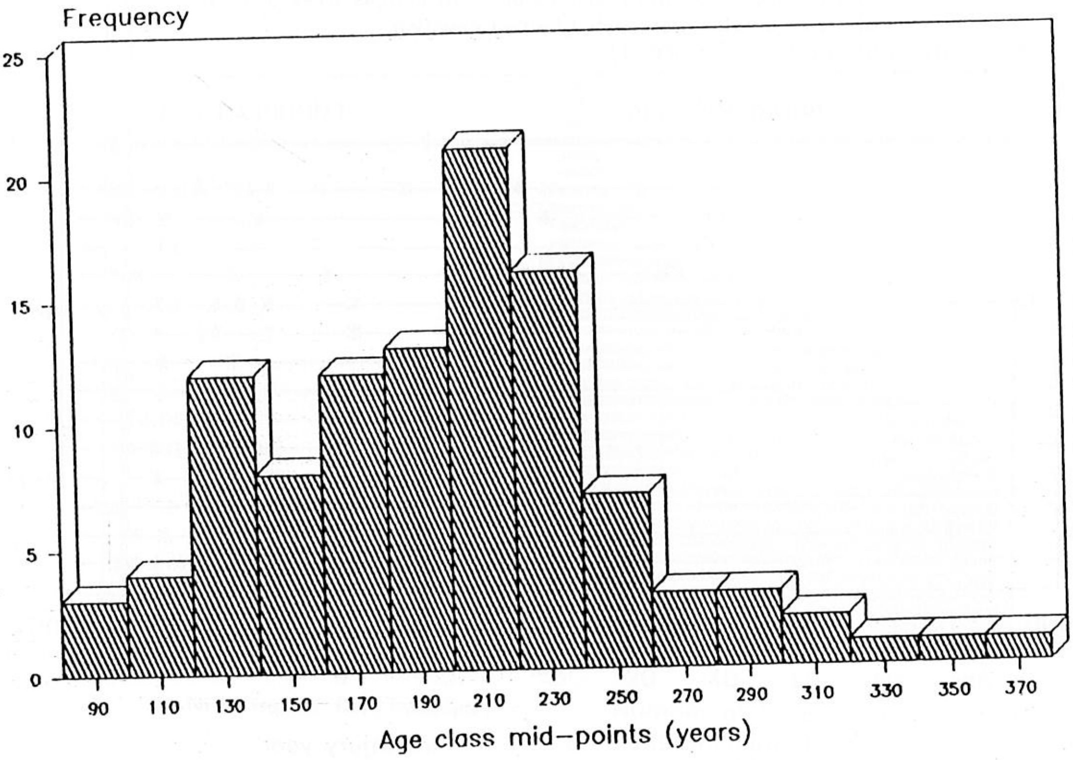

Figure 4: A chronology of fire injuries for 14 forest sites compiled from the stem analysis of 5–10 sample trees at each site. Fire injuries were dated by ring counting.

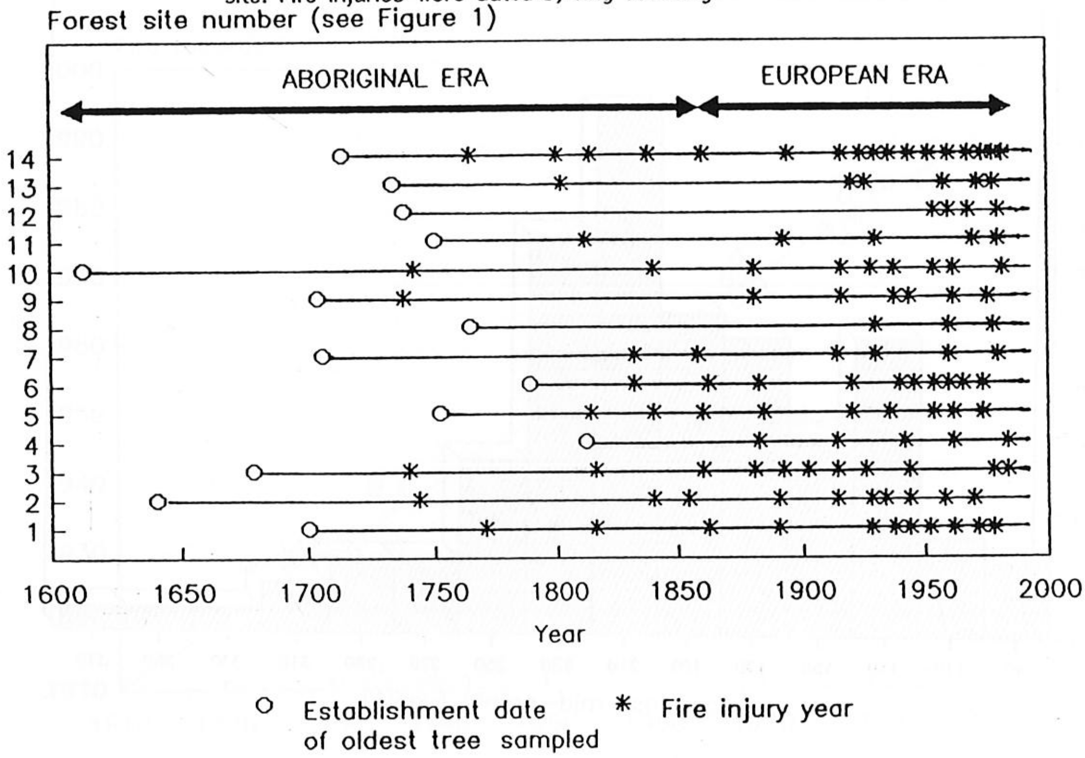

Figure 5: Total number of trees injured by fire in each decade for all sites. The number of trees in the sample for each decade is also shown.

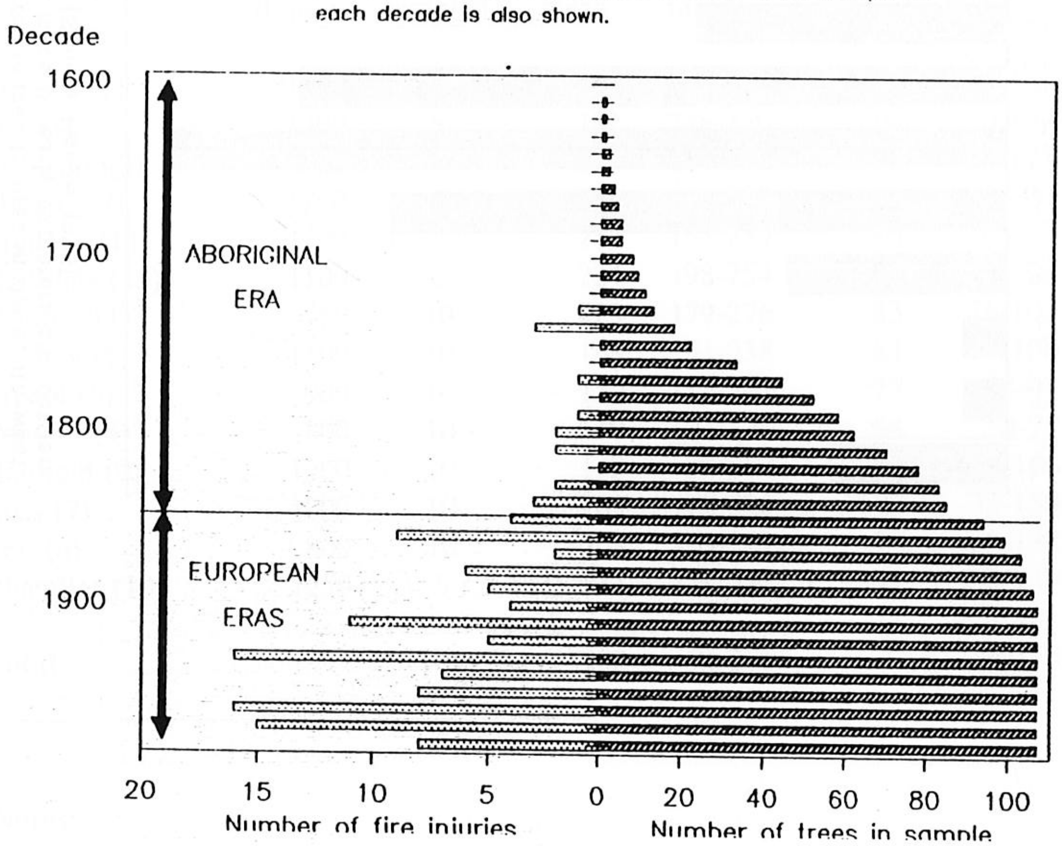

Figure 6: Historical references to fires in the south-west of Western Australia made by early explorers and settlers from 1697 to 1850. (Source: Hallam 1975)

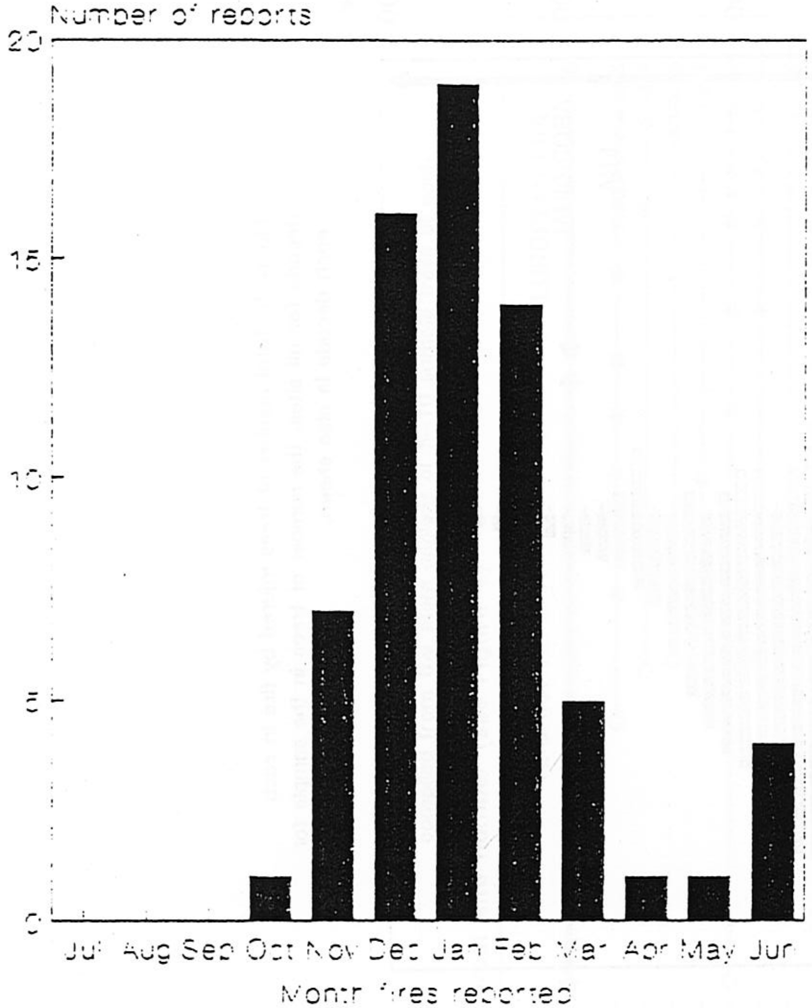

Table 1: Location and site details of jarrah trees sampled for fire injury analysis and ring counting. Numbers in parentheses refer to locations shown in Figure 1.

Forest[1]	Annual average rainfall (mm)	Number of trees sampled	Tree age[2] (yrs) mean	Tree age[2] (yrs) range	Tree[3] diam. mean	Tree[3] diam. range	Trees[4] injured by fire
Crowea (1)	1300	5	243	214-291	120	104-141	5
Treen(2)	1300	5	282	248-350	110	90-134	4
Dordagup(3)	1100	5	258	204-312	104	88-121	2
Blythe (12)	1250	4	219	206-238	99	93-104	4
Gregory (14)	1100	7	212	155-257	80	64-93	7
St. Johns (13)	1100	6	224	198-254	88	73-109	3
Munro (11)	950	10	223	179-276	83	76-102	10
Arcadia (5)	1100	10	168	91-238	84	70-106	10
Bristol (6)	900	10	150	117-201	77	58-97	8
Centaur (4)	800	10	140	103-179	64	50-77	6
Hadfield (9)	1200	10	148	90-287	103	72-166	8
Ross (7)	1000	10	203	170-283	107	73-150	9
Bell (8)	800	10	205	169-241	96	92-128	6
Chandler (10)	1250	5	245	134-377	121	78-139	5
Total		**107**	**208**	**91-377**	**95**	**50-166**	**87**

Notes:

1] See Figure 1 for location of Forest district.
2] Tree age estimated from ring counting.
3] Diameter of stump at about 50 cm above ground and under bark.
4] Fire injury includes fire scars and kino veins.

Table 2: Known history of selection logging (1920-1990) and fire (1937-1989) in jarrah forests studied to determine the pre-historical frequency of fire. Numbers in parentheses refer to locations shown in Figure 1.

Forest	Disturbance		
	Selection Logging[1]	Fire[2]	
		Wildfire	Prescribed fire
Crowea (1)	1961-70	1944, 1961	1956, 1967, 1973, 1980, 1986
Treen (2)	1920s, 1931-40	1944, 1958, 1964	1971, 1977, 1983
Dordagup (3)	Virgin (unlogged) forest	1944	1967, 1972, 1977, 1983, 1989
Blythe (12)	1930s, 1977-78		1956, 1963, 1973, 1985
Gregory (14)	1920s, 1930s		1963, 1971, 1981
St. Johns (13)	1940-49	1962	1972, 1978, 1987
Munro (11)	pre 1920, 1934. 1957-59, 1968		1934, 1963, 1969, 1977, 1984
Arcadia (5)	pre 1920s, 1940s, 1970-79		1961, 1970, 1975, 1979
Bristol (6)	pre 1920s, 1940-49	1939, 1961	1965, 1974, 1983
Centaur (4)	1980-89 (light cut)	1941, 1961	1965, 1983
Hadfield (9)	1920s, 1930-40, 1962, 1981-82	1939, 1961	1951, 1956, 1968, 1976, 1984
Ross (7)	1930s, 1967, 1989	1939	1954, 1960, 1967, 1973, 1981, 1987
Bell (8)	Virgin (unlogged) forest	1930, 1952, 1959	1964, 1970, 1978, 1986
Chandler (10)	pre 1920s, 1940-45, 1972		1945, 1955, 1962, 1969, 1976, 1982

Notes:

1] Reliable logging records are not available prior to 1920 but most forest blocks were logged to some extent prior to 1920.

2] Records show that prescribed fires prior to the 1960s were mostly small, patch strategic burns ignited by hand in both spring and autumn.

Table 3: Number of fires sufficiently intense to cause bole injury to jarrah trees in 4 jarrah forests and by cultural era. The number of trees in the sample is shown in parentheses.

Forest	Aboriginal	Cultural era 1st European	2nd European	3rd European	Total
Crowea	1700-1855: 3(5)	2(5)	5(5)	2(5)	12
Treen	1640-1855: 3(5)	2(5)	4(5)	0(5)	9
Dordagup	1678-1855: 2(5)	5(5)	2(5)	1(5)	10
Blythe	1753-1855: 1(4)	6(4)	3(4)	3(4)	13
Gregory	1743-1855: 1(7)	2(7)	2(7)	1(7)	6
St. Johns	1737-1855: 0(6)	1(6)	3(6)	2(6)	6
Munro	1714-1855: 5(10)	5(10)	6(10)	1(10)	17
Arcadia	1752-1855: 3(7)	5(10)	4(10)	2(10)	14
Bristol	1789-1855: 1(5)	3(10)	4(10)	2(10)	10
Centaur	1812-1855: 0(5)	2(10)	2(10)	1(10)	5
Hadfield	1704-1855: 1(5)	2(10)	2(10)	1(10)	6
Ross	1707-1855: 1(10)	2(10)	2(10)	2(10)	7
Bell	1763-1855: 0(9)	0(10)	2(10)	1(10)	3
Chandler	1913-1855: 2(4)	3(5)	5(5)	2(5)	12
Total	23(87)	40(107)	46(107)	21(107)	130
Mean number of injurious fires/forest	1.64	2.85	3.28	1.50	9.27
Fire caused injuries (tree^{-1} year^{-1})	1.9×10^{-3}	5.6×10^{-3}	9.7×10^{-3}	7.8×10^{-3}	4.5×10^{-3}
Mean interval between injurious fires (years)	81.6	22.3	13.4	16.6	28.7