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Fire behaviour in jarrah forest fuels: 2. Field experiments

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ABSTRACT

An ability to predict the behaviour of forest fires is fundamental to sound fire management, including fire danger rating, prescribed burning and wildfire control. Existing Australian dry sclerophyll forest fire behaviour models were developed in the 1960s from small (<0.2 ha) experimental point ignition fires set under mild weather conditions. While these guides are useful for predicting the behaviour of low intensity fires burning under mild conditions, they have been reported to seriously under predict the rate of spread of wildfires burning under dry and windy conditions.

To improve the ability of fire managers to predict fire behaviour over a wider range of burning conditions, a series of experimental fires were studied in jarrah (*Eucalyptus marginata*) forests in the south-west of Western Australia. The spread rate of these fires burning on level terrain was dependent on wind speed and fuel moisture content but was independent of fuel quantity. While mean fuel quantity varied between the plots, most of the fuels were of similar age since last fire (seven years). Fires spread up to three times faster than predicted by the existing models and under dry fuel conditions, spread rate increased rapidly with increasing wind speed when wind speed at 1.5 m in the forest exceeded about 3–3.5 km h^{-1}. Nonlinear and linear least squares fitting procedures were employed to derive regression models to predict rate of spread, flame size and fire intensity. The best fit rate of spread model incorporated power functions in wind speed and fuel moisture content. Further validation of the models is needed to determine whether they hold for larger fires and for fires burning under fuel and fire weather conditions outside those experienced during this study.

INTRODUCTION

Forest fire behaviour modelling in Western Australia (WA) has evolved over several decades (see Burrows and Sneeuwjagt 1991; Burrows 1994) and prior to the findings reported in this paper, the 1979 edition of the Forest Fire Behaviour Tables for Western Australia (FFBT) (Sneeuwjagt and Peet 1979) formed the basis for forest fire danger rating and fire behaviour prediction in jarrah (*Eucalyptus marginata*) forests. The FFBT were based on pioneering fire behaviour research by Peet in the 1960s (Peet 1965, 1972).

Peet's (1972) point ignition fire experiments were 'primarily aimed at improving the techniques for fire suppression and controlled burning'. His original research was conducted in small plots (<0.2 ha), restricting full fire development, and under relatively mild conditions. The limitations of the fire behaviour model developed from these studies have been discussed by Burrows and Sneeuwjagt (1991) and Burrows (1994). The need to conduct further fire behaviour experiments arose out of new developments in jarrah forest fire management, including higher expectations and standards of wildfire control and increasingly sophisticated applications for prescribed burning (see Burrows 1994). There was some concern among fire managers and researchers that the existing model (Sneeuwjagt and Peet 1979) underestimated fire rate of spread under dry fuel conditions (Peet personal communication). Wildfires burning under dry conditions were observed to spread significantly faster than predicted.

As well as a need to be able to forecast fire danger and accurately predict the spread of wildfires, fire managers need reliable fire behaviour models to safely implement prescribed burns over a wide range of fuel and weather conditions to achieve a variety of protection and conservation objectives. Prescribed burning under warm, dry conditions in summer or early autumn to regenerate or eradicate specific plant species or to control insect pests by fully scorching the tree canopy, is risky. Fire behaviour can quickly escalate, resulting in uncontrolled, intense fires (e.g. Burrows 1984). Wildfires caused by lightning or arsonists are, by and large, outside the control of fire management agencies, but escapes from prescribed burns are undesirable both in terms of cost and public credibility. Therefore, it is vital that fire behaviour models are reliable over the range of prescribed burning conditions and that model users are aware of model assumptions and limitations.

The experiments described in this paper aimed to accomplish the following objectives:

(1) Examine and model the behaviour of quasi steady state (mostly line ignition) fires over a wide range of fuel and weather conditions in a standard jarrah forest litter fuel. Rate of spread under these conditions represents the jarrah fire danger index (FDI) which is the basis for predicting forest fire danger and fire behaviour in all except karri forest fuel types in Western Australian forests.

(2) Compare the fire spread model developed from the laboratory experiments (Burrows this volume) with observations of field fire behaviour.

(3) Compare fire rates of spread observed in the field with those predicted using (a) the 1979 version of FFBT (Sneeuwjagt and Peet 1979), which was developed from Peet's (1972) experiments, (b) McArthur's Forest Fire Meter and (c) Rothermel's (1972) laboratory-derived model.

Fire behaviour data used in this study were from a number of sources, as described in Table 1. The majority of experimental fires were conducted in 2 ha plots in Young and Harrington State forests in the south-west of WA over the warm, dry summer months (January-March) of 1979 and 1980 (see Table 1 and Fig. 1). These experiments were conducted during the Prohibited Burning Period, when the Bush Fires Act normally prohibits the lighting of fires. A suspension of the Act was obtained to conduct these experiments, but under the conditions of the suspension, no fires could be lit when the Forest Fire Danger Rating for the region exceeded HIGH or when the Minister decreed a total fire ban. Additional fire behaviour data were gathered during the burning of fire ecology experimental sites (Boundary, Perup and McCorkhill), and from a few operational low intensity prescribed burns throughout the jarrah forest. Data from a single, well documented fast spreading wildfire which burnt in Andrew State forest west of Manjimup was also included in the data set (McCaw *et al.* 1992). Although some 300 wildfires occur in the south-west each year, the technical documentation of these fires is generally too poor for use in analysis for fire modelling.

METHODS

The research methods adopted in this study were similar to those used by most workers studying fire behaviour in the field (e.g. McArthur 1959; Peet 1972; Stocks and Alexander 1980; Stocks 1987; Alexander *et al.* 1988). Significantly, plots were considerably larger than those studied by McArthur (1959) and Peet (1972) and most fires (56 of 66 plots) were ignited by a line of fire rather than a point source. Experiments were conducted in a standard jarrah forest fuel type on flat or gently sloping terrain in plateau jarrah forest so that findings would be compatible with the FFBT and with earlier work by McArthur (1959) and Peet (1972). This fuel type is characterized by a layer of dead leaves, twigs, bark and floral parts on the forest floor with a low (<0.5 m) open (<30 per cent cover) understorey of live and suspended dead vegetation. A detailed description is given by Burrows (1994). The jarrah FDI is equivalent to headfire rate of spread in this standard fuel with a loading of 7–8 t ha^{-1} and on level terrain (Sneeuwjagt and Peet 1976 and 1979).

Site Description – Young and Harrington State Forests

The Dwellingup study site was located in Young State forest, 25 km south-east of Dwellingup (Figs 1 and 2). The area experiences a Mediterranean type climate, with warm to hot dry summers and cool wet winters with an average annual rainfall of about 1000 mm. In this dry sclerophyll forest, jarrah and marri (*Corymbia calophylla*) form the overstorey with jarrah making up about 70 per cent of the total tree basal area. The mean top height was about 25 m, mean tree basal area was about 26 m^2 ha^{-1}, and overstorey canopy cover varied from 40–70 per cent. Most (85 per cent) trees were less than 40 cm in diameter measured at breast height and over bark (dbhob). The lower tree stratum (up to 7 m above the ground) comprised mainly of scattered jarrah saplings, *Banksia grandis, Allocasuarina fraseriana* and *Persoonia longifolia.* The low, sparse understorey (mean height 0.3 m, projected ground cover <10 per cent) consisted of species such as *Adenanthos barbigera, Macrozamia riedlei, Hovea chorizemifolia, Leucopogon verticillatus, Xanthorrhoea gracilis, Hibbertia amplexicaulis, Lasiopetalum floribundum, Dryanda nivea, Loxocarya flexuosa, Acacia strigosa, Styphelia tenuiflora* and *Patersonia rudis.* A continuous ground cover of fine litter (leaves, twigs and floral parts) formed the dominant fuel.

Young State forest was selectively logged in the 1930s and regular (5–7 years) low intensity (<350 kW m^{-1}) fuel reduction burns were carried out there from the mid 1950s. Prior to these experimental fires, the study area was last burnt in spring 1973 by low intensity fire for fuel reduction so fuels were 7 years old at the time of experimentation. Forest surrounding the study site was burnt in 1979 as part of the then Forests Department's (now Department of Conservation and Land Management) fuel reduction program.

The second study site of 80 ha was located 7 km east of Jarrahwood in Harrington State forest within the Donnybrook Sunkland (Fig. 1). The geology and geomorphology of the region have been described in detail by several authors (Prider 1966; Finkl 1971; McCutcheon 1978, 1980; Churchward and Dimmock 1989). Climate is similar to that experienced at the Young site.

The fuels and vegetation of the Harrington site were similar in structure to the standard northern jarrah forest, although there was a higher understorey scrub component. The vegetation was an open forest, similar to the Young forest site but with a lower mean top height (20–25 m) reflecting the poorer quality of this forest. Jarrah and marri formed the overstorey with a projected crown cover of 30–50 per cent. Jarrah formed the dominant tree species. Lower trees (up to 6 m) consisted of scattered

TABLE 1
Summary of data sources used in analysis of fire behaviour in jarrah forests.

LOCATION (FOREST BLOCK)	YEAR BURNT	NUMBER OF PLOTS	PLOT SIZE (ha)	FUEL AGE (years)
Harrington	1979	23	2	7
Young	1980	17	2	7
Perup	1987-92	6	4	4,5
McCorkhill	1988-91	10	4	3,5,7
Boundary	1989-90	4	1	4,5
Fuel reduction	1989-91	6	2	5,7
Andrew	1991 wildfire		(McCaw *et al.* 1992)	3

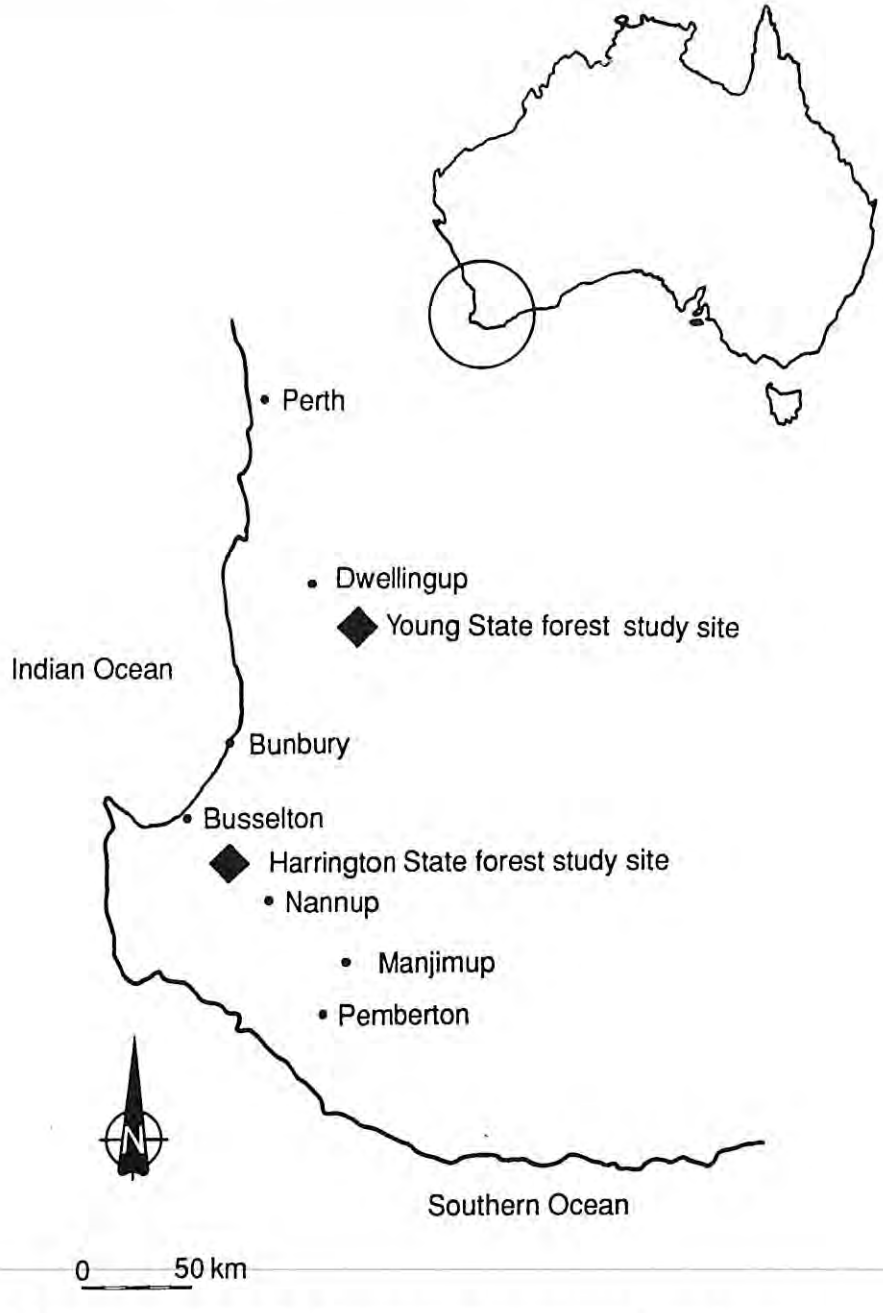


Figure 1. Location of jarrah forest fire behaviour studies in south-west Western Australia.

Banksia grandis, Allocasuarina fraseriana, and *Persoonia longifolia*. Understorey vegetation was somewhat more continuous than the Young forest site, with a projected ground cover of 20–35 per cent. Common understorey species were *Acacia browniana, Acacia pulchella, Adenanthos barbigera, Adenanthos obovata, Agonis parviceps, Burtonia villosa, Hakea lissocarpa, Hibbertia hypericoides, Leucopogon glabellus, Leucopogon verticillata*, and *Pultenaea reticulata*. Understorey height varied from 0.2–1.5 m, averaging about 0.6 m.

At both sites, a rubber-tyred tractor was used to construct 100 m x 200 m experimental burn plots, each separated by a 3 m wide mineral earth break. Plot layout for both sites is shown in Figure 2. A 20 m x 20 m grid was permanently marked in each plot using 2 m wooden pegs. This grid formed the basis for sampling fuels and fire behaviour.

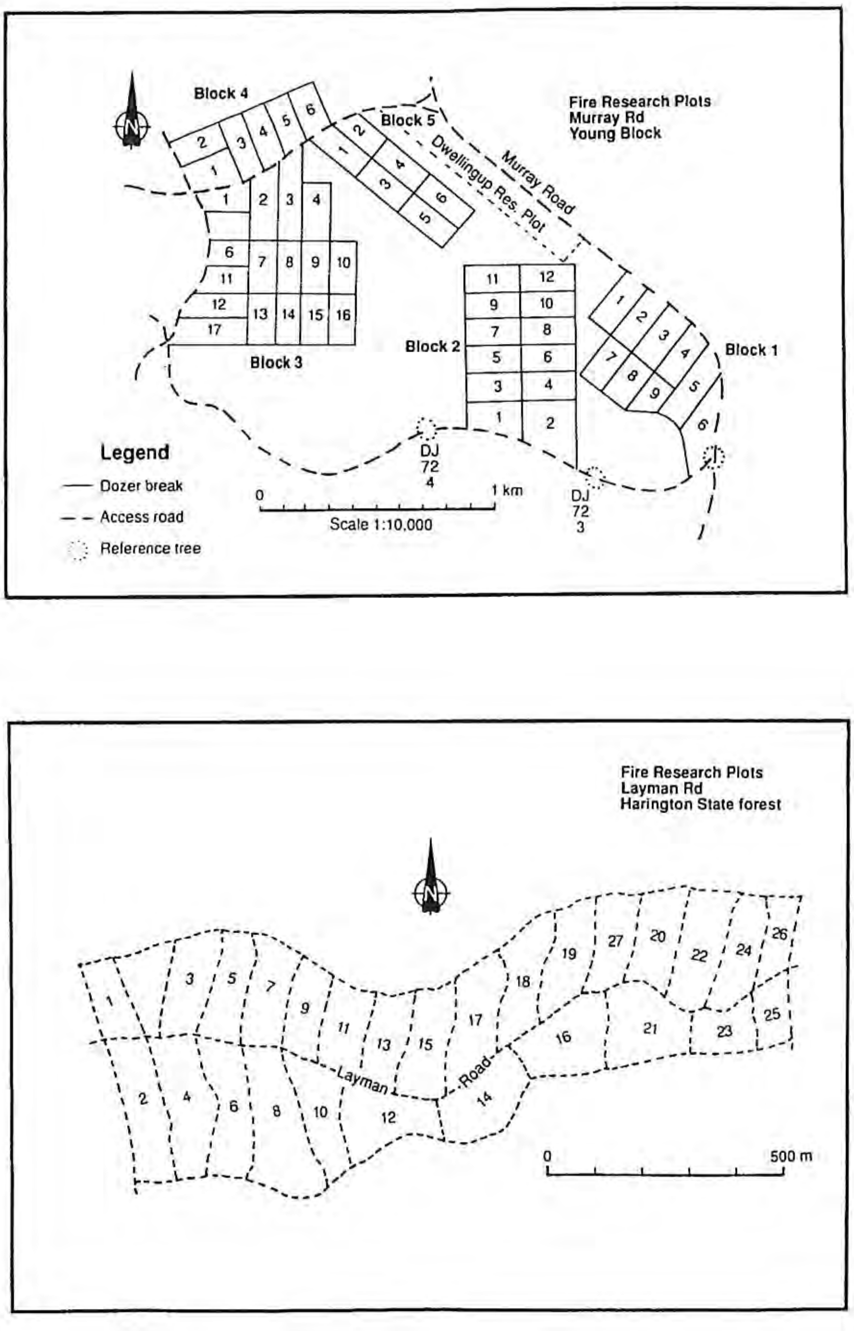


Figure 2. Location and layout of 2 ha plots to study fire behaviour in jarrah forests of south-west Western Australia.

Perup, McCorkhill and Boundary Sites

These sites were established to study the long term effects of various fire regimes on the jarrah forest and provided an opportunity for gathering additional fire behaviour data. The McCorkhill State forest site, some 25 km west of Nannup, is climatically, structurally, and floristically similar to Harrington, although with a better developed understorey. The Perup site, about 40 km east of Manjimup, is in the low rainfall forest zone (750 mm per annum) so the trees are shorter (15–20 m) and the understorey lower and more open than higher rainfall forests to the west. Understorey vegetation was low (< 0.5 m) and sparse (<15 per cent cover) and litter formed the dominant fuel. The fuels at this site were structurally similar to those in Young State forest. The Boundary site was located in high rainfall mixed jarrah forest about 10 km west of Manjimup.

The 200 m x 200 m experimental fire plots varied in fuel quantity but were mostly 5–7 years since last fire, which is a relatively narrow age range (Table 1). Variation in fuel quantity provided an opportunity to examine the effect of this parameter on rate of spread. These plots were burnt under milder weather conditions than the Harrington and Young plots so spread rates were generally less than 100 m h^{-1}. Ignition was by way of a line of fire of varying length (50–100 m). Fire behaviour observations were made over 15–60 minute intervals.

Fuel Quantity and Structure

All live and dead vegetation from the soil surface to a height of 2 m was classified according to Figure 3 and measured. Trash fuel (Fig. 3) is dead suspended vegetation. Vegetation above 2 m was too sparse to warrant inclusion as fuel. The sparsely foliaged tree crowns were 10–15 m above the litter bed and the horizontal distance between tree crowns, while variable, was mostly 5–10 m.

The quantity of litter (surface) fuel (dead leaves, twigs and floral parts < 6 mm in diameter) in each plot was measured by determining the mean depth of the litter bed within each grid cell and using a previously determined relationship between litter bed depth and quantity (Burrows 1994). Ten fuel depth measurements were made (one every 2 m) along 20 m transect lines between each grid position. Each grid cell (20 m x 4 m) was then assigned a mean litter quantity on the basis of this sampling (e.g. Fig. 4).

During the laboratory fire behaviour experiments described by Burrows (this volume), the quantity of fuel placed on the fire table varied between fires, but was constant across the table for each fire. In the field, however, fuel quantity was variable within and between plots (e.g. see Fig. 4). Therefore, determining the quantity of fuel influencing the behaviour of the field fires was not straight forward. Three methods for determining rate of spread and the quantity of fuel involved in fire spread were tested to examine the effect of fuel quantity on headfire rate of spread.

(1) The mean fuel quantity for each plot was analysed with the mean headfire rate of spread through the entire plot (plot fuel quantity).

(2) Headfire rate of spread was determined every 15–20 minutes as the crescent-shaped fire front spread through the plot. The mean of fuel cells through which the apex of the headfire spread during each spread interval was determined and used in analysis (apex fuel quantity).

(3) As for (2) above except that the mean of all fuel cells within the headfire crescent burnt out during a spread interval was determined and used in analysis (crescent fuel quantity).

The three methods described above are illustrated in Figure 4.

The quantity of large, dead, woody material (>6 mm in diameter) lying on the forest floor was measured before and after burning along the same transects (Fig. 4) and using a line intercept technique (Van Wagner 1968b). All material intercepted was tallied into 25 mm diameter size classes and the quantity of fuel in each class was calculated using the class mid-point diameter and expressed in t ha^{-1}.

Understorey vegetation (scrub fuel) within each fuel sample cell (20 m x 4 m) was first typed and mapped according to species assemblages using techniques described by Havel (1975) and McCutcheon (1980). Three vegetation types, or pyro-botanical types, were identified based on biomass and cover and are summarized in Table 2. Biomass (oven dry) samples were harvested from a number of 1 m^2 quadrats located in each type and a point sample technique (Levy and Madden 1933) used to determine mean height and cover (Table 2).

The incorporation of bark as fuel in eucalypt forests is often overlooked. Peet and McCormick (1965) reported that up to 9.7 t ha^{-1} of bark was burnt from standing trees during high intensity fires in well stocked, high quality jarrah forests near Dwellingup in 1961. Ward and Burrows (1985) working in jarrah forests similar to those reported here determined a relationship between height of bole char and quantity of bark burnt for marri and jarrah trees. For a forest with a tree basal area of about 25–30 m^2 ha^{-1}, the quantity of bark burnt during moderate to intense fires under dry conditions (outer bark moisture content 4–6 per cent of oven dry weight) was about 4.5–5.5 t ha^{-1} (Ward and Burrows 1985).

Weather Observations

Weather records were divided into historical (pre-fire) weather and weather experienced during the experimental fires. Pre-fire weather records were obtained from the nearest permanent weather stations at Dwellingup and Kirup for Young and Harrington forests respectively. Weather recorded at these centres, located some 20 km from the study sites, included daily rainfall, continuous temperature and relative humidity traces, dew point, and wind speed and direction at two-hourly intervals (during working hours; 0800–1700 h western standard time (WST)) at standard exposure (10 m into clear air)

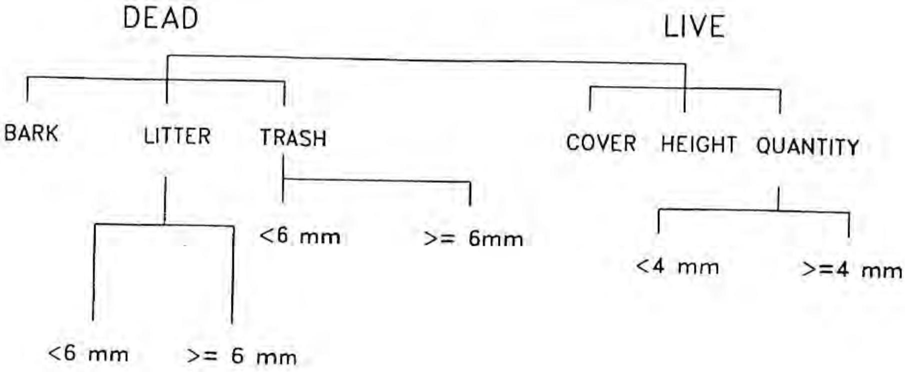
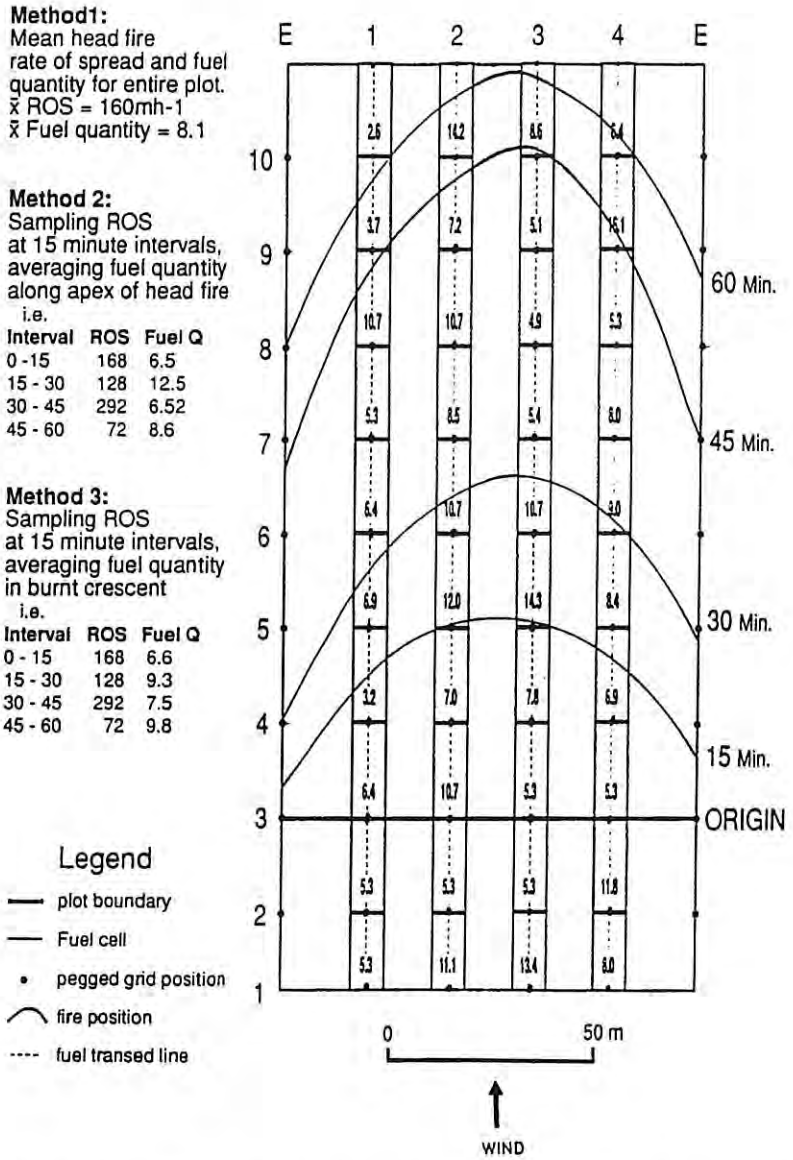


Figure 3. Classification of fuel elements in a standard jarrah forest fuel array.


Method1:
Mean head fire rate of spread and fuel quantity for entire plot.
x̄ ROS = 160mh-1
x̄ Fuel quantity = 8.1

Method 2:
Sampling ROS at 15 minute intervals, averaging fuel quantity along apex of head fire
i.e.

Interval	ROS	Fuel Q
0 -15	168	6.5
15 - 30	128	12.5
30 - 45	292	6.52
45 - 60	72	8.6

Method 3:
Sampling ROS at 15 minute intervals, averaging fuel quantity in burnt crescent
i.e.

Interval	ROS	Fuel Q
0 - 15	168	6.6
15 - 30	128	9.3
30 - 45	292	7.5
45 - 60	72	9.8

Figure 4. An example of the fire behaviour and fuel sampling grid layout in 2 ha experimental fire plots. Fuel sample cells are continuous 20 m x 4 m quadrats and examples of the mean fuel quantity (t ha^{-1}) recorded in the cells are shown. The ignition origin and position of the headfire with time after ignition is also shown. Three methods were used to investigate the relationship between fuel quantity (Fuel Q) and fire rate of spread (ROS), as described in the figure.

TABLE 2
Havel (1975) vegetation types (floristically similar assemblages) and associated fuel characteristics. Vegetation types of the same age since last fire have similar fuel properties (structure and weight), so are referred to as pyrobotanical types. Standard errors in parentheses.

	PYROBOTANICAL TYPE (CODES)		
	T	CD	G
Number of biomass samples	30	39	52
Mean biomass (t ha^{-1})	0.6 (0.04)	5.2 (0.31)	2.4 (0.18)
Mean height (m)	0.28 (0.02)	0.84 (0.12)	0.41 (0.03)
Mean cover (%)	6 (0.44)	54 (6.1)	33 (4.2)
Coverage over study site (%)	44.1	14.5	41.4

(Department of Science, Bureau of Meteorology Manual 1977). Historical weather records were primarily used to maintain the Soil Dryness Index (SDI) (Mount 1972; Burrows 1987), which is a measure of the seasonal dryness of soil, vegetation, deep forest litter fuels and logs lying on the forest floor.

During the experimental fires, a portable weather station was located on site. This consisted of (1) two sensitive cup (50 mm) analog type mechanical anemometers, one set at 1.5 m and one at 10 m above the forest floor, (2) a thermohydrograph and an aspirated physchrometer set at 1.5 m above the forest floor. The weather station was set in unburnt forest, about 50 m from the plot to be burnt, at right angles to the prevailing wind direction.

An observer recorded wind run and direction at 1.5 m and 10 m above the forest floor over five minute intervals for the duration of each fire. Wind speed and direction varied during the burning of each plot so for the various time periods over which spread rates were averaged, the resultant wind vector was determined by plotting the five minute interval wind runs (distance and direction). The resultant vector (distance) was then divided by the time over which the rate of spread was determined and used in subsequent analysis. Winds experienced at the Young site were mostly light and variable south-easterlies, whereas winds at the Harrington site were generally stronger and less variable westerly sea breezes. As well as a continuous thermohydrograph trace, ambient wet and dry bulb temperatures were recorded at the start and finish of each fire.

Fuel Moisture Content

The Soil Dryness Index (SDI) (Mount 1972; Burrows 1987) was maintained to provide a measure of the seasonal dryness of soils, vegetation and coarse fuels, as described above. At the time of igniting each plot and at hourly intervals thereafter, the moisture content of the litter fuel was determined from six samples, each of about 50 g, from the top 10–15 mm of the litter bed (surface moisture content or SMC as defined by Sneeuwjagt and Peet 1979, 1985) and six of the entire litter profile down to mineral earth (profile moisture content or PMC). Previous tests had shown that six samples provided a reliable estimate of fuel moisture in the plot, with a standard error of less than 4 per cent of the mean. During dry summer conditions, the moisture content of litter bed fuels is controlled by atmospheric humidity and temperature (Luke and McArthur 1978; Sneeuwjagt and Peet 1979), resulting in a high degree of spatial uniformity across a level experimental plot of about 2 ha. Samples were taken throughout the plot from areas in mottled shade at the time of sampling and placed in air tight containers. At a later date, samples were dried in a conventional oven for 48 hours at 105° C and moisture content calculated as percentage of oven dry weight (odw).

Initially, the leaf and fine twig (< 4 mm in diameter) moisture content of live vegetation up to 2 m was sampled daily at noon, but this was abandoned for several reasons. Firstly, there was considerable variation both between and within plant species, depending on where the sample was taken. Secondly, there was no significant diurnal trend in moisture content, even allowing for variation. Instead, live vegetation was sampled weekly during the study to monitor long term trends. This was achieved by harvesting 15, 50 g samples each of leaf and of green stem (< 4 mm diameter) material and drying it as described above for litter fuels.

The weekly moisture content of dead, coarse woody fuels lying on the forest floor was represented by extracting 10 core samples to a depth of 100 mm from a log 300 mm in diameter. In the absence of significant rain, log moisture content varied only slightly during this study. The moisture content of outer (dead) and inner (live) bark of jarrah and banksia trees was also sampled weekly.

Fire Behaviour

Gill and Knight (1991) have emphasized the importance of accurate fire measurement in order to develop accurate fire models. They also acknowledge the difficulties of obtaining accurate measurements in the field. Fire behaviour characteristics (linear rates of spread, fire area and fire perimeter) of point source fires have usually been measured in the field by some method of tagging the fire perimeter at regular time intervals (e.g. McArthur 1962; Peet 1965; Cheney 1971; Alexander *et al.* 1988). Another technique which has been used successfully is sequential remote sensing using oblique or aerial photography, video and infra-red imagery, either from a mobile platform such as a fixed wing aircraft, or a stationary platform, such as a tower or helicopter (Packham and McArthur 1966; Cheney *et al.* 1968; Johns 1986; Adkins and Rodgers 1986; Mak and Hutchins 1987; Alexander *et al.* 1988; Cheney *et al.* 1989). In some instances, fire spread has been determined by recording the time at which the flames reach a fixed point in a pre-determined grid or some referenced position (e.g Woolliscroft 1968, 1969; Alexander *et al.* 1988). A variation on this technique involves using thermocouples or electronic timers with fusible links set on a grid to record the arrival of flames (Blank and Simard 1983).

Whatever the technique, fire rate of spread is the easiest fire behaviour variable to measure. However, the turbulent and dynamic nature of fast spreading flames makes flame dimensions difficult to measure accurately in all but the mildest of bushfires. Flames are normally described according to height, length, depth and angle, as defined by Byram (1959), Rothermel and Deeming (1980), Cheney (1981) and Alexander (1982). In the field, flame dimensions are commonly estimated visually, often against a calibrated scale of some type. Various forms of imagery, such as photographic and video, have also been used to measure flame dimensions (Alexander *et al.* 1988). Ryan (1981) described a method for estimating flame height using a cotton string soaked in fire retardant.

Ultimately, the technique used to measure fire behaviour depends on the needs and circumstances of each situation. Here, aerial photography or video recording of fires was unsuitable because smoke and vegetation would quickly obscure the flames. Infra-red technology was beyond the capacity of this project and probably not warranted given the size of the plots. Tagging the fire perimeter at regular intervals is a sound technique when it is safe to do so, but is inaccurate, dangerous or impossible during periods of intense fire behaviour.

Jarrah forest fire danger rating and fire behaviour predictions are based on headfire rate of spread in standard fuel on level terrain. Headfire is the most active in terms of spread rate, intensity and flame dimensions so is of greatest concern to fire managers. The steady build-up and acceleration of fires ignited from a point source is a well documented phenomenon (McArthur 1967; Luke and McArthur 1978; Cheney 1981; McAlpine 1988), although none of the present models has been tested in jarrah forest fuels over the range of potential burning conditions. Weber (1989) has advanced an understanding of the build-up phenomenon, through a physical model which identifies the curvature of the fire front as the entity that drives fire acceleration. Depending on fuel and surface burning conditions, fires originating from a point source can take several hours and develop to a considerable size before reaching a 'quasi steady state' (Cheney 1981). Even under mild conditions, Peet (1962) showed that fires lit from a point source took 20–30 minutes to reach a steady rate of spread of 40–60 m h^{-1}.

The primary aim of this experiment was to model steady state headfire spread rate in standard jarrah fuel. To reduce the build-up time of the experimental fires in the 2–4 ha plots, 57 of the 67 plots were ignited by a 50–100 m line of fire set along the up-wind edge of each plot. Usually, the fire was allowed to burn for 20–40 m before monitoring commenced. Based on current understanding of fire build-up (e.g. Cheney 1981; Weber 1989; Cheney *et al.* 1993), line ignition reduces the build-up time considerably, allowing fires to reach a steady state relatively quickly. Ignition time was recorded and fire rate of spread was measured by observers who walked parallel to the flames, down each side firebreak and recorded the time flames reached each peg on a grid system (described above). The position of the flames in relation to the grid positions was also mapped at 5-minute intervals.

Normal procedures for executing a burning program under suspension of the Bush Fires Act were followed. Forests Department (now CALM) suppression crews from Dwellingup and Nannup contained the fires and mopped up after each plot was burnt.

When flames reached each grid position, visual estimates of mean flame height, length and depth were made. Flame height was the vertical distance from the leading tip of the flame to the fuel bed, flame length was the distance from the tip of the flame to mid-way along the base of the flame. Flame depth was the horizontal distance from the base of the leading edge of the flame to the base of the trailing edge of the flame. It was difficult to decide exactly where the trailing edge of the flames was, particularly for fast moving fires. Flame dimensions of fast moving, unstable fires proved very difficult to estimate accurately in the field. Difficulties in obtaining accurate and precise measures of flame dimensions in the field have also been reported by Johnson (1983). The three observers assisting with these experiments were experienced fire researchers and made similar estimates of flame size. The 2 m high pegs marking the grid positions were also used as height references, which assisted observations. Opportunistic observations of spotting, smoke colour and unusual fire behaviour such as torching, were also made.

Byram's fire intensity (Byram 1959) was calculated for each observation period (20–100 m of fire run; see data analysis section below) using the average headfire spread rate over that period (distance fire travelled/time), the average quantity of fuel consumed and a heat yield of 18700 kJ kg^{-1} (dry) adjusted for dead fuel moisture content (Alexander 1982). The quantity of fuel consumed in the flaming zone was estimated in the field by sampling fine fuel ($<$ 6 mm diameter dead, $<$ 4 mm live) quantity before and after the fire, as described above. It was assumed that all material in these size classes was in fact consumed in the flaming zone by flaming combustion. Depth of burn, a commonly used measure in Canada (Stocks 1987, 1989), was not measured in this study as the dry conditions resulted in almost total combustion of the litter profile down to mineral earth over most of the plots. The contribution of coarse ($\geq$ 6 mm diameter) fuels (logs etc.) to flaming zone combustion was calculated using the rate of weight loss relationships developed in Section 4. Bark loss, measured as described above, was included in the intensity calculation. A high proportion (up to 90 per cent based on observations of bark burn-out time) of all bark combustion on the lower portion of the tree boles occurred during the residence time of surface flames, therefore within the flaming zone. Bark loss was calculated from bole char height measurements and then using the relationship reported by Ward *et al.* (1985).

Data Analysis

Two fire behaviour data sets were generated. Firstly, up to five headfire rate of spread observations were extracted at different times and from a single fire in each plot as the line fires progressed through the plot. Selection was based on wind alignment to ensure that only headfire runs were included in analysis. Careful selection of observations by excluding those which were affected by wind shifts removed a significant amount of variability in rate of spread owing to changes in wind direction. However, this process risked violating normality assumptions because multiple observations from the same fire were not necessarily independent. For line ignition fires, the minimum time interval for an observation used in the data set was 15 minutes. Point ignition fires were allowed to burn for 45–120 minutes before headfire spread rates were used in the analysis. By this time, fires were generally wider than about 50 m. Fuel moisture and weather conditions (wind speed, temperature and relative humidity) were averaged over the same time as the spread rates. This data set was used to model fire behaviour.

In addition to multiple observations from the same fire, the average rate of spread for the entire fire (plot) was also determined for each plot. These data were analysed separately to examine the effect of fuel quantity on headfire rate of spread.

Data analysis and the headfire rate of spread model building procedure followed along the lines of that described for the laboratory studies (Burrows this volume). A Pearson correlation coefficient matrix was generated to screen for those variables important in affecting headfire rate of spread and for those which were not. Important variables were then plotted against rate of spread to provide a graphical view of the form of the relationship. Linear and nonlinear least squares fitting procedures (SAS Institute Inc. 1985; Myers 1990) were employed to formulate regression models to estimate functional relationships describing the data. Myers (1990) is of the opinion that simplifying regression analysis by performing transformations alters the error structure and risks violating either the homogeneous variance assumption or the normality assumption. A disadvantage of nonlinear regression analysis is that confidence intervals and prediction intervals are very difficult to determine (Myers 1990). Criteria used to choose the best prediction model were (after Myers 1990):

(1) Coefficient of determination (R^2 for linear regression and S, or goodness of fit, for nonlinear regression).
(2) Estimate of error variance or residual mean squares (s^2).
(3) Bias and precision, as defined in this volume.
(4) Analysis of residuals.

Where several models could be fitted to the data with nearly equal effectiveness against the above criteria, then final model selection was based on a judgement of which was most suitable for predicting fire behaviour for applied fire management, the primary aim of this study.

Actual rates of spread and model predictions developed from these field experiments were compared with:

(1) the model developed from laboratory studies,
(2) predictions made using the 1979 edition of FFBT (Sneeuwjagt and Peet 1979),
(3) McArthur's (1973) Forest Fire Meter,
(4) Rothermel's (1972) model.

Predictions using the 1979 version of the FFBT were made using the standard procedure of working through the various tables and interpolating between rate of spread classes. Actual field observations of wind speed, fuel moisture content and fuel quantity were used.

Results and Discussion

Statistics describing the variable ranges and variation during these field experiments are shown in Table 3. Generally, weather conditions over the duration of the study were warm, dry and stable with light winds. The SDI for the Young and Harrington experimental series is graphed in Figure 5. Experimental fires were not permitted by law on days of VERY HIGH or EXTREME fire danger, thereby excluding the opportunity to study fires burning under unstable, hot and windy conditions. The maximum headfire spread rate recorded during the experimental fires was 660 m h^{-1}, with most fires spreading less than 150 m h^{-1}. Data from a well documented wildfire (McCaw *et al.* 1992) burning in upland jarrah forest with a headfire rate of spread of 1000 m h^{-1} were included in the analysis.

Owing to the dry conditions under which most of the experimental fires burnt (SDI > 1200), litter fuel was completely consumed down to mineral earth. The proportion of coarse fuels (> 6 mm in diameter) which burnt varied but generally increased with fire intensity and SDI. Aerial fuel, consisting primarily of live scrub, was low and sparse. Under these conditions, the crowns of mid and upper strata trees were not incorporated as fuel, although there was occasional and localized 'torching' or flame extension through to the upper canopy. There was considerable crown fire development during the wildfire reported by McCaw *et al.* (1992). The quantity and particle size of scrub fuel which burnt varied considerably. Generally, in the flaming zone, all live leaf and twig material up to 2 mm in diameter was consumed by low intensity fires (<500 kW m^{-1}), and all material up to about 4 mm was consumed by higher intensity fires. Aerial fuel did not contribute noticeably to fire rate of spread.

Modelling Headfire Rate of Spread

Pearson correlation coefficients for primary dependent and independent variables are shown in Table 3. Headfire rate of spread was strongly dependent on wind speed, weakly dependent on fuel moisture content and independent of fuel quantity. The effect of fuel quantity on headfire rate

TABLE 3
Descriptive statistics for fuel, weather, and fire behaviour variables measured from 206 observations made during fire behaviour studies in jarrah forest litter fuels in which 67 plots were burnt. Pearson correlation coefficients (R_C) of variables with headfire rate of spread are also shown.

VARIABLE	RANGE	MEDIAN	MODE	R_C
Litter fuel < 6 mm (t ha^{-1})	3.2–19.5	8	10	-0.16
Coarse fuel ≥ 6 mm (t ha^{-1})	0.0–128.2	-	-	-
Litter fuel moisture (% odw)	3.0–18.6	6.6	6	-0.41
Ambient temperature (°C)	15–43	27	30	0.56
Relative humidity (%)	15–68	39	42	-0.38
Wind speed (1.5 m) (km h^{-1})	1.6–8.8	3.9	3.4	0.77
Wind speed (10 m) (km h^{-1})	2.6–12.0	5.6	5.0	0.76
Headfire rate of spread (m h^{-1})	12–1,000	73	30	-
Headfire flame height (m)	0.1–6.6	1.4	0.5	0.89
Headfire flame length (m)	0.1–10.0	1.8	2.0	0.90
Headfire intensity (kW m^{-1})	37–4,368	355	86	-

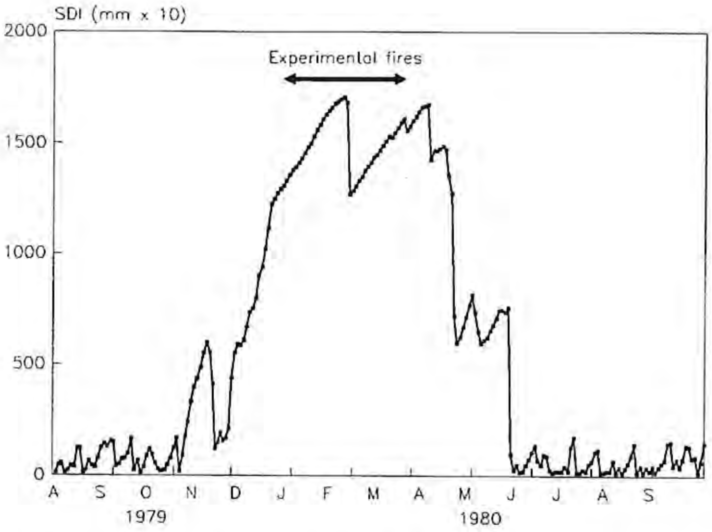


Figure 5. The Soil Dryness Index (SDI) during the period of the Young forest fire behaviour experiments.

of spread was analysed further (see below) using the whole plot data set, as described above.

Headfire rate of spread is graphed with wind speed for all fires in Figure 6. Laboratory fire data (from Burrows this volume) are graphed for comparison. The limitations imposed by scale in attempting to develop fire rate of spread prediction models from the laboratory experiments are evident in Figure 6. The relationship between the rate of spread of laboratory fires and wind speed is linear above a wind speed of about 3.5 km h^{-1} whereas the field data appear to show a nonlinear relationship. Clearly, laboratory fires burning under the influence of strong winds had not reached a steady state and spread rates were significantly lower than field fires experiencing similar wind speeds (Fig. 6).

The importance of wind speed on headfire rate of spread has been widely reported in the literature for a range of fuel types, both natural and artificial, and is reported by Burrows (this volume). On many occasions during these field experiments wind speeds in the forest and at 1.5 m were < 3.5 km h^{-1}, resulting in low, erect, stable and slow spreading fires. When the wind speed was sufficiently high to tilt the flames over the fuel bed, then fires spread rapidly; strong wind gusts blew the flames down onto the fuel bed causing very rapid fire spread. Observations made during the course of the experiments suggest that there are wind speed thresholds which must be exceeded before flames are tilted sufficiently over the fuel resulting in headfires developing and rapid fire spread. While the threshold appeared to vary inversely with fuel moisture content and directly with fuel quantity, wind speeds exceeding about 3.0–3.5 km h^{-1} (or about 10–12 km h^{-1} tower wind speed) were necessary before there were any indications of strong headfire development. This threshold windspeed range is similar to that reported for the laboratory studies (Burrows this volume). While a definitive threshold relationship could not be described from the field data, this phenomenon is reflected in the form of the equations in Table 3 which are graphed in Figure 7. Beer (1991) suggested that the effect of wind speed on headfire rate of spread also depended on atmospheric stability, with fires spreading faster under unstable conditions. Atmospheric stability was not measured during these experiments so its effects on headfire rate of spread could not be determined.

Headfire rate of spread was graphed with wind speed by fuel moisture content classes to determine the best form of the relationship between the two variables, as shown in Figure 7. There were insufficient data for fuel moisture content classes above 12 per cent to warrant graphing. Statistical criteria for model comparisons are presented in Table 4.

Based on the statistical criteria presented in Table 4, the power equation form is better than the exponential at predicting headfire rate of spread, with both non-linear forms being superior to the linear form over the range of the data. The power functions under-predict slightly at very low wind speeds, but more importantly, the exponential forms make unrealistically high predictions on extrapolation to high wind speeds. While there are no sound data to confirm headfire rates of spread at high wind speeds and under dry fuel conditions, casual observations of wildfires suggests that the spread rates predicted by the exponential form seriously over predict across the full range of potential fire conditions likely to be experienced in jarrah forests, and particularly at high wind speeds.

McArthur (1961) and Underwood *et al.* (1985) summarized weather conditions and the behaviour of notable wildfires in jarrah forests and some of these data are contained in Table 5 below. The wind speed data were from 2–3 hourly observations made 25–30 km from the fires. It is not clear from McArthur's (1961) tabulated summaries whether these observations are averages over the three hours or are spot readings made every three hours. The latter is most likely the case given the nature of the instruments used. The maximum wind speed recorded for each fire spread interval is presented in Table 5. Fuel moisture content was estimated from temperature and relative humidity data provided by McArthur (1961) and Underwood *et al.* (1985) and using a relationship between fine fuel moisture content, temperature and relative humidity developed by Luke and McArthur (1978).

The observed wildfire data in Table 5 must be interpreted cautiously. Apart from doubts about the

TABLE 4

Summary of statistics for comparing candidate models for predicting headfire rate of spread (r_f) from wind speed (U) by fuel moisture content classes (SMC). Linear models apply for U > 3.5 km h^{-1}. Numbers bolded and in parentheses refer to equations graphed in Figure 7.

EQUATION	S	s^2	RESIDUALS		PRECISION	BIAS
R_F =			RANGE	MEAN		
			3% < SMC ≤ 4%			
$25.88e^{0.494U}$ (1)	0.97	2349	–66.6–74.8	–5.8	15.3	–7.5
$3.78U^{2.78} - 9.23$ (2)	0.98	748	–49.0-37.2	0.5	19.1	3.1
$220.3U - 730.3$ (3)	0.96	2679	–87.1-59.2	–1.9	41.4	13.9
			4% < SMC ≤ 6%			
$20.97e^{0.38U}$ (4)	0.82	1984	–77.2–213.3	–1.1	28.9	–4.6
$5.84U^{2.04} - 10.1$(5)	0.83	1841	–76.1–199.0	0.6	26.1	0.2
$66.35U–171.9$ (6)	0.81	1998	–81.7–187.0	0.0	39.9	7.5
			6% < SMC ≤ 8%			
$13.65e^{0.45U}$ (7)	0.88	955	–69.6–166.2	–1.3	29.7	–9.4
$1.65U^{2.63} + 4.56$ (8)	0.91	723	–66.0–140.7	1.3	31.7	2.5
$68.65U - 206.8$ (9)	0.79	1772	–86.0–154.5	0.7	35.5	8.2
			8% < SMC ≤ 12%			
$6.80e^{0.45U}$ (10)	0.85	82	–12.2–17.0	0.6	28.6	0.1
$2.29U^{2.09} + 2.1$(11)	0.87	78	–10.8–19.6	0.4	30.4	1.6
$22.78U - 43.86$ (12)	0.84	85	–11.3–22.3	0.0	42.4	5.3

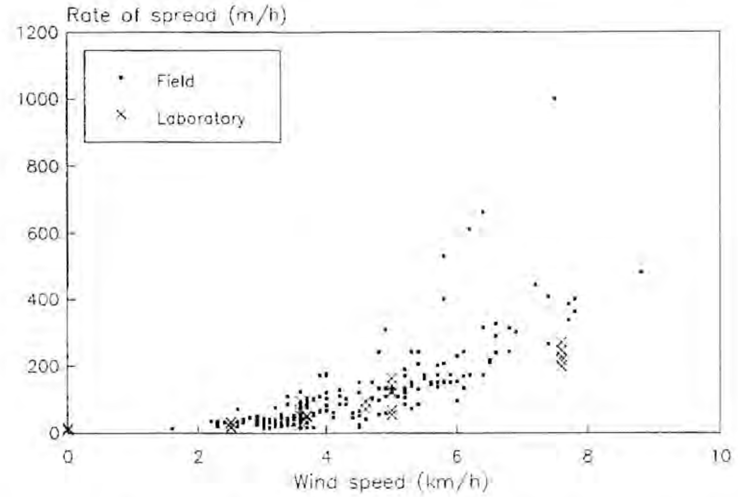


Figure 6. Rate of spread graphed with wind speed for field and laboratory fires (Burrows this volume) in jarrah forest litter fuels.

validity of using wind speed information from a distant station, these fires burnt in undulating terrain and often through different fuel types. In addition, headfire behaviour was probably influenced by intense downwind spotfire development commonly associated with jarrah forest fires under severe conditions. Despite these limitations, these data are a guide to the range of fire behaviour possible in south-west forests under severe fire weather conditions, which assists with appropriate model selection. In choosing between exponential and power equation forms, it was decided to risk slight under prediction at very low wind speeds by the power form rather than serious over prediction at high wind speeds by the exponential form (Table 5). It is also clear from Table 5 that while the power equation form fits the range of experimental data well, it over predicts rate of spread at very high wind speeds (not as seriously as the exponential). This suggests that the relationship between wind speed and rate of spread may be a sigmoidal one. Further research and carefully documented wildfire observations are needed to confirm the form of the relationship between wind speed and spread rate under high wind conditions.

The relationship between headfire rate of spread and surface fuel moisture content (SMC) was examined by stratifying the data according to wind speed classes (Fig. 8) and fitting various models to the data. Of the candidate models shown in Table 6, the power form was the preferred model for the range of experimental data. Without the inclusion of a third parameter (constant) the power form presents a problem when SMC is 0 per cent. In the field, SMCs less than 3 per cent odw have never been recorded and it is highly unlikely that field SMC would ever reach 0 per cent odw. At the other end of the

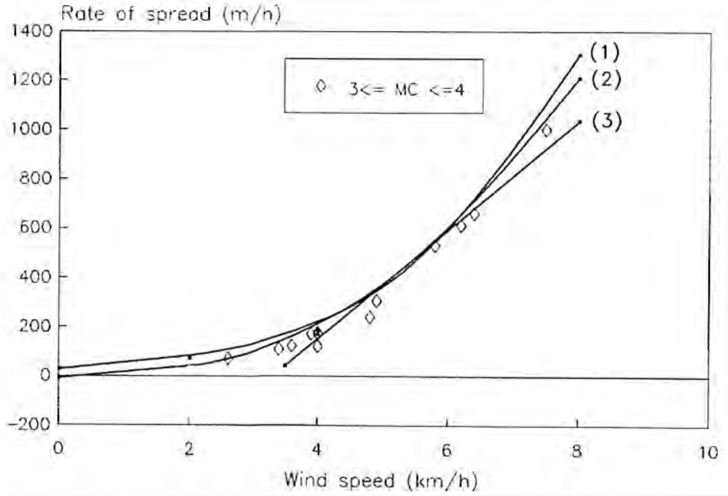


Figure 7. Rate of spread of field fires graphed with wind speed measured at 1.5 m above the forest floor and by fine fuel moisture content classes. Numbers in parentheses refer to equations in Table 4.

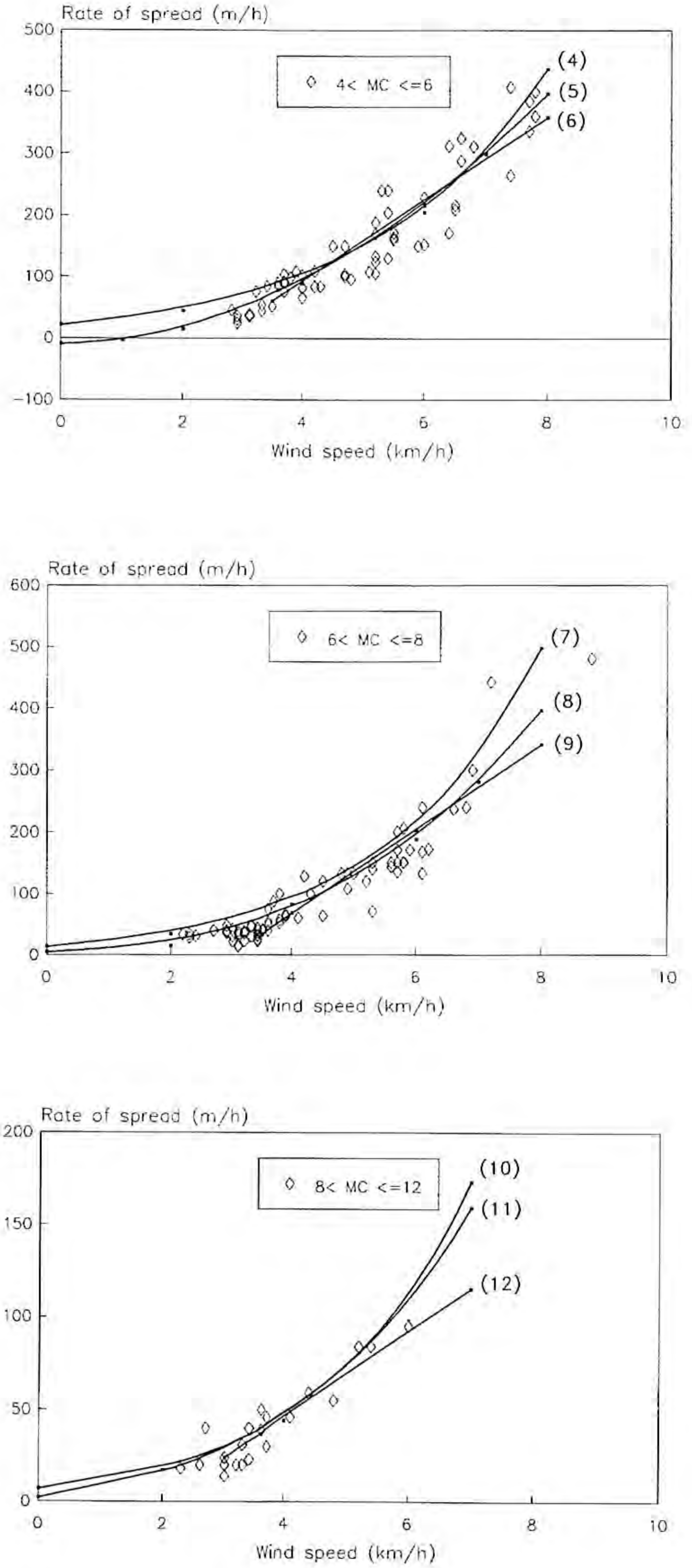


Figure 7 (continued). Rate of spread of field fires graphed with wind speed measured at 1.5 m above the forest floor and by fine fuel moisture content classes. Numbers in parentheses refer to equations in Table 4.

moisture content range, the nonlinear relationships do not intercept the x-axis at moisture content of extinction, which for jarrah eucalypt litter bed is about 21 per cent odw (Burrows this volume).

On the basis of the results presented in Tables 4 and 6, a headfire rate of spread prediction model incorporating a power function in wind speed and a power function in fuel moisture content was developed using a single nonlinear least squares fitting procedure (SAS Institute Inc. 1985). The final form of the model was:

$$r_F = 23.192(SMC)^{-1.495} * U^{2.674} + 11.60 \qquad \text{(Equation 1)}$$

(4.036) (0.044) (0.095) (4.376) (parameter standard errors).

An alternative model was developed by transforming the data to linearize the relationship between rate of spread, wind speed and fuel moisture content. This model was developed to generate a coefficient of determination and so that confidence limits could be determined. Natural log transformations on the independent variables resulted in the model;

$$\ln(r_F) = 2.16(\ln U) - 1.05(\ln SMC) + 3.25 \qquad R^2 = 0.85,$$

where;

r_F = headfire rate of spread (m h^{-1}),

SMC = surface fuel moisture content (% odw),

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

The analysis of variance and residual statistics for Equation 1 are contained in Table 7. Residuals (observed rate of spread minus that predicted using Equation 1) were checked for normality by examining their frequency distribution, the Shapiro-Wilk (W) statistic (SAS Institute Inc. 1985), skewness and kurtosis (0.946, 0.910 and 5.516 respectively). These statistics support the null hypothesis that the residuals are normally distributed and variance is homogeneous, so a transformation (described above) is appropriate.

Residual outliers coincided with fire spread intervals where wind gusts were observed at the fire face but not recorded by the anemometers and vice versa. Rate of spread predicted using Equation 1 adjusted for tower wind speed is graphed for five surface fuel moisture contents in Figure 9.

Headfire rate of spread was poorly correlated with fuel quantity for laboratory experiments described by Burrows (this volume). The relationship was equally poor (Table 2) for field data where the average rate of spread over selected time intervals (intermediate rates of spread) within each plot was regressed with mean fuel quantity burnt over the same interval (see Methods section). Headfire rate of spread is graphed with fuel quantity by wind speed classes in Figure 10 with no relationship apparent between the two variables. The relationship was further examined using whole of plot data where the mean plot rate of spread and the mean plot fuel quantity were analysed on the assumption that estimates of mean fuel quantity over the entire plot (see Methods section) may better reflect fuel involved in headfire spread. However, this procedure also failed to show any significant relationship between headfire rate of spread and fuel quantity (Pearson correlation coefficient = –0.165). Mean plot headfire rate of spread is graphed with mean plot fuel quantity in Figure 11. Eliminating variation in rate of spread owing to wind speed and moisture content using Equation 1 also failed to show any significant relationship between rate of spread and fuel quantity.

The lack of a relationship between headfire rate of spread and litter fuel quantity reported in this study contrasts with widely held beliefs within the Australian fire community and with commonly used Australian forest fire behaviour guides (McArthur 1962; Peet 1965; Sneeuwjagt and Peet 1979) which assume that spread rate is directly related to fuel quantity. Cheney *et al.* (1989) and Gould (1991) found that the rate of spread in grassland fuels was not related to fuel quantity but was related to fuel height and continuity. Cheney (1990b) also noted in a discussion paper that statistical support for the notion that rate of spread and fuel quantity are directly

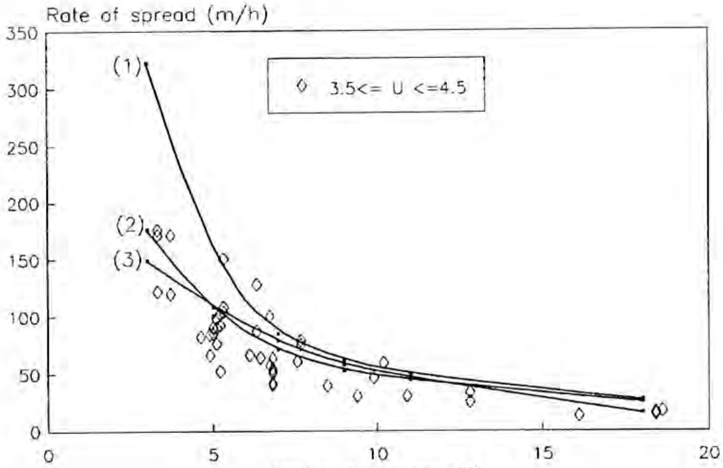


Figure 8. Rate of spread of field fires with fine fuel moisture content by wind speed classes. Numbers in parentheses refer to equations in Table 6.

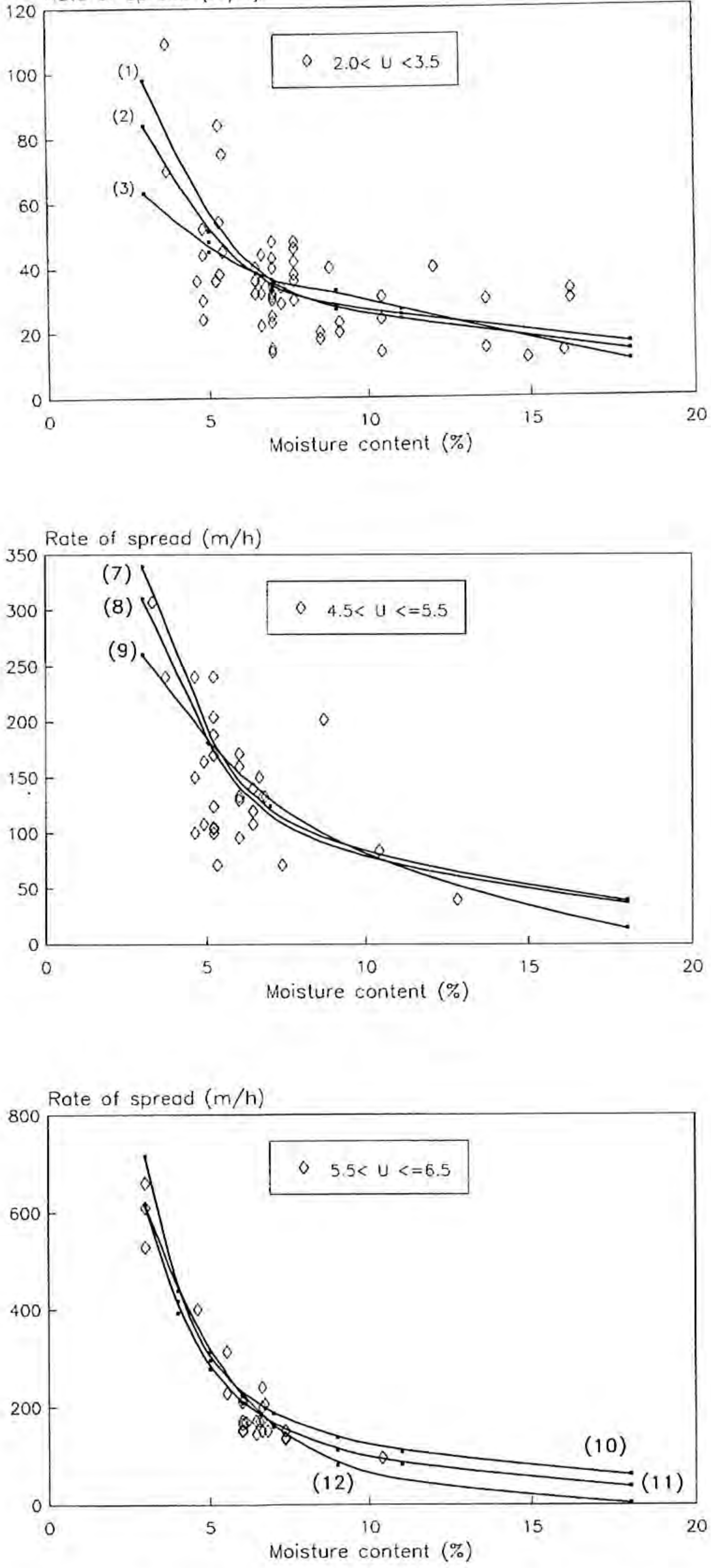


Figure 8 (continued). Rate of spread of field fires with fine fuel moisture content by wind speed classes. Numbers in parentheses refer to equations in Table 6.

TABLE 5

Headfire rates of spread (ROS) and associated wind speeds observed during wildfires in various fuel types in the south-west of Western Australia are compared with rates of spread predicted by linear and non-linear models described in Table 3 for jarrah forest fuel and flat terrain. Surface fuel moisture content (SMC) was estimated using temperature and relative humidity (Luke and McArthur 1978). The tower wind speed-to-wind speed at 1.5 m in the forest (U) ratio is assumed to be 3:1 or 4:1 depending on forest type and topography. The serious over-prediction by the exponential model at high winds and under-prediction by the linear one is clearly evident. (Source: McArthur 1961 and Underwood *et al.* 1985).

FIRE	OBSERVED ROS (m h^{-1})	U (km h^{-1})	SMC (%)	PREDICTED ROS (m h^{-1}) EXPONENTIAL	POWER	LINEAR
			McArthur (1961)			
Torrens	1328	6.8	4	744	770	767
Marrinup	2414	8.0	4	1346	1215	1032
Duncans	1609	8.0	4	1346	1215	1032
Gidgegannup	2343	8.8	4	1999	1587	1208
			Underwood *et al.* (1985)			
Rocky Gully	6400	15.0	4	42764	7021	2574
Lake Muir	1000	6.6	4	674	735	723
Lake Muir	3000	10.0	4	3617	2268	1473
Bruswick	8000	20.0	4	50558	15644	3676
Gervasse	10000	25.0	4	5.97×10^6	29082	4777
Colonel's	400	6.2	4	553	603	635

TABLE 6

Candidate models and associated statistics relating headfire rate of spread (r_F) and surface fuel moisture content (SMC) by wind speed classes (U). Numbers bolded and in parentheses refer to equations graphed in Figure 8.

EQUATION R_F =	S	s^2	RESIDUALS RANGE	RESIDUALS MEAN	PRECISION	BIAS
			$2.0 \leq U < 3.5$			
1/(0.0046SMC–0.0035) (1)	0.41	158	−29.8–36.1	0.2	40.7	5.3
$253.9\mathrm{SMC}^{-1.01}$ (2)	0.41	152	−28.0–41.6	0.0	38.1	2.7
$88.7e^{-0.12\mathrm{SMC}}$ (3)	0.31	176				
			$3.5 \leq U \leq 4.5$			
1/(0.0022SMC–0.0035) (4)	0.71	492	−35.9–56.8	0.0	29.2	−2.8
$563.1\mathrm{SMC}^{-1.07}$ (5)	0.74	456	−36.8–55.4	0.6	28.5	−3.6
$240.3e^{-0.16\mathrm{SMC}}$ (6)	0.72	481	−43.7–47.0	−2.4	27.2	1.2
			$4.5 < U \leq 5.5$			
1/(0.0015SMC–0.0015) (7)	0.62	1344	−85.1–81.2	−2.7	24.7	−1.2
$1141.9\mathrm{SMC}^{-1.20}$ (8)	0.61	1369	−82.9–82.8	−0.9	25.0	0.2
$453.7e^{-0.19\mathrm{SMC}}$ (9)	0.55	1560	−89.3–71.0	−6.3	28.8	0.9
			$5.5 < U \leq 6.5$			
1/(0.001SMC–0.0016) (10)	0.92	1840	−185.2–66.6	−34.0	49.8	−12.8
$3400.7\mathrm{SMC}^{-1.56}$ (11)	0.92	1674	−83.7–85.4	−4.0	16.6	−2.2
$1705.5e^{-0.34\mathrm{SMC}}$ (12)	0.92	1631	−86.0–59.1	−8.5	24.7	−0.8
			$U > 6.5$			
1/(0.00063SMC–0.00089)	0.80	6686	−101.6–214.8	−0.6	27.1	1.3
$5051.6\mathrm{SMC}^{-1.49}$	0.79	7234	−104.4–223.9	−1.9	28.7	1.1
$2590.9e^{-0.33\mathrm{SMC}}$	0.73	9195	−109.1–254.5	−3.9	35.1	2.1

TABLE 7
Analysis of variance and residual statistics for regression Equation 1.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE
Regression	4	5861205.75	1465301.43
Residual	202	201653.92	849.04
U/C Total	206	6032712.99	
C Total	205	3335664.25	

RESIDUALS

Range	Mean	Bias	Precision
92.1–159.6	0.097	0.50	29.48

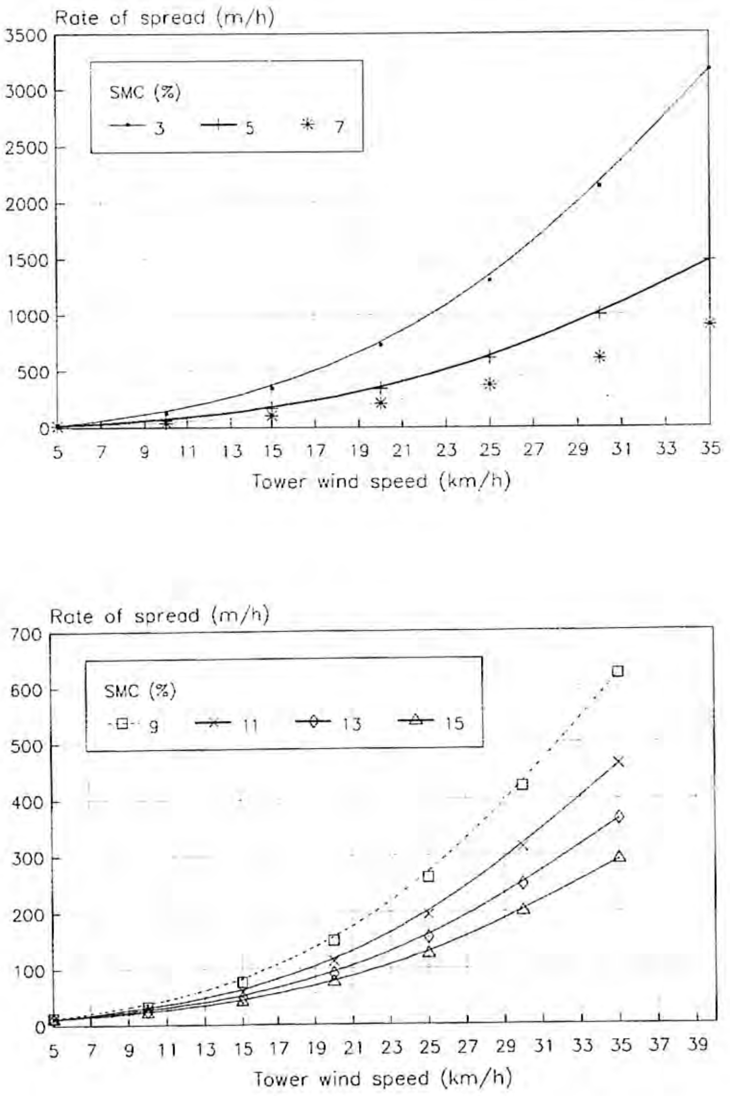


Figure 9. A fire rate of spread prediction model for standard jarrah forest fuels; $r_F = 23.192(SMC)^{-1.495} * (0.33W_T)^{2.674}$ *where* r_F *= headfire rate of spread (m* h^{-1}*), SMC = fine fuel moisture content (% of oven dry weight) and* W_T *= tower wind speed (km* h^{-1}*).*

related was 'difficult to find'. McAlpine (1995), working in a variety of Canadian forest fuels, showed a weak, undefined relationship between rate of spread and fuel load. He doubted whether including the relationship in the Canadian fire behaviour system would improve its predictive capacity.

McArthur and Luke (1963) and McArthur (1967) reported a positive linear correlation between rate of spread and available fuel quantity for jarrah forest fires; doubling fuel quantity caused a doubling of rate of spread (Fig. 14). McArthur's (1961 and 1967) relationship was derived by comparing the rates of spread of wildfires in different fuel ages (and quantities) and by monitoring the development of experimental fires lit simultaneously in forest and woodlands of different fuel age (and different fuel quantity). Data from nine experimental fires lit in jarrah forests were extracted from Leaflet 107 (McArthur 1967) and a linear regression model fitted to these data (Fig. 14). These fires were set in very light fuels and, based on the low rates of spread, burnt under mild weather conditions. The data show a strong linear relationship between rate of spread and fuel quantity which contrasts with the findings of this study.

There are three possible explanations for the contrast in findings. The first possibility is that rate of spread is in fact affected by fuel quantity but the experimental procedures adopted here failed to demonstrate this. Secondly, it is possible that in McArthur's experiments, fire behaviour was responding to fuel structural differences associated with the various ages and not to fuel quantity *per se*. This could not be examined by this study because of the narrow range of fuel ages. Data presented by Burrows (1994) for jarrah litter fuels show that the structure and composition changes in the first four years following fire. After this time, the structure of the litter bed does not vary significantly but the fraction of fine

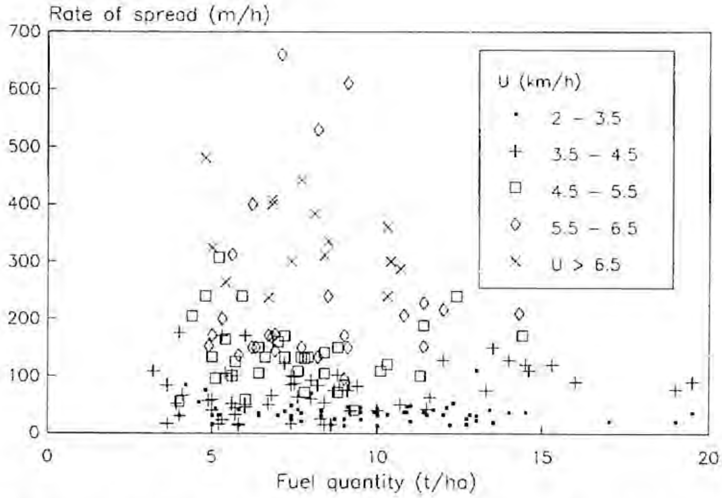


Figure 10. Mean headfire rate of spread with mean fuel quantity by wind speed classes for multiple observations per plot (see Method 2, Fig. 4).

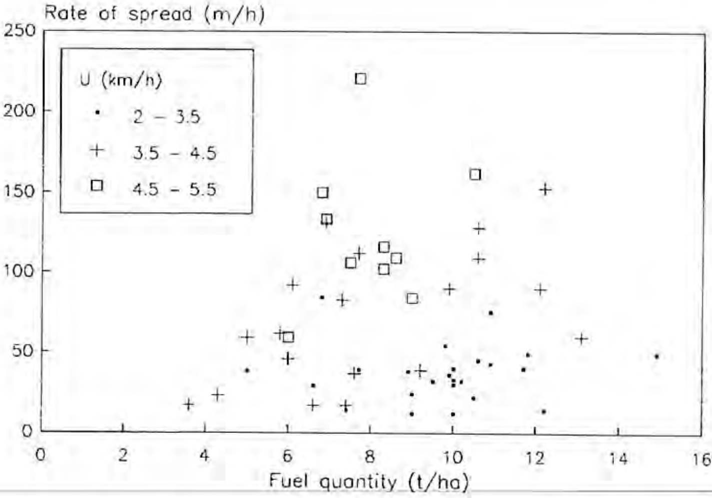


Figure 11. Mean headfire rate of spread through each plot with mean plot fuel quantity (see Method 1, Fig. 4).

round wood, which is the most flammable component of the litter bed, increases with time. The structure of the understorey vegetation changes with time after fire for up to 20 years (Burrows 1994). Temporal changes in the composition of the litter bed and in the structure of the understorey are likely to affect fuel flammability. Another explanation is that the jarrah fires studied by McArthur were not wind-driven, but were largely convection dominated fires (i.e. flames virtually erect). The fires were lit from a point source and were monitored for some 20–30 minutes. The very low rates of spread of these fires (Fig. 12) suggests that they burnt under very light winds, probably below the threshold for wind driven headfire development (no meteorological data are presented). If this was the case, then these fires were probably behaving similarly to backfires and sub-threshold wind speed (<3.5 km h^{-1}) fires reported by Burrows (this volume). Unlike wind-driven fires, the rates of spread of low wind fires and backfires were found to be dependent on fuel quantity in much the same way as reported by McArthur. McArthur (1967) does not provide sufficient detail about fuel structure and weather conditions to allow a thorough interpretation of his findings with regard to the effect of fuel quantity on rate of spread.

Peet (1972) reported a poor relationship between fuel quantity and rate of spread for small, low intensity jarrah litter fires both in the field and during 'tray' experiments. However, he felt that this was probably owing to poor fuel sampling techniques in the field, so opted to use the linear relationship developed by Fons (1946) and McArthur (1962) when developing the first version of Forest Fire Danger Rating guides for WA (Peet 1965). This relationship was carried through to updated guides. The 1979 edition of FFBT incorporates a fuel quantity correction factor for predicting rate of spread such that at low moisture contents (3–9 per cent), doubling fuel quantity results in a two-fold increase in predicted rate of spread (Sneeuwjagt and Peet 1979). This is similar to the relationship developed in the laboratory studies reported for zero wind fires and backfires (Burrows this volume). It is possible that the original relationship between rate of spread and fuel quantity (Fons 1946) was developed under zero or sub-threshold wind conditions in the laboratory where radiation is the primary spread mechanism, and was assumed to hold for wind-driven fires, where forced convection (flame contact) is probably the primary spread mechanism.

Nelson and Adkins (1987) have proposed that the horizontal displacement of flame at the fuel surface, by a convection mechanism related to wind speed, is the key to fire spread. Results reported here support this theory. The quantity of fuel undergoing combustion in the flaming zone, other things being equal, is a function of horizontal flame depth and the rate of vertical depth of burn into the fuel profile (Byram 1959). This may not be a function of fuel quantity *per se* but of fuel particle size and arrangement, packing ratio and fuel bed bulk density, as recognized by models developed by Rothermel (1972) using artificial fuel beds. Jarrah litter fuel has a high bulk density and a high packing ratio, and individual particles have a low surface area-to-volume ratio (Burrows 1994) compared with grassland and heathland fuels (e.g. Rothermel 1972; Catchpole 1985). The mean packing ratio for jarrah litter fuel is about 0.079, based on the linear depth-weight relationship presented by Burrows (1994). Blake and Johnson (1973) found that the packing ratio of the litter in a eucalypt forest in New South Wales varied considerably, but was mostly greater than 0.07. Eucalypt litter fuel beds are very compacted compared with some other litter bed fuel types. For example, Brown (1970) determined a packing ratio of 0.03 for ponderosa pine forest needle litter. The optimum packing ratio for

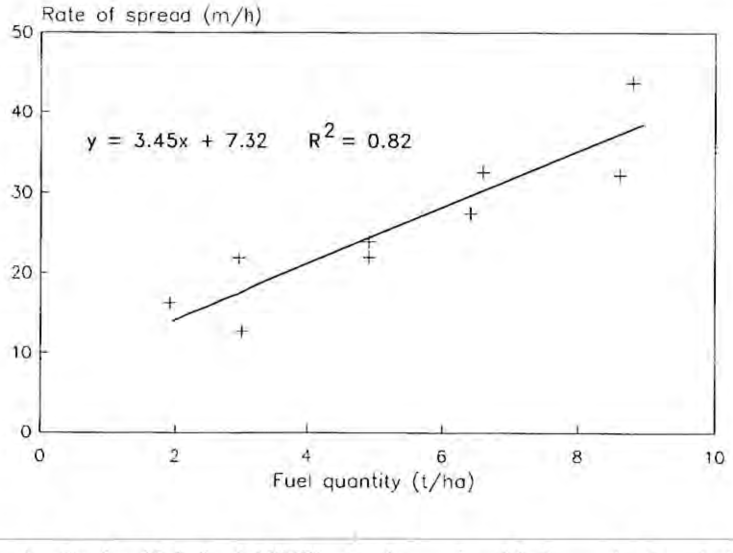


Figure 12. Linear regression fitted to McArthur's (1967) rate of spread and fuel quantity data derived from small scale experimental plots in jarrah forest.

eucalypt litter fuel particles, using Rothermel's (1972) equation, is about 0.006, so jarrah forest litter is far from an optimum fuel according to this definition. Significant increases in rate of spread with increasing fuel quantity are only likely in fuel beds at or near optimum packing ratio (Rothermel 1972; Chandler *et al.* 1983). For poorly aerated, compacted fuel beds, the rate of flame spread across the surface of the fuel bed, where aeration is best, will be considerably greater than the rate of combustion vertically through the fuel bed. Therefore, most of the heat energy for flame propagation will be provided by the combustion of surface particles in the forward portion of the flaming zone, with the combustion of particles deeper in the fuel bed occurring progressively further behind the leading edge, and so contributing little or nothing to flame propagation. If bulk density and packing ratio are constantly high with increasing fuel quantity (as is more or less the case with jarrah litter fuels), then changes in fuel quantity are unlikely to significantly affect rate of spread. Observed higher spread rates in old and heavy eucalypt fuels (not including fire perimeter extension by spotting or crown fire development) is probably in response to changes in fuel composition and structure. This is likely to be particularly important in forests with a dense understorey supporting a significant quantity of suspended dead material (trash fuel). The effect of temporal changes in eucalypt forest fuel structure on fuel flammability requires further investigation.

Rate of Spread Predicted using the Forest Fire Behaviour Tables

Headfire rate of spread observed during these experiments is graphed with headfire rate of spread predicted using the Forest Fire Behaviour Tables for WA (FFBT) (Sneeuwjagt and Peet 1979) in Figure 13. Predictions were made using actual weather and fuel moisture content data rather than forecast data. A wind speed ratio of 1:1 (i.e. wind speed measured in the forest at 1.5 m) was used and normal procedures for correcting for fuel quantity were followed.

The FFBT 1979 edition under estimates the rate of spread of fires spreading faster than about 50–60 m h^{-1} by a factor of about two on average (Fig. 13) and over estimates the rate of spread of slower fires burning under light winds. The R^2 value for the regression graphed in Figure 13 is 0.59, indicating a mediocre linear relationship between predicted and observed rates of spread. The FFBT over estimated the influence of low fuel moisture content on spread rate at very low wind speeds (< 3.5 km h^{-1}). For example, at a wind speed of 2 km h^{-1} (1:1 wind speed ratio) and a moisture content of 3 per cent, the FFBT predicts a spread rate of 148 m h^{-1} in standard jarrah fuel, compared with a prediction of 40 m h^{-1} using Equation 1.

The jarrah FDI (Sneeuwjagt and Peet 1979) is defined as the maximum rate of spread predicted from wind speed and surface fuel moisture content under standard conditions, i.e. on level terrain and in jarrah litter fuels of 7.6–8.5 t ha^{-1}. For other than standard conditions, slope and fuel quantity correction factors are applied to the FDI for predicting rate of spread (Sneeuwjagt and Peet 1979). The FDI, or the predicted rate of spread under standard conditions, is graphed with observed rate of spread in Figure 14. Although the predictions are lower than observations, the correlation coefficient is significantly better ($R^2 = 0.78$) than that for predictions which have been corrected for fuel quantity ($R^2 = 0.59$, Fig. 13).

While about 20 per cent of the variation between FFBT predictions and observed rates of spread can be explained by the FFBT assumption that there is a strong relationship between rate of spread and fuel quantity, this does not account for under prediction at higher wind speeds. The magnitude of under prediction cannot be totally explained by the fact that Peet's (1972) wind speed measurements were made at four feet (1.2 m) compared with 1.5 m during this study. The most likely explanation is that as Peet's experimental fires were mostly small and lit from a point source, they had not reached their potential rate of spread (quasi-steady state) for the prevailing fuel and weather conditions. Cheney and Gould (1995) showed headfire width to be an important factor affecting the rate of spread of grassland fires. They found that, for a given wind speed, a quasi-steady rate of spread was not achieved until the headfire had reached a minimum width. For grassy woodlands, this was between 100–200 m and if the same conditions apply for eucalypt fuels, then it is possible that the fire behaviour model developed here (Equation 1) may also under predict, but not to the same extent as earlier models. This needs validation.

Rate of Spread Predicted using the McArthur Forest Fire Danger Meter

Headfire rate of spread predicted using McArthur's Forest Fire Danger Meter (FFDM) equations developed by Noble *et al.* (1980) are graphed with observed rate of spread in Figure 15 and McArthur's Forest Fire Danger Index (Mark 5) is graphed with observed rate of spread in Figure 16. The relationship between predicted (FFDM) and observed rate of spread is very poor ($R^2 = 0.26$) with the FFDM over predicting during conditions of low fuel moisture, low wind speeds and high fuel quantities, and seriously under predicting (by a factor of up to 3) during conditions of high wind speeds and low fuel quantities. A better relationship was obtained between McArthur's Forest Fire Danger Index and observed rate of spread (Fig. 16).

Rate of Spread Predicted using the Rothermel Model

Observed rates of spread are plotted with predictions made using Rothermel's (1972) model in Figure 17. Jarrah fuel parameter values used in the Rothermel model (e.g. packing ratio, surface area-to-volume ratio) are described by Burrows (1994) and are summarized in Appendix 1. Weather and fuel moisture content inputs were measured in the field, with wind speed measured at 1.5 m and not at mid-flame height, as required by the Rothermel model. Equations used to calculate the Rothermel predictions in metric units are contained in Appendix 1.

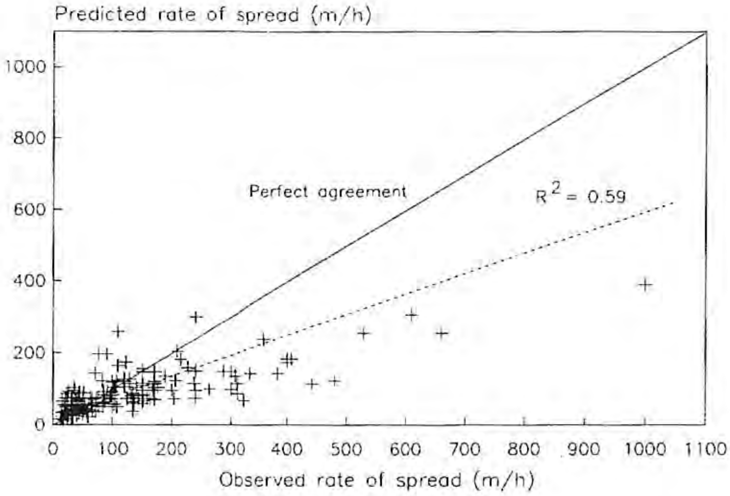


Figure 13. Rate of spread predicted using the 2nd edn Forest Fire Behaviour Tables for Western Australia (Sneeuwjagt and Peet 1979). Later editions incorporate some of the findings of the work described here.

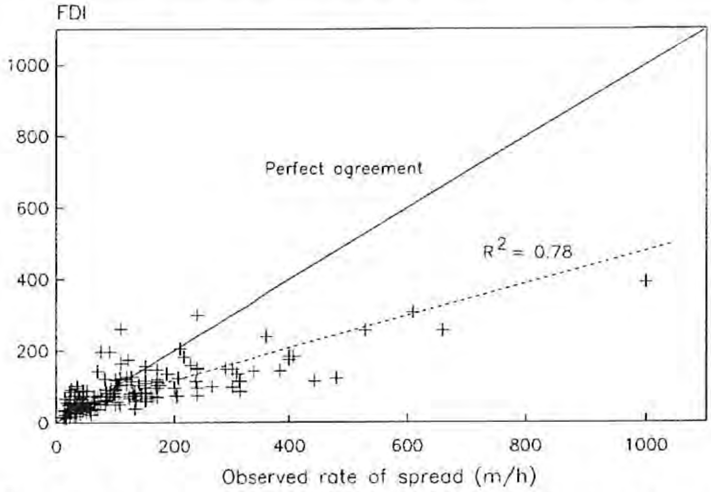


Figure 14. The jarrah Forest Fire Danger Index (FDI), or the rate of spread in a standard jarrah fuel on level terrain (2nd edn Forest Fire Behaviour Tables for Western Australia, Sneeuwjagt and Peet 1979) graphed with observed rate of spread.

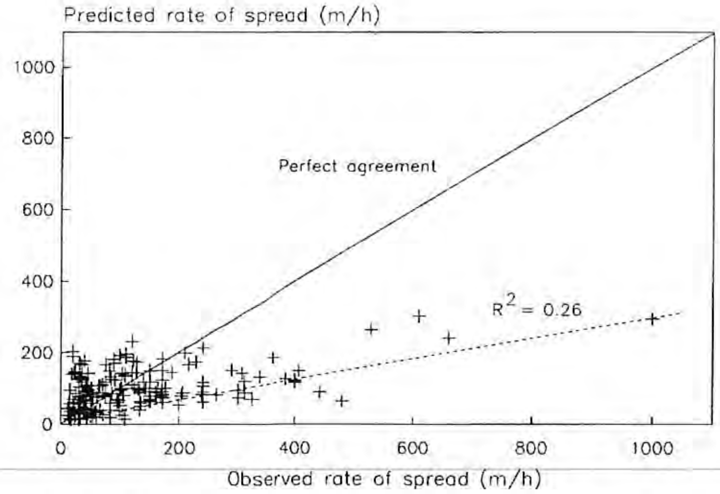


Figure 15. Rate of spread predicted using the McArthur Forest Fire Danger Meter with observed rate of spread.

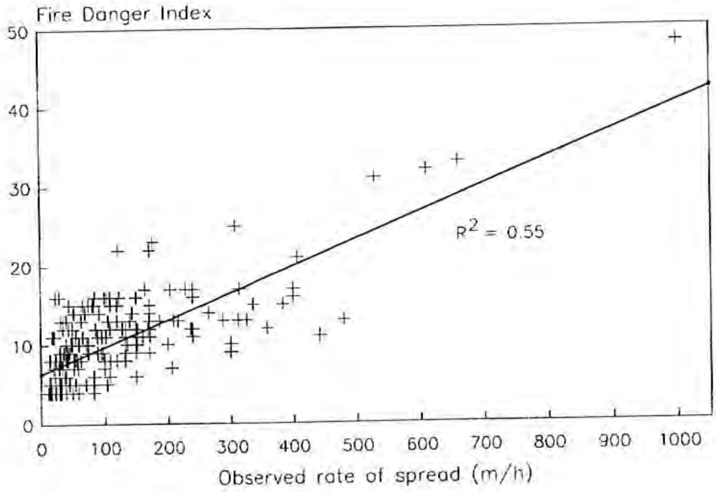


Figure 16. McArthur Forest Fire Danger Index with observed rate of spread in jarrah forest fuels.

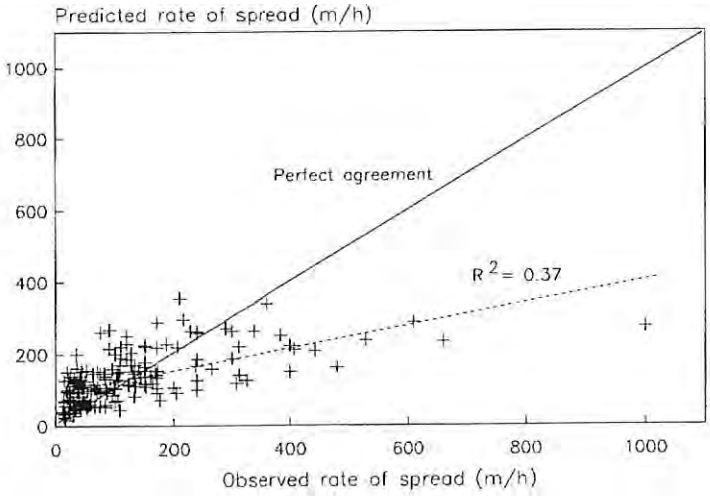


Figure 17. Rate of spread predicted using Rothermel's (1972) model with observed rate of spread in jarrah forest fuels.

As with the McArthur model, the Rothermel model over predicts rate of spread when wind speeds are low (<3.5 km h^{-1}) and when fuel quantities are high. Both models assume a direct relationship between fuel quantity and rate of spread. The model seriously under predicts the spread rate of fires burning under high wind speeds and low fuel moisture contents although the Rothermel model makes marginally better predictions than the McArthur model ($R^2 = 0.37$).

The Rothermel model has been tested for a number of fuel types including slash fuels (Brown 1971), grassland (Sneeuwjagt and Frandsen 1977; Van Wilgen and Wills 1988; Everson *et al.* 1988; Gould 1991), palmetto-gallberry (Hough and Albini 1978), fynbos (Van Wilgen 1984) and heathland (Catchpole 1985) and was found to perform reasonably well in most cases, with R^2 values (actual vs. predicted rate of spread) of 0.89–0.92. However, the model did not perform as well during grassland experiments conducted in the Northern Territory (Gould 1991) with an R^2 (actual vs. predicted rate of spread) of 0.55. In all cases, fuels were considerably deeper and more aerated than the jarrah litter fuel bed described here. Andrews (1980) summarized the results of most of these validation studies and also compared Rothermel predictions with spread rates observed during several wildfires. No fuel, weather or topographical details are provided for the wildfire conditions, but in all cases, the Rothermel model performed considerably better than reported here.

Flame Dimensions and Fire Intensity

Flame height and length are important measures of the heat energy output of a fire, hence its severity both in terms of control difficulty and impact on the biota (Byram 1959; Luke and McArthur 1978). Accurate measurements of flame dimensions are difficult to obtain in the field, especially for moderate to high intensity fires. The ocular method used during this study may not have been accurate, but the observers showed an acceptable level of consistency with estimations. Headfire flame height (h_F) increased with headfire rate of spread (r_F) according to Equation 2. Predictability of flame height was improved by incorporating fuel quantity (w_C) as shown in Equation 3. Flame size was a consequence of factors affecting rate of spread (wind speed and fuel moisture content) and fuel quantity; large flames did not cause fires to spread faster, but were a consequence of these factors. Flame height is graphed with rate of spread by fuel quantity classes in Figure 18. Flame length (L) was strongly related to flame height by Equation 4.

$$h_F = 0.062(r_F)^{0.687} \qquad \text{(Equation 2)}$$

$$h_F = 0.00335(r_F) * w_C \qquad \text{(Equation 3)}$$

$$L = 1.33h_F \qquad \text{(Equation 4)}$$

where:
h_F = flame height (m),
L = flame length (m),
r_F = rate of spread ($m\ h^{-1}$),
w_C = fuel quantity ($t\ ha^{-1}$).

The general form of flame height and length relationships presented above is similar to those reported for other fuels (e.g., Byram 1959; McArthur and Cheney 1966; Luke and McArthur 1978).

Byram (1959) derived an equation approximating the relationship between flame length and fire intensity (Fig. 19). Other fire researchers have rearranged this equation to determine fire intensity from direct observation of flame length (see Alexander 1982). The relationship between flame length and fire intensity for standard jarrah fuel was:

$$L = 0.0147(I)^{0.767} \qquad \text{(Equation 5)}$$

where L = flame length (m) and I = Byram's intensity ($kW\ m^{-1}$).

Equation 5 is graphed in Figure 19 with Byram's (1959) relationship. The coefficients in the equations shown in Figure 19 are significantly different, resulting in considerable divergence of predictions of intensity with increasing flame length beyond a flame length of about 1.5–2.0 m. Byram's (1959) equation predicts significantly higher intensities for a given flame length than Equation 5. Although Byram (1959) warned that his relationship would give better approximations for lower intensity fires, it is possible that equation coefficients may vary with fuel type, reflecting different flame characteristics. For example, Cheney (1981) estimates that a moderate intensity (501–3000 kW m^{-1}) fire in open *Eucalyptus* forest will have a maximum flame height of 6.0 m (therefore a flame length greater than 6 m, probably near 8 m). Using data from Luke and McArthur (1978) (Figure 6.15, page 93), a fire in dry sclerophyll (open *Eucalyptus*) forest with an intensity of about 2500 kW m^{-1} will have an estimated flame height of 5–7 m (length about 6.6–9.3 m) depending on wind speed. These values are similar to those presented in Figure 19 for jarrah forest. However, Byram's (1959) equation, presumably developed from observations of North American conifer forests, predicts that a fire with an intensity of 3000 kW m^{-1} will have a flame length of about 3.1 m. Clarke (1983), working in grassland fuels, reported a fire intensity-flame length relationship which differed from that presented by Byram (1959) and concluded that flame length was neither a good nor consistent estimator of fire intensity.

Fire intensity can be predicted from observed flame length by rearranging Equation 5 as follows:

$$I = 293.871(L)^{1.118} \qquad \text{(Equation 6)}$$

Byram's (1959) equivalent equation is (after Alexander 1982):

$$I = 259.833(L)^{2.174}$$

Clearly, the equations will predict significantly different intensities for a given flame length confirming

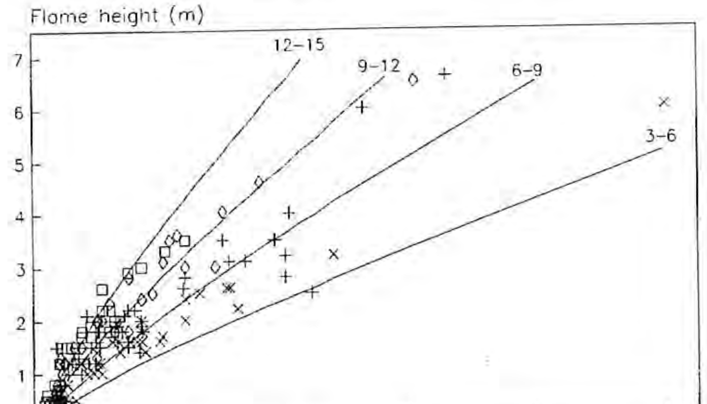


Figure 18. Relationship between flame height (h), headfire rate of spread (rF) and fuel quantity (w): h = 0.00335(r_F) x w.

recommendations by Alexander (1982) and Cheney (1990a) that fire intensity should not be used to make comparisons between fires in different fuel types.

Flame Residence Time

Flame residence time (t_R - seconds), as defined by Fons *et al.* (1962), was calculated from flame depth and headfire rate of spread (Cheney 1981) and is graphed in Figure 20 with fuel quantity, the only variable to show a reasonable correlation with residence time (Pearson correlation coefficient = 0.55). As indicated by the plotted data and by the low R^2 value for the no intercepts model, the relationship is a poor one reflecting unmeasured variation in fuels, the difficulty of accurately measuring flame depth and natural, unexplained variation. McArthur (1967) reported a decrease in residence time with increasing wind speed and decreasing fuel moisture content for eucalypt litter fuel beds in the field, but laboratory studies reported by Burrows (this volume) and studies by Byram *et al.* (1966) and Rothermel and Anderson (1966) found residence time to be unaffected by these variables.

Flame residence times observed during the field fires were considerably longer than the times reported by Burrows (this volume) during the laboratory studies. The difference may be attributable to the different composition of the fuel beds. Only fresh fine leaf and twig material were used in the laboratory whereas field fuels consist of a shallow surface layer of fresh fuel underlain by material at various stages of decomposition. Field fuels also contain a range of larger fuel particles which were not a feature of the laboratory fuels.

CONCLUDING DISCUSSION

Headfire rates of spread up to 660 m h^{-1} were recorded during fire experiments described in this study which is significantly higher than previously reported by other

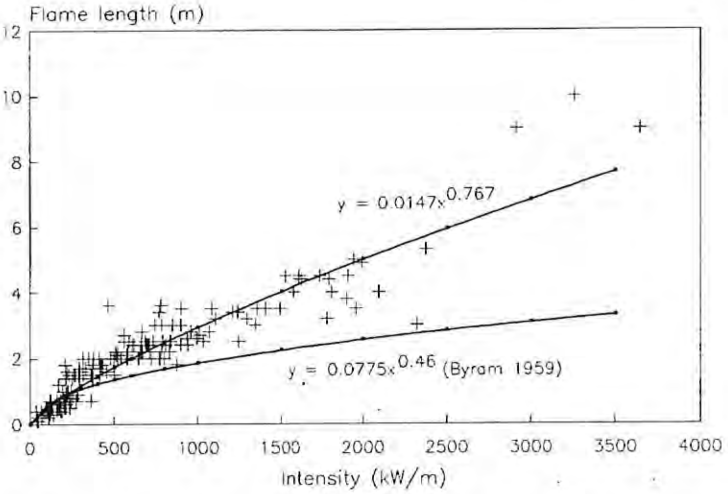


Figure 19. Flame length with fire intensity. Byram's (1959) relationship is shown for comparison.

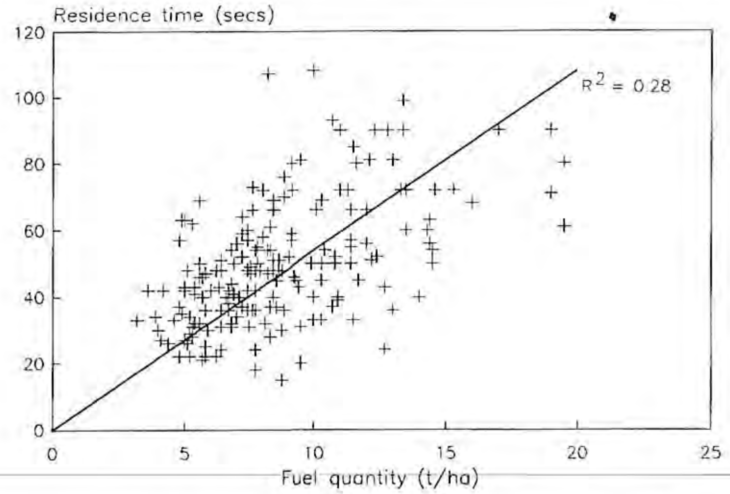


Figure 20. Flame residence time calculated from flame depth and rate of spread with fuel quantity.

eucalypt forest fire behaviour experiments. Observed rates of spread were up to three times faster than predicted using existing eucalypt forest fire behaviour guides.

Most variation in rate of spread could be explained by wind speed and fuel moisture content. Headfire rate of spread was found to be independent of litter fuel quantity providing there was sufficient fuel to sustain a spreading fire (i.e. more than about 4.0 t ha^{-1}). A new jarrah forest fire danger rating and fire behaviour prediction model incorporating a power function in wind and a power function in fuel moisture content was developed using non-linear regression techniques. On extrapolation to higher wind speeds (> 10 km h^{-1} at 1.5 m in the forest or > 30 km h^{-1} tower wind speed) the model is apt to over predict especially under dry (<6 per cent moisture content) fuel conditions. It is possible that the relationship between rate of spread and wind speed is a sigmoidal one; further studies of the behaviour of fires under extreme conditions are needed to confirm this.

This study has also demonstrated the importance of scale or fire size on fire behaviour. Laboratory-scale studies are inadequate for the empirical development of fire behaviour models, although they are a useful adjunct to understanding fire spread. It is also clear that the small scale (<0.2 ha) field experiments conducted during the 1960s also led to fire behaviour models which under predict the spread rate of large fires.

While the experimental fires reported in this study were significantly larger than earlier studies, it is possible that the fire size threshold may not have been reached for the wind and fuel moisture conditions. Since the implementation of these experimental fires, Cheney and Gould (1995) have shown that headfire width affects rate of spread and that a quasi-steady spread rate is unlikely to be achieved until headfire width exceeds100–200 m. The headfire width of most of the fires studied here was 50–100 m. Wildfire data presented in Table 5 suggest that the fire spread model developed here generally under-predicts the rate of spread of large wildfires burning under severe conditions. A major collaborative study involving scientists from the Western Australian Department of Conservation and Land management and the Commonwealth Scientific and Industrial Research Organisation is planned for the near future to closely investigate the affects of fuel quantity and structure on rate of spread and to examine the relationship between wind speed and rate of spread of 200 m line fires in 4 ha plots.

Flame size, although difficult to measure accurately, was directly related to rate of spread and fuel quantity. Fire intensity and flame length were related by a power function but the model coefficients were significantly different to those reported by Byram (1959). It is likely that model coefficients vary between fuel types so flame length is not a reliable estimator of fire intensity when comparing fires in different fuels.

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REFERENCES

Adkins, C.W. and Rogers, S.L. (1986). A video image analysis system for measuring fire behaviour. *Fire Management Notes* **47**(1), 10–15.

Alexander, M.E. (1982). Calculating and interpreting forest fire intensities. *Canadian Journal of Botany* **60**, 349–357.

Alexander, M.E., Lawson, B.D., Stocks, B.J. and Van Wagner, C.E. (1988). Fire behaviour in spruce-lichen woodland: the Porter Lake Project. Northern Forest Centre, Canadian Forestry Service Information Report No. NOR-X-000.

Andrews, P.L. (1980). Testing the fire behaviour model. In: Proceedings of the 6th Conference on Fire and Forest Meteorology, Seattle, WA. April 22–24. Society of American Foresters.

Beer, T. (1991). The interaction of wind and fire. *Boundary Layer Meteorology* **54**, 287–308.

Blake, T.J. and Johnson, T. (1973). Estimation of fuel compaction. Institute of Foresters of Australia *Newsletter* **14**, 24–27.

Blank, R.W. and Simard, A.J. (1983). An electronic timer for measuring spread rates of wildland fires. USDA Forest Service *Research Note* NC–304.

Brown, J.K. (1970). Physical properties of ponderosa pine forest floors and cheatgrass. USDA Forest Service *Research Paper* INT–74.

Brown, J.K. (1971). Field test of a rate of spread model in slash fuels. USDA Forest Service *Research Paper* INT–116.

Burrows, N.D. (1984). Predicting blow-up fires in the jarrah forest. Forest Department of Western Australia *Technical Paper* No. 12.

Burrows, N.D. (1987). The soil dryness index for use in fire control in Western Australia. Department of Conservation and Land Management Western Australia, *Technical Report* 17.

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

Burrows, N.D. and Sneeuwjagt, R.J. (1991). McArthur's forest fire danger meter and the forest fire behaviour tables for Western Australia: derivation, applications and limitations. In Proceedings of a Conference on Bushfire Modelling and Fire Danger Rating Systems, Cheney, N.P. and Gill, A.M. (eds.) pp. 64–78, CSIRO, Canberra.

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

Byram, G.M., Clements, H.B., Bishop, M.E. and Nelson, R.M. (1966). An experimental study of model fires. Final Report. USDA Forest Service.

Catchpole, W. (1985). Fire models for heathland. University of New South Wales, Faculty of Military Studies, Department of Mathematics *Report* No. 21/85.

Chandler, C., Cheney, P., Thomas, P. Trabaud, L. and Williams, D. (1983). *Fire in Forestry* Vol. 1: *Forest Fire Behaviour and Effects*. John Wiley & Sons, New York.

Cheney, N.P. (1971). Forest industries feasibility study, Zambia: Fire protection of industrial plantations. FAO UN Rome, Italy. FO:SF/ZAM 5 *Technical Report* 4.

Cheney, N.P. (1981). Fire behaviour. In *Fire and the Australian Biota,* Gill, A.M., Groves, R.H. and Noble, I.R. (eds) pp. 151–175. Australian Academy of Science, Canberra.

Cheney, N.P. (1990a). Quantifying bushfires. *Mathematical and Computer Modelling* **13**, 9–15.

Cheney, N.P. (1990b). Fuel load or fuel structure: Discussion paper for Research Working Group 6. Unpublished paper presented to a meeting of the Australian Forestry Council Research Working Group 6, Fire Management, Adelaide, 1990.

Cheney, N.P. and Gould, J.S. (1995). Fire growth in grassland fuels. *International Journal of Wildland Fire* **5**(4), 237–247.

Cheney, N.P., Gould, J.S. and Catchpole, W.R. (1993). The influence of fuel, weather and fire shape variables on fire spread in grasslands. *International Journal of Wildland Fire* **3**, 31–44.

Cheney, N.P., Gould, J.S. and Hutchings, P.T. (1989). Prediction of fire spread in grasslands. CSIRO Division of Forestry, Bushfire Research Unit, Canberra.

Cheney, N.P., Hooper, R., McArthur, A.G, Packham, D.R. and Vines, R.G. (1968). Techniques for aerial mapping of wildfires. *Australian Forest Research* **3**, 3–20.

Churchward, H.M. and Dimmock, G.M. (1989). The soils and landforms of the northern jarrah forest. In *The Jarrah Forest*, Dell, B, Havel, J.J. and Malaczjuk, N. (eds) pp. 13–21. Kluwer Academic Press, Dordrecht, The Netherlands.

Clarke, R.G. (1983). Threshold requirements for fire spread in grassland fuels. Ph.D. Thesis, Texas Technical University.

Department of Science. (1977). *Manual of Meteorology* Part 1: *General Meteorology*. Australian Government Publishing Service, Canberra.

Everson, T.M., Van Wilgen, B.W. and Everson, C.S. (1988). Adaptation of a model for rating fire danger in the Natal Drakensburg. *South African Journal of Science* **84**, 44–49.

Finkl, C.W. (1971). Soils and geomorphology in the middle Blackwood River catchment, Western Australia. Ph.D. Thesis, University of Western Australia.

Fons, W.L. (1946). Analysis of fire spread in light fuels. *Journal of Agriculture* **27**, 93–121.

Fons, W.L., Clements, H.B., Elliot, E.R. and George, P.M. (1962). Project fire model. Summary Progress Report -2. USDA Forest Service.

Gill, A.M. and Knight, I.K.(1991). Fire measurement. In: Proceedings of a Conference on Bushfire Modelling and Fire Danger Rating Systems, 11–12 July 1988, Cheney, N.P. and Gill, A.M. (eds), pp. 137–146. CSIRO, Canberra.

Gould, J.S. (1991). Validation of the Rothermel fire spread model and related fuel parameters in grassland fuels. In: Proceedings of a Conference on Bushfire Modelling and Fire Danger Rating Systems, 11–12 July 1988, Cheney, N.P. and Gill, A.M. (eds), pp. 51–64. CSIRO, Canberra.

Havel, J.J. (1975). Site-vegetation mapping in the northern jarrah forest (Darling Range), 1: Definition of site-vegetation types. Forests Department of Western Australia *Bulletin* No. 86.

Hough, W.A. and Albini, F.A. (1978). Predicting fire behaviour in palmetto-galberry fuel complexes. USDA Forest Service *Research Paper* SE–174.

Johns, L. (1986). The use of aircraft in bushfire control. Fire Science '86. The 4th Australian National Biennial Conference of the Institute of Fire Engineers, Perth Western Australia.

Johnson, V.J. (1983). The dilemma of flame length and intensity. *Fire Management Notes*, Fall 1982/83, 3–7.

Levy, E.B. and Madden, E.A. (1933). The point method of pasture analysis. *New Zealand Journal of Agriculture* **46**, 267–279.

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

Mak, E. and Hutchins, P. (1987). Processing airborne infra-red images for the measurement of rate of spread of high intensity experimental fires. Proceedings of a Symposium on Computer Modelling and Remote Sensing in Relation to Bushfires in Australia, 3–4 June, Canberra.

McAlpine, R.S. (1988). The acceleration of point source fire to equilibrium spread. M. Sc. Thesis, University of Montana.

McAlpine, R.S. (1995). Testing the effect of fuel consumption on fire spread rate. *International Journal of Wildland Fire* **5**, 134–152

McArthur, A.G. (1959). Report on fire behaviour studies in jarrah fuel types, Dwellingup, Western Australia. Report to the Forests Department of Western Australia, April 1959.

McArthur, A.G. (1961). The origin and development of the Dwellingup fires, 19th–25th January, 1961. Forestry and Timber Bureau unpublished report. Commonwealth of Australia, Canberra.

McArthur, A.G. (1962). Control burning in eucalypt forests. Forestry and Timber Bureau of Australia Leaflet No. 80.

McArthur, A.G. (1967). *Fire behaviour in eucalypt forests.* Commonwealth of Australia Forestry and Timber Bureau.

McArthur, A.G. (1973). Grassland Fire Danger Meter Mk. V. Country Fire Authority, Melbourne, Victoria.

McArthur, A.G. and Cheney, N.P. (1966). The characterisation of fires in relation to ecological studies. *Australian Forest Research* **2**, 36–45.

McArthur, A.G. and Luke, R.H. (1963). Fire behaviour studies in Australia. *Fire Control Notes* **24**, 87–92.

McCaw, L., Simpson, G. and Mair, G. (1992). Extreme wildfire behaviour in 3 year old fuels in a Western Australian mixed *Eucalyptus* forest. *Australian Forestry* **55**, 107–117.

McCutcheon, G.S. (1978). Broadscale forest site survey techniques used in the Donnybrook Sunkland. Forests Department of Western Australia *Research Paper* No. 48.

McCutcheon, G.S. (1980). Field classification of vegetation types as an aid to soil survey. Forests Department of Western Australia *Research Paper* No. 57.

Mount, A.B. (1972). The derivation and testing of a soil dryness index using run-off data. Tasmania Forests Commission *Bulletin* No. 4.

Myers, R.H. (1990). *Classical and Modern Regression with Appliances* (2nd edn). PWS – Kent Publishing Co., Boston.

Nelson, R.M. and Adkins, C.W. (1987). A dimensionless correlation for the spread of wind-driven fires. *Canadian Journal of Forest Research* **18**, 391–297.

Noble, I.R., Barry, G.A.V. and Gill, A.M. (1980). McArthur's fire danger meters expressed as equations. *Australian Journal of Ecology* **5**, 301–302.

Packham, D.R. and McArthur, A.G. (1966). Reports on mapping of forest fires through smoke cover and particle sizing of bushfire smoke. CSIRO Division of Physical Chemistry, Melbourne.

Peet, G.B. (1962). Western Australian fire weather. B.Sc. Thesis, University of Western Australia.

Peet, G.B. (1965). A fire danger rating and controlled burning guide for the northern jarrah forest of Western Australia. Forests Department of Western Australia.

Peet, G.B. (1972). Fire studies in jarrah (*Eucalyptus marginata* Sm.) forest. M.Sc. Thesis, University of Melbourne.

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

Prider, R.T. (1966). Laterized surfaces of Western Australia. *Australian Journal of Soil Science* **28**, 443–450.

Rothermel, R.C. (1972). A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service *Research Paper* INT–115.

Rothermel, R.C. and Anderson, H.E. (1966). Fire spread characteristics determined in the laboratory. USDA Forest Service *Research Paper* INT–30.

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

Ryan, K.C. (1981). Evaluation of a passive flame height sensor to estimate forest fire intensity. USDA Forest Service *Research Not*e PNW–390.

SAS Institute Inc. (1985). *SAS Users Guide: Statistics,* version 5 edn. Cary, NC:SAS Institute Inc. 1985.

Sneeuwjagt, R.J. and Frandsen, W.H. (1977). Behaviour of experimental grass fires vs. predictions based on Rothermel's fire model. *Canadian Journal of Forest Research* **7**, 357–367.

Sneeuwjagt, R.J. and Peet, G.B. (1976). *Forest Fire Behaviour Tables for Western Australia* (1st edn). Forests Department of Western Australia.

Sneeuwjagt, R.J. and Peet. G.B. (1979). *Forest Fire Behaviour Tables for Western Australia* (2nd edn). Forests Department of Western Australia.

Sneeuwjagt, R.J. and Peet, G.B. (1985). *Forest fire behaviour tables for Western Australia* (3rd edn). Department of Conservation and Land Management Western Australia.

Stocks, B.J. (1987). Fire behaviour in immature jack pine. *Canadian Journal of Forest Research* **16**, 80–86.

Stocks, B.J. (1989). Fire behaviour in mature jack pine. *Canadian Journal of Forest Research* **19**, 783–790.

Stocks, B.J. and Alexander, M.E. (1980). Forest fire behaviour and effects research in northern Ontario: a field oriented program. In: Proceedings of the 6th Conference on Fire and Forest Meteorology, Seattle, WA. 22–24 April 1980. Society of American Foresters.

Underwood, R.J., Sneeuwjagt, R.J. and Styles, H.G. (1985). The contribution of prescribed burning to forest fire control in Western Australia: case studies. In: Fire ecology and management in Western Australian ecosystems, pp. 153-170. J.R. Ford (ed.). WAIT Environmental Studies Group Report No. 14.

Van Wagner, C.E. (1968b). The line intercept method in forest fuel sampling. *Forest Science* **14**, 20–26.

Van Wilgen, B.W. (1984). Adaptation of the United States Fire Danger Rating System to fynbos conditions, Part 1: A fuel model for fire danger rating in the fynbos biome. *South African Forestry Journal* **129**, 61–65.

Van Wilgen, B.W. and Wills, A.J. (1988). Fire behaviour prediction in savanna vegetation. *South African Journal of Wildlife Research* **129**, 41–46.

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

Weber, R.O. (1989). Analytical models for fire spread due to radiation. *Combustion and Flame* **78**, 398–408.

Woolliscroft, M.J. (1968). A statistical analysis of some rates of spread of forest fires. *Fire Research Note* No. 732.

Woolliscroft, M.J. (1969). Notes on forest field work (New Forest, 1967). Ministry of Technology and Fire Offices Commission Joint Fire Research Organisation, *Fire Research Note* No. 740.

APPENDIX 1

Equations used to predict rate of spread of fires in jarrah forest litter fuels using Rothermel's (1972) model.

W_o = litter quantity (t ha^{-1})*0.02048....convert to lb. ft.$^{-2}$
D = litter depth (mm)*0.00328.....convert fuel depth to ft.
SA = 2194..... fuel particle surface area-to-volume (ft.$^{-1}$)
H = 7996..... fuel particle low heat content (B.t.u. lb.$^{-1}$)
P = 34.3..... particle density (lb. ft.$^{-3}$)
M_f = moisture content (%)*0.01
S_T = 0.0555..... fuel total mineral content
S = 0.01...... fuel effective mineral content
U = wind speed (km h^{-1})*54.68.....convert wind to ft. min.$^{-1}$
S_l = 0.....slope
M_x = 0.21.....moisture content of extinction
P_R = 0.080....packing ratio
Q_{ig} = 250+(1 116*M_f)....heat of preignition (B.t.u. lb.$^{-1}$)
E_h = 2.71828**(–138/SA).... effective heating number
F_b = W_o/D.... oven dry bulk density (lb. ft.$^{-3}$)
SF = 0......slope factor
W_n = W_o/(1+S_T)...net fuel loading (lb. ft.$^{-2}$)
E = 0.175*(2.71828**(–3.59*0.0001*SA))
B = 0.02526*(SA**0.54)
C = 7.47*(2.71828**(–0.133*SA**0.55))
B_{op} = 3.348*(SA**–0.8189)....optimum packing ratio
W_c = (C*(U**B))*((P_R/B_{op})**–E)....wind coefficient
P_F = ((192+0.259*SA)**1)*2.72**((0.792+0.681*SA**0.5)*(P_R+0.1)) propagating flux ratio
N_S = 0.174*S_e**–0.19....mineral dampening coefficient
N_M = 1–2.59*(M_f/M_x)+5.11*((M_f/M_x)**2)–3.52*((M_f/M_x)**3) moisture dampening coefficient
A = 1/(4.774*(SA**0.1)–7.27)
R_{ma} = SA**1.5*((495+0.0594*SA**1.5)**–1)...maximum reaction velocity (min.$^{-1}$)
R_{opt} = R_{max}*((P_R/B_{op})**A)*2.71828**(A*(1–P_R/B_{op}))... optimum reaction velocity (min. $^{-1}$)
I_R = R_{opt}*W_n*H*N_M*N_S....reaction intensity (ft. min. $^{-1}$)
ROS = 18.288*((I_R*P_F*(1+W_c))/(F_b*E_h*Q_{ig}))...rate of spread (m h^{-1})