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

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ABSTRACT

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

INTRODUCTION

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

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

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

METHODS

Study Area

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

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

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

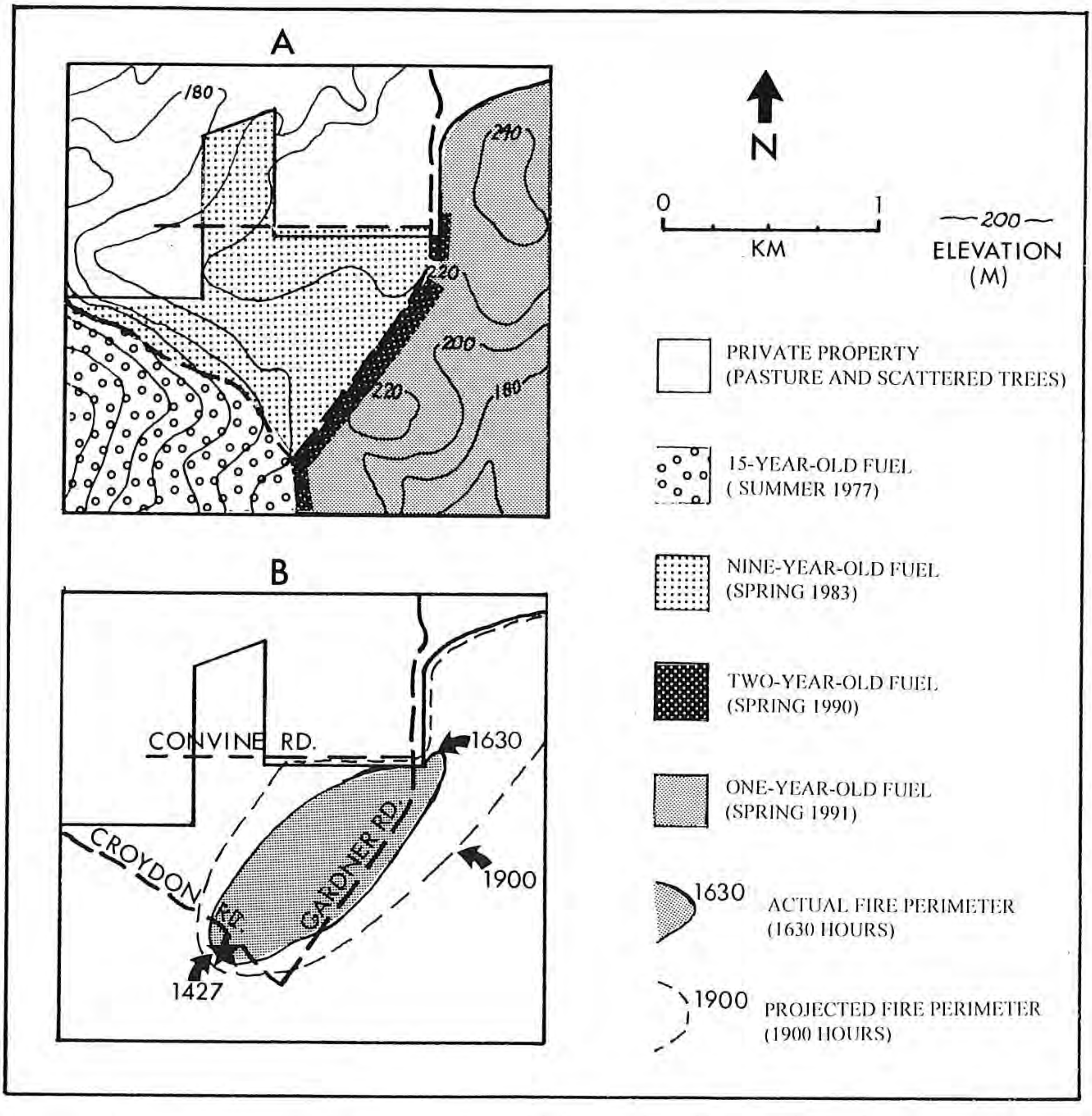

Figure 1. (A) Map showing elevation (in m), land tenure, and fuel ages within publicly-owned native forest; (B) map showing roads mentioned in the text, the ignition point of the fire at 1427 hours, the actual perimeter of the fire at 1630 hours and the projected perimeter of the fire at 1900 hours had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

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

Data Collection and Analysis

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

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

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

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

RESULTS

Fuel characteristics

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

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

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

TABLE 1

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

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

Burning Conditions

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

(a)

(b)

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

TABLE 2

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

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

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

Fire Origin and Development

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

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

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

Suppression Action

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

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

DISCUSSION

The behaviour of this fire clearly illustrates that relatively narrow fuel breaks such as rural roads <20 m wide are insufficient to contain the spread of fires in jarrah forest when the fire danger is Very High or Extreme. Gardner Road provided sufficient break in the continuity of the fuels to temporarily halt the run of the headfire, but was not wide enough to prevent firebrands from being blown across from the main fire and igniting the fuels on the eastern side of the road. The effectiveness of roads and other fuel breaks (e.g. rock outcrops, dunes, lakes) as barriers to fire spread depends on their width, the type of fuel in which the fire is burning, and the severity of the burning conditions (Wilson 1988). Fires in eucalypt forests are renowned for their ability to propagate by means of spot-fires started ahead of the main fire front and this characteristic may negate the effect of fuel breaks even at relatively low levels of fire danger, particularly where trees carry large accumulations of fibrous stringybark or loose ribbons of smooth bark which can act as firebrands (Luke and McArthur 1978; Wilson 1992a). Rotational fuel reduction burning, in addition to limiting the accumulation of litter and understorey shrub fuels, also typically removes loose, fibrous bark from the bottom few metres of stems thereby reducing the quantity of bark fuel which may contribute to flame extension up the stem and which is available for the generation of firebrands. Observed spotting distances were substantially less than predicted by the McArthur FFDM, and a possible explanation for this is that the amount of loose, fibrous bark on the stems of trees in the nine-year-old fuel area was still limited as a result of prescribed burning in spring 1983. Accumulation of fibrous bark on jarrah and marri stems becomes noticeably greater in stands from which fire has been excluded for 15 years or more (McCaw, unpublished data). Better understanding of the relationships between bark characteristics, firebrand generation, and spotting would allow the effect of fuel reduction burning on bark fuel hazard to be objectively assessed. This should be a priority for future fire research.

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

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

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

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

CONCLUSION

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

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Abbreviations used in this paper

SDI = Soil Dryness Index

FFBT = Forest Fire Behaviour Tables

SMC = surface moisture content

FROS = forward rate of spread

FFDI = Forest Fire Danger Index

FFDM = Forest Fire Danger Meter