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Fire behaviour in jarrah forest fuels: 1. Laboratory experiments

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ABSTRACT

A firm knowledge of fire behaviour is necessary for forecasting fire danger, for implementing prescribed fires and for controlling wildfires in fire-prone ecosystems such as the jarrah forests of south-west Western Australia. Laboratory experiments are a relatively safe and inexpensive method of improving an understanding of the relationships between dependent fire behaviour variables and independent fuel and weather variables. While the scale of laboratory fires is a limiting factor, this technique can be used in conjunction with field studies to advance bushfire science.

Key findings to emerge from an analysis of 122 experimental fires in jarrah forest litter fuels in the laboratory were:

(1) Rate of spread of wind-driven fires was independent of fuel quantity, most variation being explained by wind speed and fuel moisture content. However, a direct relationship existed between rate of spread and fuel quantity for zero-wind fires. This suggests that forced convection (flame contact) rather than radiation is the primary mechanism of fire spread for wind-driven fires in this fuel type.

(2) Wind speed was the most important variable affecting rate of spread with a linear relationship existing between the two variables for wind speeds between 3 km h^{-1} and 8 km h^{-1}.

(3) Wind-driven fires would not spread when fuel moisture content exceeded 21 per cent (of oven dry weight) or when fuel quantity was less than about 3.5 t ha^{-1}.

(4) The effects of slope on rate of spread and of wind speed on fire shape, were similar to that reported by other workers.

INTRODUCTION

Accumulations of flammable fuel and a Mediterranean-type climate have ensured that fire is an important environmental factor which has shaped dry sclerophyll, jarrah (*Eucalyptus marginata* Donn ex Sm.) forest ecosystems of south-west Australia. Fire impacts on every aspect of forest management, including timber and water production, recreation and wildlife conservation. Fire management involves controlling destructive wildfires and prescribing fires over a range of burning conditions to achieve a variety of protection, production and conservation objectives. A sound understanding of fire behaviour, of the physical impacts and of the long term ecological and commercial effects of fire is essential to planning and implementing fire regimes and suppression activities pertinent to current and foreseeable management.

Fire behaviour is the general term used to describe the way in which fires ignite, how fast flames spread, flame dimensions, energy outputs and fire shape and size (e.g. Brown and Davis 1973; Luke and McArthur 1978; Gill *et al.* 1981). An ability to make reasonably accurate fire behaviour predictions is essential for fire danger rating, wildfire suppression and for planning and implementing prescribed burns. Fire behaviour characteristics such as rate of spread, flame size, fire intensity, flame residence time, fuel burn-out time and flame temperature histories are also linked to the various physical impacts of fire and subsequent ecological responses.

Eucalypt forest fire behaviour models developed in the 1960s (McArthur 1962; Peet 1972) from small, low intensity experimental fires set under mild weather conditions perform adequately over the low intensity range (<350 kW m^{-1}), but are deficient at predicting the behaviour of moderate and high intensity fires burning under warm, dry conditions. These models make some important assumptions and extrapolations about aspects of fire behaviour with little supporting theoretical or statistical basis (see Burrows and Sneeuwjagt 1991). These assumptions need to be validated, and where necessary, better functional relationships developed for the behaviour of forest fires.

Since the pioneering work of McArthur (1962) and Peet (1972), there has been little detailed experimental and statistical examination of fire behaviour relationships for eucalypt forest fuels. Laboratory studies are an important, safe and inexpensive adjunct to the field studies described later in this volume to further the understanding of fire behaviour. While scale is an important factor with regard to an equilibrium being reached (a quasi-steady state) between fire behaviour and fuel and weather factors, relationships between these factors can be examined in the controlled laboratory environment. This study aimed to examine relationships between fire behaviour (dependent variables) and factors affecting fire behaviour (independent variables) under laboratory conditions.

Fire behaviour variables examined here were:

(1) rate of fire spread (r_F for headfire and r_B for backfire)
(2) flame height (h_F), length (L), depth (D) and angle (A)
(3) fire intensity (I) (Byram 1959)
(4) heat load (H_L)
(5) flame residence time (t_r)
(6) fuel burnout time (t_b)
(7) fire shape (L/W)

Independent variables measured were:

(1) fuel quantity (w)
(2) fuel depth (f_D)
(3) fuel moisture content (MC)
(4) wind speed (U)
(5) slope (S)

METHODS

Experiments were conducted in the fire laboratory at the Department of Conservation and Land Management (CALM) Manjimup Research Station, Western Australia (WA). The fire laboratory consisted of a galvanized, steel framed shed 7 m x 5 m x 4 m high with a concrete slab floor. The gable roof could be rolled open to allow smoke and the convection column to escape unimpeded. Louvres set into the walls near floor level could be opened to control ventilation.

Experimental fires were set on a 'fire table', which was 4 m x 2 m and set 1.2 m above the floor. The table was constructed of a heavy box steel frame with a 20 mm thick asbestos top. Wind was generated by a bank of four variable speed domestic fans approximately 60 cm in diameter. The fans were mounted in line on a wooden frame in such a manner that the base of the fans was about 5 cm above the top of the fire table. A light gauze was erected some 30 cm in front of the fans to further provide a turbulent air flow to reflect conditions in the forest (Anderson and Rothermel 1966). The fans were mounted on a jig and could be maintained at a constant distance from the flaming zone as the fires burnt down the length of the table. This was achieved by setting the wooden board on which the fans were mounted, on greased metal skids. An electric winch and pulley system enabled the fans to be hauled along the skids.

A metal pointer ensured the fans were maintained at a constant distance from the front of the flames. Wind speed was varied by either changing the speed of the fans, or by moving the fans closer to the flames. Wind speeds down the fire table were measured before any fires were set using two 50 mm sensitive cup type Cassella anemometers. For the various combinations of fan speed and distance of fans from the flames the actual wind speed at 20 cm above the surface of the table was measured by leaving the fans running in a set configuration (speed/distance) for two hours and then determining the mean wind speed from the anemometers. The anemometers were set across the fire table some 70 cm apart. When the wind speeds for each combination of fan speed and distance from flaming zone had been determined, experimental fires were set without having to further measure wind speeds. Wind speeds above the height of the anemometers were not measured.

Fuel for the experimental fires consisted of fresh leaves and small twigs (L layer) < 6 mm in diameter collected from the floor of jarrah forests near Manjimup. The material was dried in an oven at 105° C for 48 hours (to obtain oven dry weight), weighed and distributed evenly over the fire table. The fuel bed was arranged to ensure that bulk density was as uniform as possible over the table and similar to natural forest litter bed fuels. Fuel depth at 20 positions was measured to the nearest millimetre and mean bulk density determined for each fire. Bulk density varied within and between fuel beds with the mean being 46.8 kg m^{-3}. It was not possible to increase the bulk density of low fuel quantities (28.6 kg m^{-3}) without physically breaking up the fuel particles. A reasonably consistent fuel bed was achieved by gently shaking the litter from oven drying bags and arranging the leaves on the table by hand. The fuel bed was then left for about three hours to cool and to reach a moisture equilibrium with atmospheric conditions inside the laboratory.

Fuel moisture content was varied by (1) natural variations in atmospheric temperature and humidity and (2) wetting the fuels on a screen prior to arranging them on the fire table. During the series of backfire experiments, fuel moisture content was held constant at about 8 per cent of oven dry weight (odw). This was achieved by loading a large drying oven with fuel and drying it as normal. After the drying process, the oven was opened for four hours and then sealed. Fuel for each experimental fire was taken from the oven, spread onto the fire table and ignited. Samples were collected from the fuel bed for moisture content determination. Fuel quantity (t ha^{-1} oven dry) was calculated from the known oven dry weight of fuel placed on the table.

Two sets of 30 gauge chromel-alumel wire thermocouples were fixed onto the fuel bed surface and 10 cm above the fuel bed to assist with determining flame residence and burnout times. Each probe was read every 2 seconds until thermocouple temperatures returned to within 5 °C of ambient temperature. Ambient air temperature and humidity inside the laboratory could not be controlled and were generally similar to conditions outside. Experiments were conducted over the warmer, drier weather conditions of spring, summer and autumn.

Simultaneous and continuous line fire ignition was achieved by igniting a 2 m length of cotton wick soaked in methylated spirits. Fires were lit at one end of the table and allowed to burn for 50 cm before measurements were made. Headfires and backfires were studied by allowing flames to burn with the wind (headfires) or against a wind speed of 4.6 km h^{-1} (backfires). A series of zero wind fires were also studied. For backfires, fuel moisture content, slope and wind speed were held near constant at 8 per cent, 0° and 4.6 km h^{-1} respectively. Fuel quantity was varied in order to determine its effect on fire behaviour.

A stop watch was used to measure the time taken for the fires to travel down the 4 m long table. Fire travel time was measured to the nearest second. A calibrated steel 'L' shaped rod was used to measure flame height, length and depth from three positions on the table. Flame angle was measured from the side of flames using crude metal callipers and a protractor. The operator visually aligned one leg of the callipers with the leading edge of the flame and the other with the fuel bed. Several estimates were made during a fire and the mean angle used in regression analysis.

A small number of experiments (15) were conducted to examine the shapes of fires burning in eucalypt (jarrah/ marri) leaf litter at different wind speeds. These fires were set in the laboratory on a larger table (3 m x 4 m) and were ignited from a point source. Fuel quantity and fuel moisture content were constant at about 7–8 t ha^{-1} and 7–8 per cent respectively. A 35 mm still camera with motor drive was mounted vertically above the table and black and white photographs were taken when the fires had reached maximum size. The length and maximum width of each fire was measured from the photographs and the length-to-width ratio was regressed with wind speed. Owing to the small scale of the laboratory fires, no attempt was made to examine fire acceleration from a point source. Laboratory studies by McAlpine (1988) and Green (1983) have provided useful information about fire acceleration and fire shape in other fuel types.

The effect of slope on the average rate of spread of jarrah litter fires, burning under zero wind conditions, was investigated by changing the inclination of a smaller fire table (1 m x 1.6 m) from –16° through to +16° at 2° increments. Fuel moisture and fuel quantity were held constant at about 7–8 per cent and 7–8 t ha^{-1} respectively.

Data Analysis

The first step was to generate Pearson correlation coefficients to identify relationships between variables. Secondly, scatterplots and three-dimensional plots were generated to see whether relationships were non-linear. Finally, models were developed by regression analysis. R^2 values (coefficient of determination) were generated for linear regressions as a measure of model fit. For zero intercept models, R^2 is computed from sum of squares values representing dispersion around zero and not around the mean of y, leading to artificially high values (Myers 1990). Non-linear relationships were modelled using non-linear least squares fitting techniques (SAS Institute Inc. 1985; Myers 1990) rather than transforming the data to linearize the model. Linearization of non-linear models does not produce an equivalent model; transformation to linearize produces a different and unreasonable error structure and poorer properties of the parameter estimates (Myers 1990). The goodness of fit of non-linear models was determined from the standard error statistics and the coefficient of determination:

$$S = 1-(SS_{RES}/SS_{TOT}),$$

where S = coefficient of determination, SS_{RES} = sum of squares of residuals and SS_{TOT} = total sum of squares (corrected).

Residuals were also analysed to determine model underspecification or deviation from the homogeneous variance assumption. Measures of model bias and precision were determined from residual statistics by:

Error = (Residual/Predicted)*100,
Bias = mean of Error,
Precision = standard deviation of Error.

RESULTS

Of the 122 laboratory fires, 54 were wind-driven (headfires), 13 were backfires burning into wind (-4.6 km h^{-1}), 6 were fires burning under zero wind conditions, 15 fires were lit to examine fire shapes and 34 fires were set to examine the effect of slope on headfire spread rate.

The range of conditions experienced during 60 of the experimental fires used to examine fire behaviour are summarized in Table 1. The size of the laboratory facilities meant that fires were restricted to flame lengths of less than about 1.5 m. Flames in the field have been observed to exceed 10 m, so these laboratory fires were at the very low end of the range of potential surface fire behaviour in jarrah forest fuels.

Rate of Spread (ros)

Headfires (wind-driven) did not spread when fuel moisture content exceeded about 21 per cent of oven dry weight or when fuel quantity was less than about 3.0 t ha^{-1}.

There was no relationship between the rate of spread of wind-driven fires and the quantity of fuel (t ha^{-1}) on the fire table, as shown by the Pearson correlation matrix in Table 2 and the data graphed in Figure 1. Rate of spread was positively related to wind speed, which explained most variation in rate of spread, but negatively related to fuel moisture content (Table 2). At high wind speeds, the flames spread rapidly across the surface of the fuel bed. In deep and heavy fuel beds only the surface 15–20 mm of the fuel bed was actually consumed in the flaming zone during wind-driven fires. The remainder of the fuel bed burnt by smouldering and glowing combustion after the passage of the main flaming zone. A variable but significant proportion (10–30 per cent) of heavy fuel beds remained as carbonized, charred and thermally degraded material.

The vertical rate of spread (down through the fuel bed), calculated from flame residence time and fuel bed depth, varied from 3.0–14.1 m h^{-1} with a modal value of 5 m h^{-1}.

In contrast to the findings of Steward (1974) and others, and in contrast to the wind-driven fires studied here, the rate of spread of backfires and zero wind fires

TABLE 1
Variable bounds and descriptive statistics for 60 laboratory fires (wind speed $\geq$ 0 km h^{-1}) burning in jarrah forest litter fuel.

VARIABLE	UNITS	MEAN	MINIMUM	MAXIMUM	STANDARD DEV.
Rate of spread (r_F)	m h^{-1}	75.3	8.4	270.6	70.8
Flame height (h_F)	m	0.27	0.04	0.99	0.16
Flame length (L)	m	0.35	0.05	1.20	0.23
Flame depth (D)	m	0.32	0.02	1.45	0.38
Residence time (t_r)	s	13.3	5.0	32.0	6.15
Smoulder time (t_s)	s	119	18	300	62.3
Intensity (I)	kW m^{-1}	242	12	1123	247.0
Energy release rate (E_R)	kJ min^{-1}	24292	535	100997	26585
Fuel consumption rate (c_r)	kg min^{-1}	3.04	1.2	6.5	1.35
Temperature 10 cm (T_{10})	^{o}C	499	100	988	206.2
Fuel quantity (w_C)	t ha^{-1}	7.9	3.4	15.3	3.1
Fuel depth (f_D)	mm	17.4	4.0	50	8.4
Moisture content (MC)	%	7.6	3.0	14.0	2.4
Wind speed (U)	km h^{-1}	3.8	0.0	7.6	1.9
Temperature (T_A)	^{o}C	26.9	17	37	4.9
Relative humidity (RH)	%	38.5	18	80	11.6

TABLE 2
Pearson correlation coefficients for variables likely to affect headfire rate of spread of laboratory fires in jarrah litter fuel. The significance probability of the correlation, under the null hypothesis that the correlation is zero, is in parentheses.

VARIABLE	HEADFIRE RATE OF SPREAD (R_F)
Wind speed (U)	0.94 (0.0001)
Fuel quantity (w_C)	–0.12 (0.364)
Fuel depth (f_D)	–0.03 (0.782)
Moisture content (MC)	–0.31 (0.022)

was directly related to fuel quantity (Fig. 2) such that doubling fuel quantity resulted in an approximate doubling of spread rate. Backfires and zero wind fires would not spread when fuel quantity was less than about 4.0 t ha^{-1}. Unlike wind-driven fires, backfires burnt uniformly through the fuel bed. Vertical rate of spread ranged from 2.0–7.4 m h^{-1}, with most fires burning at about 4 m·h^{-1} which is slightly lower than the value calculated for headfires (about 5 m h^{-1}).

Headfire rate of spread is graphed with wind speed, the most dominant variable influencing rate of spread, in Figure 3. Other variables such as fuel moisture content are not controlled. Both exponential and power equation forms were fitted to the data (Fig. 3), with the power being the best fit (statistically) over the entire range of conditions of wind speed and fuel moisture content (Table 3).

Headfire rate of spread was relatively insensitive to wind speeds below about 3.0 km h^{-1} but increased sharply as wind speed increased above this level (Fig. 3). This is interpreted as representing the transition from convection-dominated fires to wind-driven fires, as evidenced by the flame angle. At low wind speeds, the flames were more or less vertical and the fires spread slowly whereas at higher wind speeds, the flames were tilted and the fires spread faster. The transition occurred at a wind speed of around 3–3.5 km h^{-1}. Above this 'threshold' wind speed, a strong linear relationship existed between rate of spread and wind speed (Fig. 3 and Table 3). However, attempting to fit all data (including low wind speed data) to a linear model resulted in a poor fit with a low R^2 value, poor precision and considerable bias (Equation 1 in Table 3). The linear model (Equation 2 in Table 3) for wind speeds > 3.0 km h^{-1}, but which ignores fuel moisture content, shows poor precision even though the R^2 value is relatively high. Equation 3, in the same group but for low wind speeds ($\leq$ 3.0 km h^{-1}), was a poor fit using wind speed alone, probably because both fuel moisture content and quantity affect rate of spread at low wind speeds as shown by the backfire data above.

The effect of wind speed alone (including zero wind) on headfire rate of spread was analysed by firstly stratifying the data according to fuel moisture content classes ($3.0 \leq \text{MC} \leq 5.0$ and $6.0 \leq \text{MC} \leq 8.0$) and then according to whether wind speed was above or below 3.0 km h^{-1}. There were insufficient data to attempt linear regression by moisture content classes for the < 3.0 km h^{-1} wind speed class, so all moisture contents were included in this analysis. Both linear and non-linear equation forms were compared to determine the best fit model. Power equations best fitted the data for all wind speeds, but a strong linear relationship existed for data sets where U > 3.0 km h^{-1}. Equation forms, parameter estimates and measures of the goodness of fit of models are summarized in Table 3. While both linear and non-linear equation forms predict similar rates of spread over the range of experimental data, there is strong divergence on extrapolation to high wind speeds.

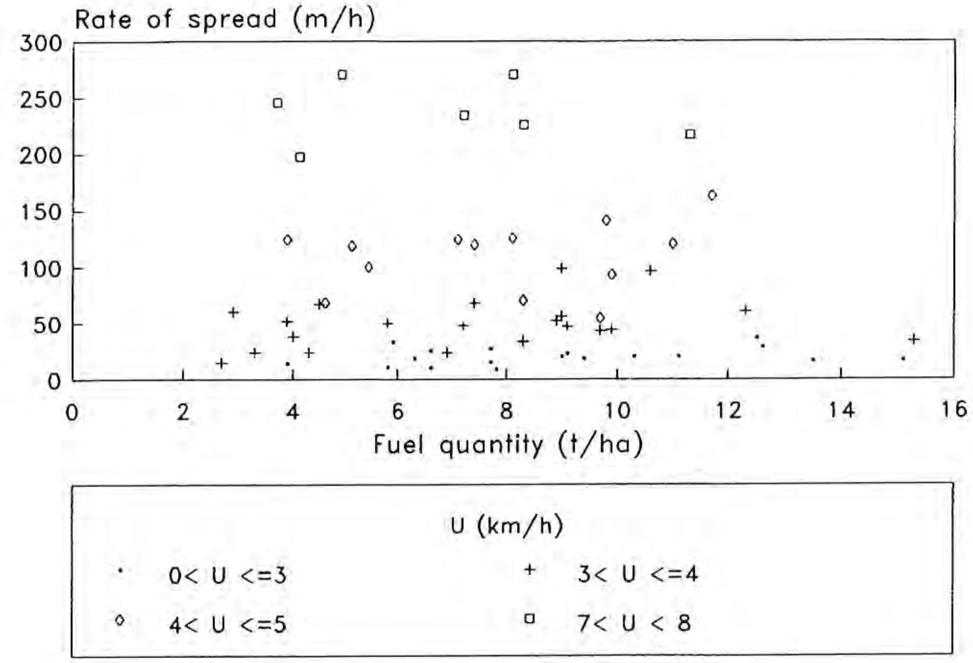

Figure 1. Headfire rate of spread with fuel quantity by wind speed (U) classes. U measured at 20 cm above the fire table.

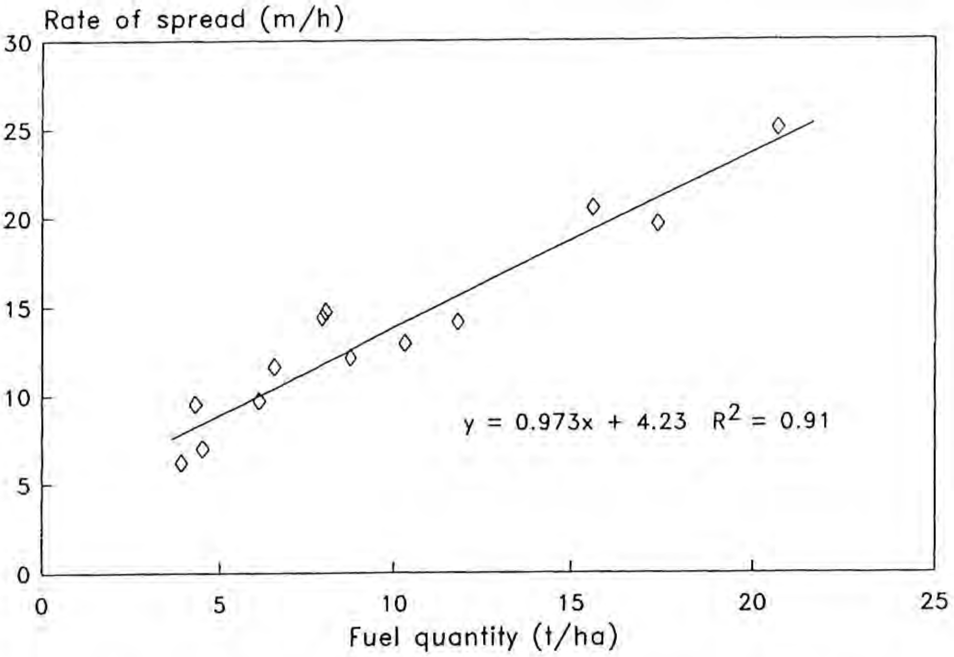

Figure 2. Backfire rate of spread with fuel quantity. Wind speed (U) = –4.6 km h^{-1} and fuel moisture content (MC) = 7–8 per cent of oven dry weight.

The form of the relationship between rate of spread and fuel moisture content varies with physical fuel properties. For example, Rothermel and Anderson (1966) reported a linear relationship between rate of spread and fuel moisture for ponderosa pine and white pine needles. Van Wagner (1967) and McArthur (1977) found that a curvilinear relationship was a better fit for red pine needles and for grassland fuels respectively.

The relationship between headfire rate of spread and fuel moisture content (Fig. 4) for jarrah litter fuels was determined by firstly stratifying the data according to wind speed classes then fitting various equations. The equations are shown in Table 4. There were insufficient data over a range of moisture contents at high wind speeds (U > 6.0 km h^{-1}) to warrant analysis. The relationship was a poor one at low wind speeds (U < 3.0 km h^{-1}), probably

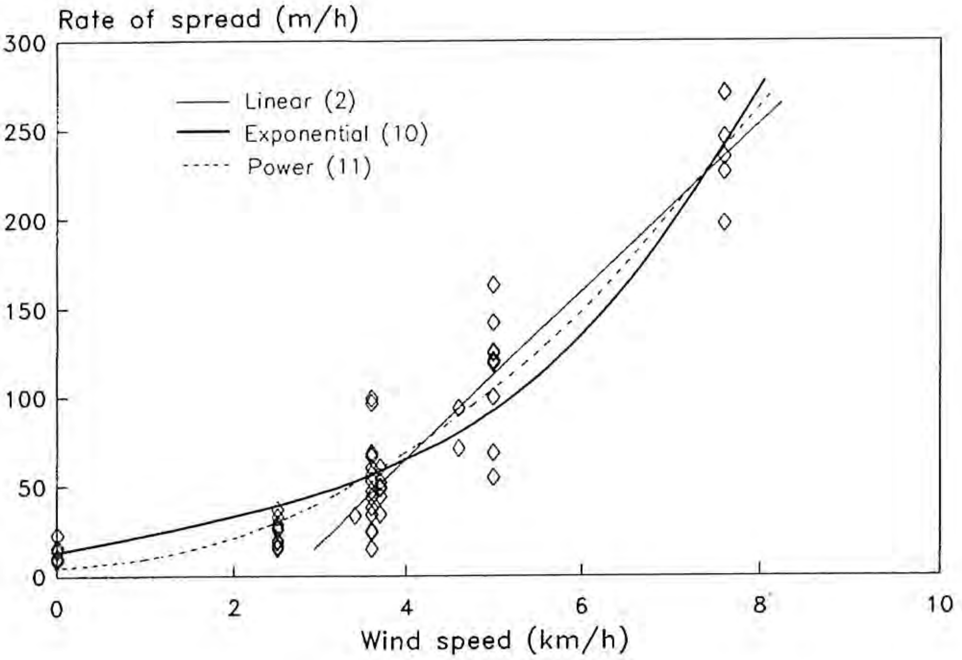

Figure 3. Headfire rate of spread with wind speed. Three equations forms are fitted to the data. Equation numbers refer to equations in Table 3.

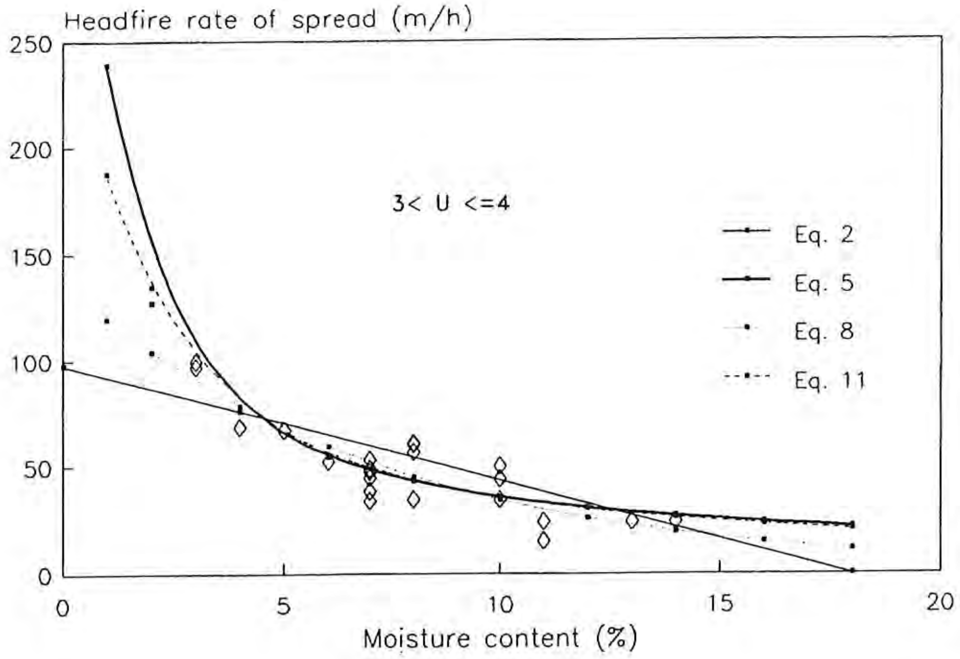

Figure 4. Headfire rate of spread with fuel moisture content by wind speed (U = km h^{-1}) classes. Equation numbers refer to equations in Table 4.

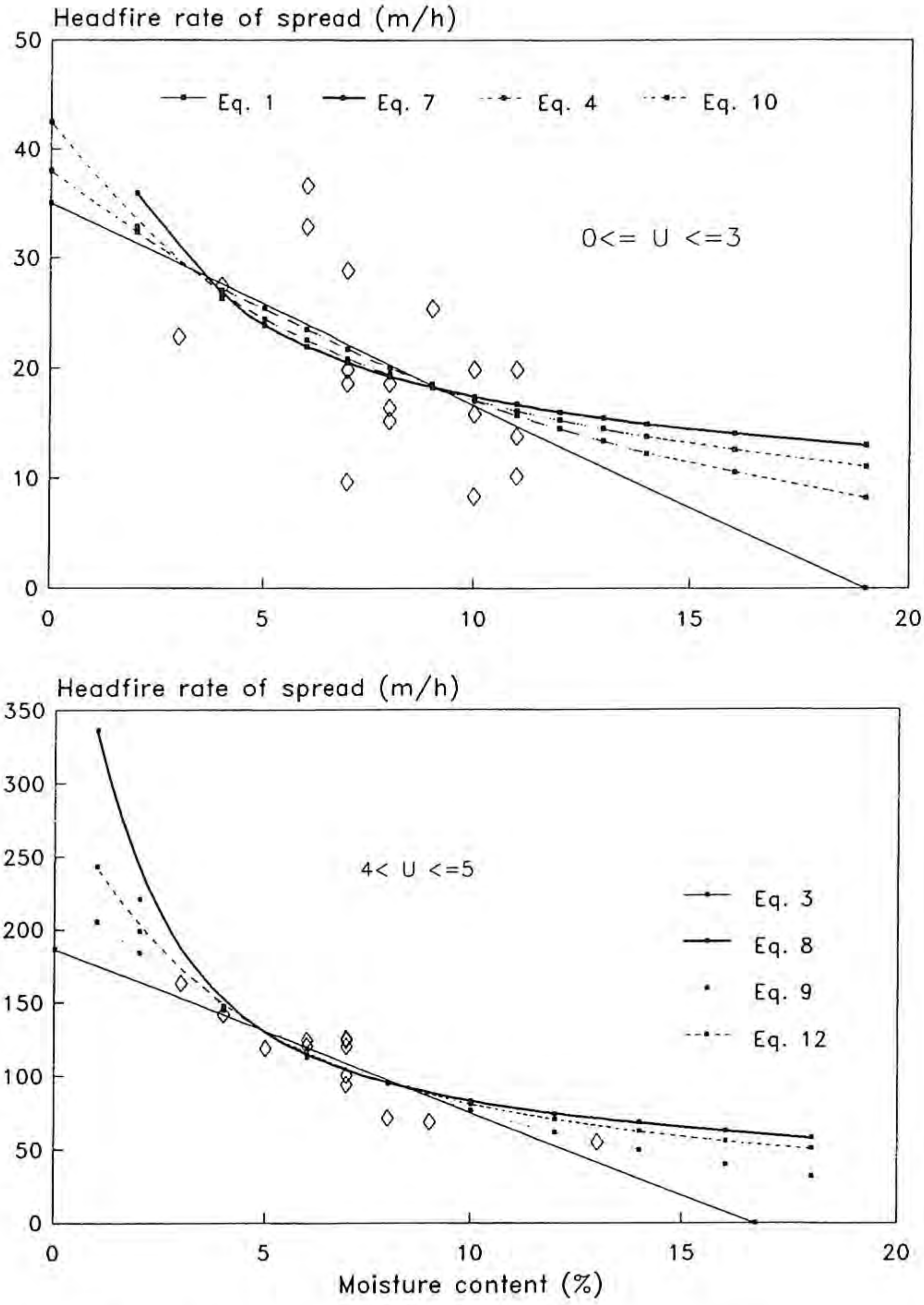

Figure 4 (continued). Headfire rate of spread with fuel moisture content by wind speed (U = km h^{-1}) classes. Equation numbers refer to equations in Table 4.

because of the influence of fuel quantity on the rate of spread of convection dominated fires. Based on S (goodness of fit), and error values (Table 4), power and inverse functions fit the data equally well and better than other forms. However, power functions result in dangerously high extrapolations at low moisture contents so the inverse was the preferred form (Equations 11 and 12 in Table 4). At higher wind speeds and low moisture contents, the linear equation under-predicted rate of spread and gave a projected moisture content of extinction of about 17 per cent of oven dry weight (odw), which is about 4 per cent below that determined from experimentation.

Based on the best fit regressions described in Tables 3 and 4, a non-linear least squares fitting technique (SAS Institute 1985) was used to derive the best fit single equation for predicting headfire rate of spread (r_F) from wind speed (U) and fuel moisture content (MC) together. For the entire range of data, including zero wind speed, the following equation was derived. Parameter standard errors

TABLE 3
Summary of equation forms and parameter estimates for predicting headfire rate of spread (r_F) from wind speed (U) for various moisture content (MC%) and wind speed classes. N = equation number and n = number of observations. Regressions are unbiased if the absolute value of bias = 0 and precise if the precision value = 0.

						RESIDUALS		ERROR	
N	MC	n	U	EQUATION	R^2	RANGE	MEAN	BIAS	PRECISION
GROUP 1: Linear models, MC not controlled									
1	3–14	60	>0.0	$r_F = 31.7(U)-44.7$	0.76	−59.2 – 74.3	0.04	−28.7	45.5
2	3–14	42	>3.0	$r = 47.4(U) - 123.1$	0.87	−59.1–1.6	0.00	0.26	35.3
3	3–14	18	<3.0	$r_F = 3.9(U) + 13.4$	0.33	−8.0 – 3.4	0.00	0.00	32.0
GROUP 2: Linear models, MC partially controlled									
5	3–5	7	>3.0	$r_F = 41.6(U) - 67.2$	0.75	−22.3–21.8	0.00	0.00	17.47
6	6–8	26	>3.0	$r_F = 47.7(U) - 125.0$	0.95	−40.5–32.7	0.01	0.12	14.68
7	9–15	9	>3.0	$r_F = 22.8(U) - 1.9$	0.60	−15.2–17.3	0.00	0.22	33.72
GROUP 3: Non-linear models, MC not controlled									
10	3–14	60	>0.0	$r_F = 14.3e^{0.37U}$	0.88	−45.5–70.5	1.50	−7.80	36.10
11	3–14	60	>0.0	$r_F = 3.2U^{2.10}+4.3$	0.90	−39.6–33.5	0.19	0.08	11.45
GROUP 4: Non-linear models, MC partially controlled									
12	3–5	9	>0.0	$r_F = 3.7U^{2.18}+17.5$	0.87	−22.4–21.7	0.72	1.68	24.03
13	6–8	35	>0.0	$r_F = 5.5U^{1.87}-7.2$	0.96	−41.4–31.7	0.17	−8.70	44.51
14	9–15	16	>0.0	$r_F = 0.4U^{2.9}+12.7$	0.76	−16.1–17.2	0.14	0.46	28.75

TABLE 4
Summary of equation forms and parameter estimates for predicting headfire rate of spread (r_F) from fuel moisture content (MC%) and controlling wind speed (U). N = equation number and n = number of observations. For non-linear regressions, $R^2 = S$. Regressions are unbiased if the absolute value of bias = 0 and precise if precision = 0.

						RESIDUALS		ERROR	
N	MC	n	U	EQUATION	R^2	RANGE	MEAN	BIAS	PRECISION
Group 1: Linear functions									
1	3–11	18	0.0–3.0	$r_F = 34.7-1.85(MC)$	0.30	−12.2–12.9	−0.04	−0.37	31.7
2	3–14	22	3.1–4.0	$r_F = 97.6-6.18(MC)$	0.69	−20.6–19.9	0.07	4.40	35.3
3	3–13	13	4.1–5.0	$r_F = 186.3-11.2(MC)$	0.78	−25.9–17.5	−0.02	0.96	16.4
Group 2: Non-linear functions									
4	3–14	18	0.0–3.0	$r_F = 49.1MC^{-0.45}$	0.22	−10.8–14.6	−0.05	−0.84	33.7
5	3–14	22	3.1–4.0	$r_F = 239.0MC^{-0.83}$	0.79	−17.6–18.0	0.32	0.24	24.6
6	3–13	13	4.1–5.0	$r_F = 335.6MC^{-0.61}$	0.74	−23.6–22.9	−0.47	−1.10	16.6
7	3–13	18	0.0–3.0	$r_F = 38.0e^{-0.08MC}$	0.29	−12.1–13.0	−0.06	−3.00	31.4
8	3–14	22	3.1–4.0	$r_F = 137.1e^{-0.14MC}$	0.77	−17.8–15.9	−0.07	0.90	24.6
9	3–13	13	4.1–5.0	$r_F = 228.6e^{-0.11MC}$	0.80	−24.0–19.5	−1.40	−1.58	13.2
10	3–13	18	0.0–3.0	$r_F = 1/(0.00235+0.00348MC)$	0.26	−11.2–14.0	−0.11	−1.21	32.7
11	3–13	22	3.1–4.0	$r_F = 1/(0.00278+0.00255MC)$	0.79	−17.4–17.4	−0.43	−0.60	24.2
12	3–13	13	4.1–5.0	$r_F = 1/(0.00319+0.000928MC)$	0.77	−23.4–22.2	−0.47	−1.14	15.0

are in parentheses.

$$r_F = (0.0245\,(U)^{2.22} + 0.071)^* \quad (1/(0.003+0.000922(MC) \qquad \text{(Equation 1)}$$
$$(0.0075) \quad (0.142) \quad (0.050) \quad (0.00029)$$

Residual range = –43.9–50.4,
Mean residual = 0.17,
Bias = 5.20
and Precision = 39.58.

Observed rate of spread is graphed with rate of spread predicted by Equation 1 in Figure 5. Residuals (observed-predicted) and residual statistics are plotted with observed rate of spread in Figure 6. There is evidence of model underspecification over the middle and high range of rates of spread. The error variance is not constant, but increases with rate of spread (Fig. 6). This probably reflects the scaling problems associated with laboratory studies; spread rate had not reached equilibrium at high wind speeds.

Flame Dimensions

Flame length was weakly related to rate of spread (Fig. 7), indicating that large flames are not necessary for high rates of spread and that flame size was not a primary causal factor affecting rate of spread. Flame height and length tended to plateau beyond a rate of spread of about 100 m h^{-1}, supporting the observation that flames were driven across the surface of the fuel bed and that sub-strata fuels contributed little to the flame front at higher wind speeds. This phenomenon may have been exaggerated in the small laboratory fires where fires fanned by strong winds were in an early build-up phase. Given sufficient time and space, a deeper flaming zone would probably develop as the fire burnt down into the fuel bed behind the flame front, creating a strong convection column centered further behind the leading edge. This would tend to hold the flames up, retarding their spread across the fuel bed surface.

Flame length and depth, although variable, increased linearly with increasing wind speed and rate of spread. Most variation (62–67 per cent) in flame size was explained by wind speed, the quantity of fuel consumed and to a lesser extent, fuel moisture content (Table 5). Large flames did not cause high rates of spread but were a consequence of strong wind, high quantity of fuel consumption and dry fuels. Stepwise linear models relating flame dimensions with these variables are summarized in Table 5.

As headfire rate of spread (r_F) is mainly a function of wind speed and fuel moisture content (Equation 1), it can be substituted for these variables and used with fuel quantity consumed (w_C) to predict flame dimensions (Equations 2, 3 and 4). In these equations the regressions were forced through the origin resulting in re-defined R^2 values which have limited meaning (Myers 1990). Headfire flame angle (A), measured from the horizontal (see Rothermel 1983), varied inversely with wind speed and with headfire rate of spread but directly with fuel quantity (w_C) (Fig. 8 and Fig. 9). Wind speed accounted for 63 per cent and fuel quantity 20 per cent of the variation explained by Equation 5, and rate of spread accounted for 51 per cent and fuel quantity 23 per cent of the variation explained by Equation 6. Hamada (1952) reported flame angle in building fires to be a function of wind speed squared then divided by four times flame depth. Laboratory studies by Szczygiel (1988) using scotch pine litter, produced an inverse relationship between flame angle and wind speed.

$$h_f = 0.0013(r_F)+0.0328(w_C) \qquad R^2 = 0.88 \qquad \text{(Equation 2)}$$
$$L = 0.0024(r_F)+0.036(w_C) \qquad R^2 = 0.90 \qquad \text{(Equation 3)}$$
$$D = 0.0046(r_F)+0.028(w_C) \qquad R^2 = 0.85 \qquad \text{(Equation 4)}$$
$$A = -5.08(U)+2.01(w_C)+77.4 \qquad R^2 = 0.83 \qquad \text{(Equation 5)}$$
$$A = -0.13(r_F)+2.18(w_C)+66.5 \qquad R^2 = 0.74 \qquad \text{(Equation 6)}$$

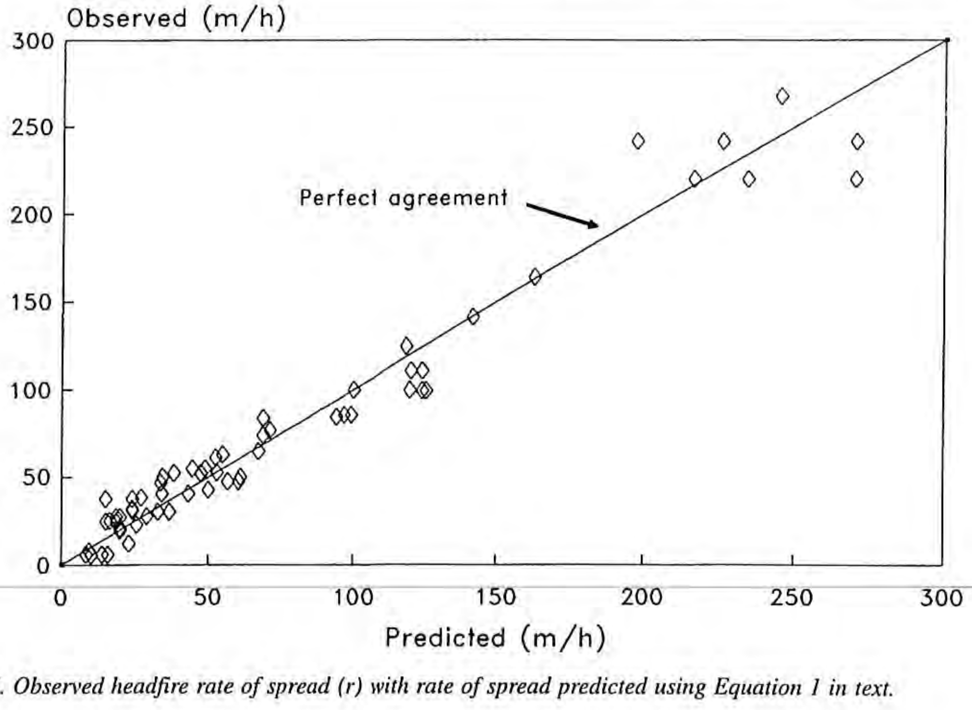

Figure 5. Observed headfire rate of spread (r) with rate of spread predicted using Equation 1 in text.

The linear regressions in Figure 9 define the theoretical threshold wind speed for a wind-driven fire as between 1–2 km h^{-1} depending on fuel quantity; the threshold increasing with fuel quantity. However, this assumes that a fire is wind-driven when $A < 90°$. Based on the data in Figure 3, the threshold was estimated to be closer to 3.5 km h^{-1} for moderate fuel quantities (6.0–10.0 t ha^{-1}).

Backfire flame length, flame depth and flame height were directly related to fuel quantity, hence rate of spread (Fig. 10). Backfire flame angle (between flame face and the unburnt fuel bed) was inversely related to fuel quantity with flames approaching vertical with increasing fuel quantity. The higher correlation coefficients (Table 5) reflect the relative ease of measuring the small, discrete backfire flames.

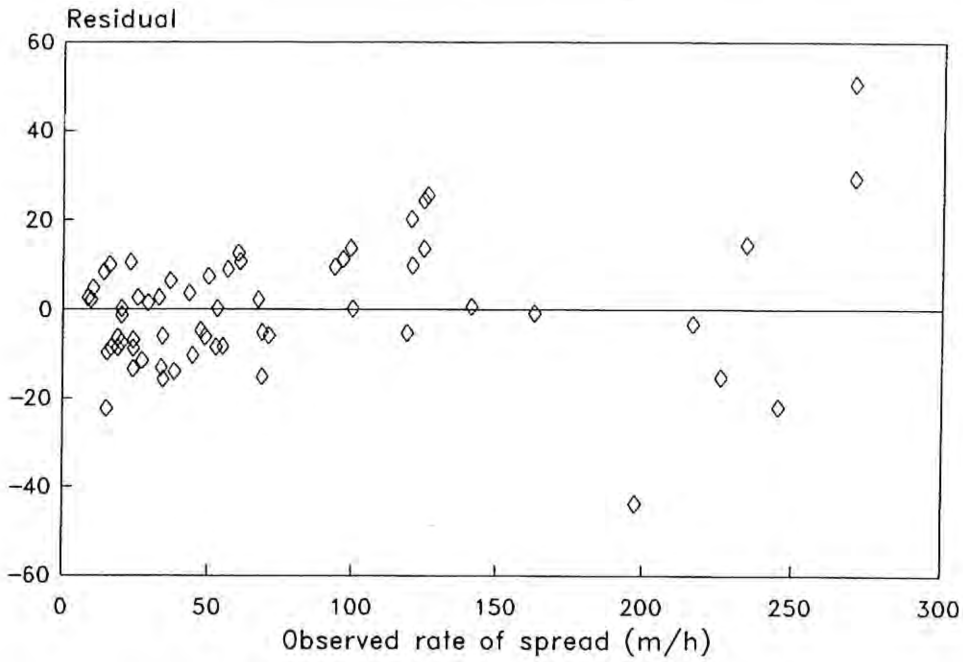

Figure 6. Residuals (observed minus predicted) with observed rate of spread.

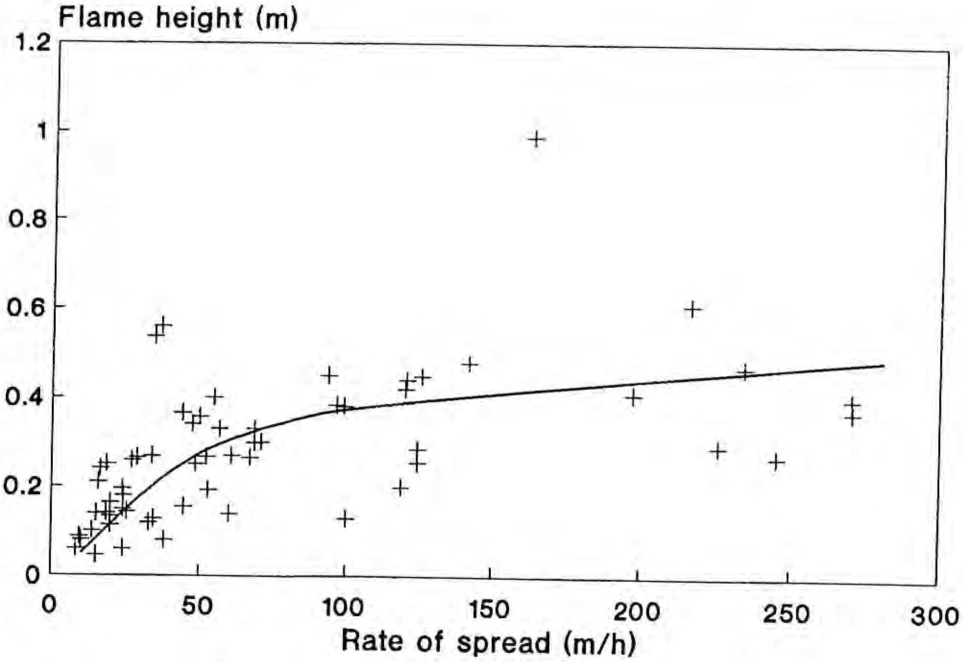

Figure 7. Flame dimensions with rate of spread.

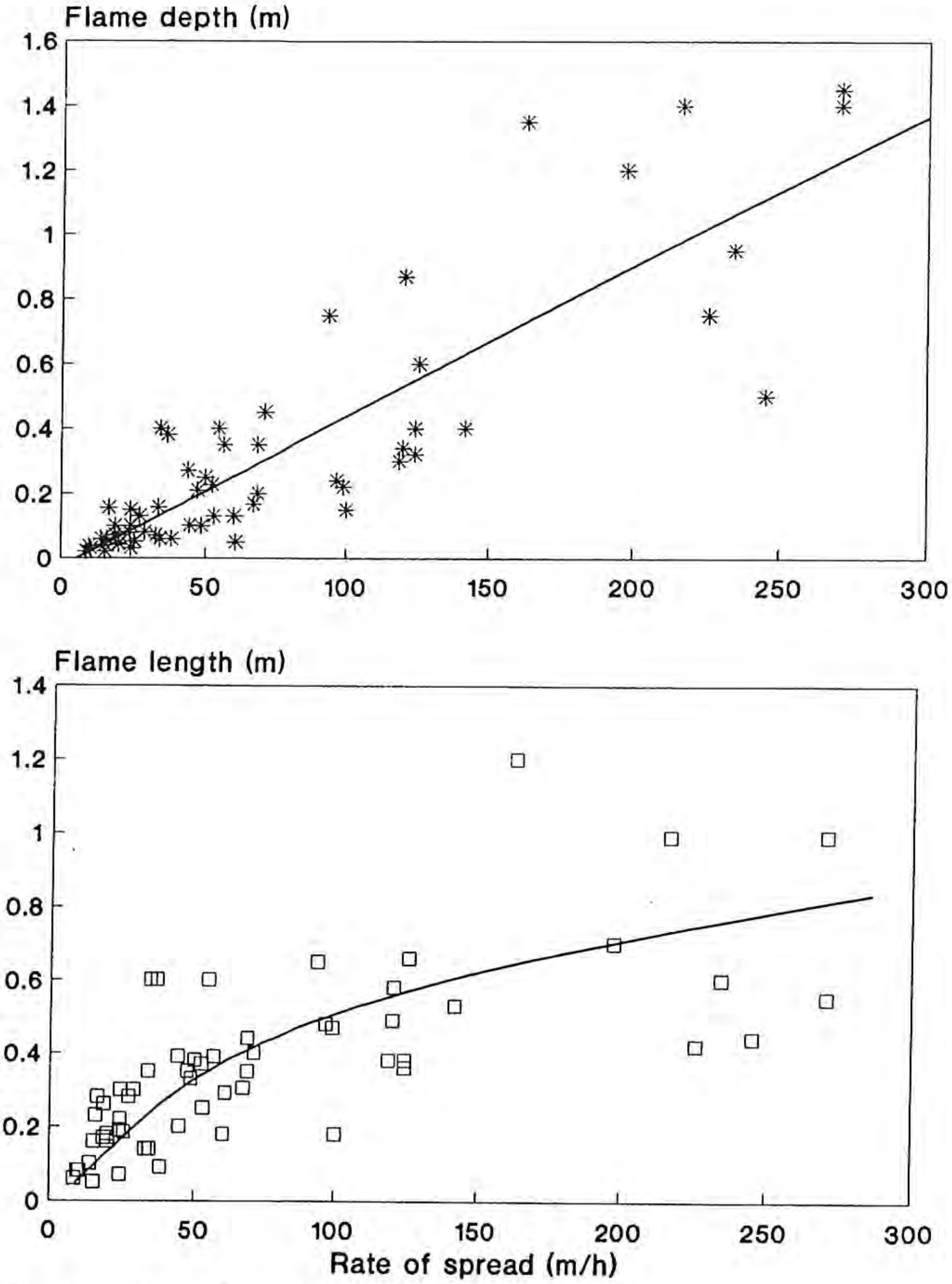

Figure 7. Flame dimensions with rate of spread.

Fire Intensity

Byram's fireline intensity (Byram 1959) is widely used to describe the energy output or the power of a fire. It has often been described as the single most important characteristic of a fire's general behaviour (Van Wagner 1970; Alexander 1982). It is used as a measure of suppression difficulty, to set limits for prescribed burning, and as a measure of the direct impact of fire on above ground vegetation (e.g. Cheney 1981, 1990a; Andrews 1991). Fire intensity is calculated by:

$$I = Hwr$$ (Byram 1959);

where H is the fuel low heat of combustion (18700 kJ kg^{-1} used here), w is the weight of fuel consumed in the flaming zone and r is flame rate of spread. Intensity (I) is usually expressed in kilowatts per metre. Alexander (1982) provides a detailed description of how to calculate and interpret fire intensity.

Fire intensity is also directly related to flame dimensions and can be used to calculate flame length or vice versa (e.g. Byram 1959; Sneeuwjagt and Frandsen 1977; Luke and McArthur 1978; Rothermel and Deeming 1980; Nelson and Adkins 1987). Field experiments have

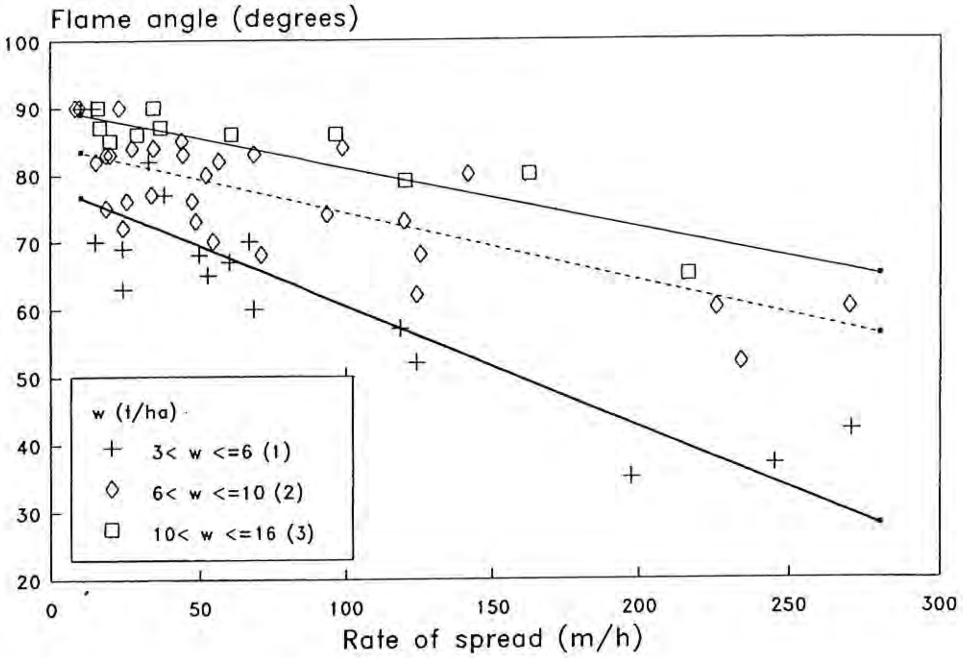

Figure 8. Flame angle with rate of spread by fuel quantity (w = t ha^{-1}) classes.

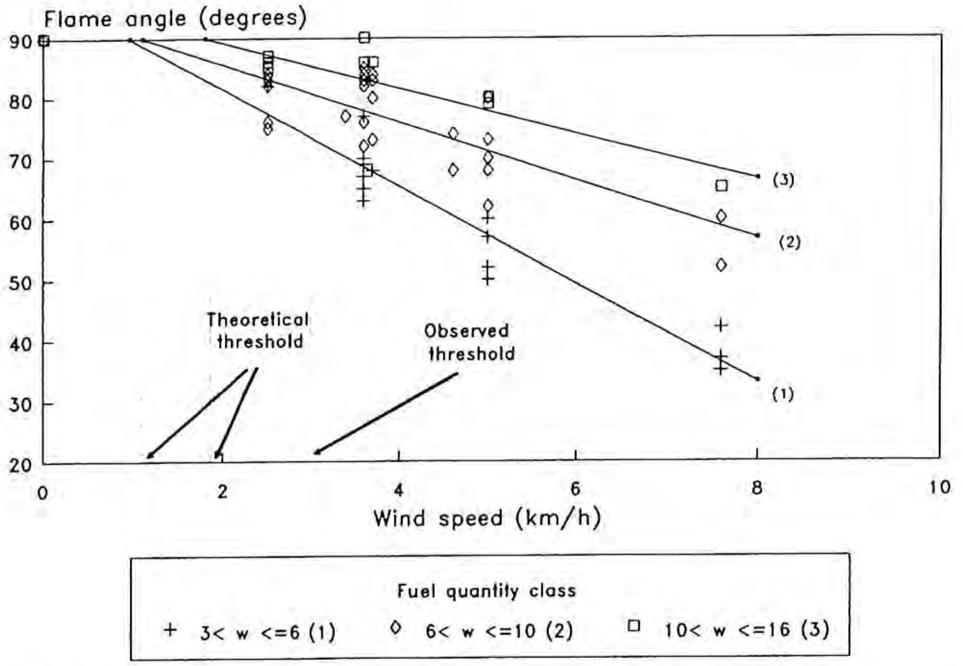

Figure 9. Flame angle as a function of wind speed and quantity of fuel consumed. The theoretical wind speed at which fires become wind-driven (threshold wind speed) is shown with the observed threshold wind speed.

generally resulted in good agreement with Byram's (1959) original relationship between flame length and fire intensity (e.g. Van Wagner 1968; Thomas 1971; Sneeuwjagt and Frandsen 1977). However, Nelson and Adkins (1987) found that flame length in their laboratory fires was more or less constant at 0.5 m, regardless of fire intensity, whereas in the field flame lengths were proportional to the square root of fire intensity. They concluded that further studies were needed to resolve the relationship between flame characteristics and fire intensity.

The weight of fuel consumed in the flaming zone, w_c, is a vital but difficult to measure component of the intensity equation. It is generally accepted that fine fuels less than 6 mm in diameter are mostly consumed in the flaming zone of a forest fire. However, during these laboratory experiments, it was visually evident that a significant proportion of the fuel bed, especially of deeper

TABLE 5
Linear regression models of the dependency of flame dimensions (m) on wind speed (U = km h^{-1}), fuel quantity consumed (w_c = t ha^{-1}) and fuel moisture content (MC = per cent of oven dry weight).

DEPENDENT VARIABLE	INDEPENDENT VARIABLE	PARAMETER ESTIMATE	STANDARD ERROR	PARTIAL R^2	MODEL R^2
Flame height	w_c	0.0322	0.005	0.32	0.32
	U	0.041	0.006	0.28	0.60
	MC	-0.009	0.005	0.02	0.62
	Intercept	-0.013	0.067		
Flame Length	U	0.079	0.009	0.47	0.47
	w_c	0.038	0.006	0.20	0.67
	MC	0.007	0.007	0.02	0.69
	Intercept	-0.044	0.046		
Flame depth	U	0.147	0.015	0.59	0.59
	w_c	0.033	0.011	0.05	0.64
	Intercept	-0.194	0.063		

MC did not meet model entry requirements

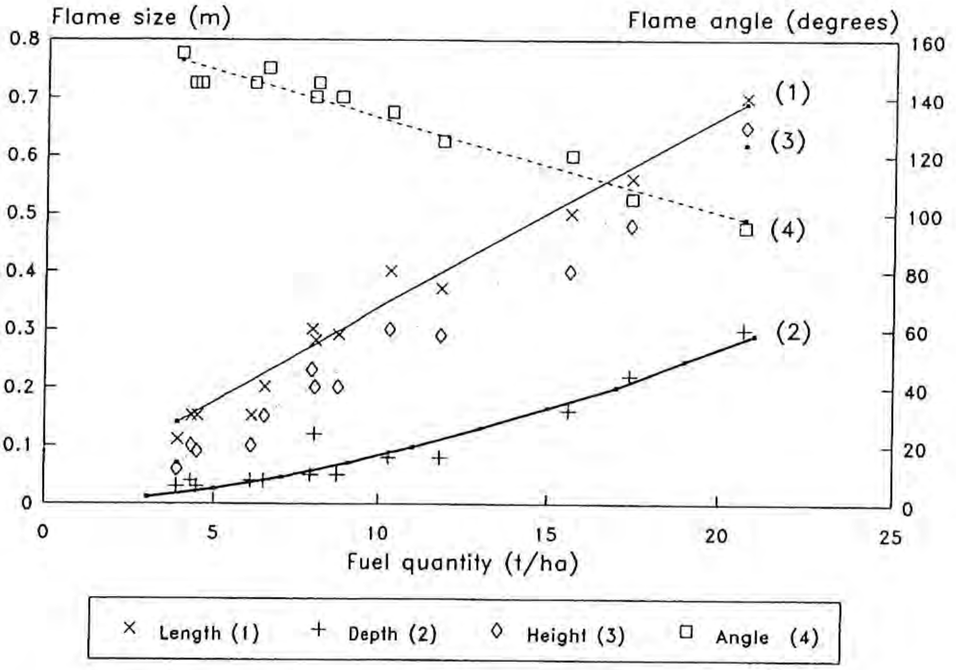

Figure 10. Backfire flame dimensions and flame angle with quantity of fuel consumed.

(heavier) fuel beds burning under high wind speeds, was not burnt in the flaming zone, but burnt as either 'flickering', glowing or smouldering combustion after the passage of the main flame structure. It appeared that most active flaming combustion was associated with the top 15–20 mm of the fuel bed, as discussed above. This phenomenon has been observed for other well packed fuel beds and coarse, woody fuel particles (e.g., Kiil 1971; Alexander 1982; Cheney 1990a). This is unlikely to be an artefact of small scale laboratory studies although the effect may have been exaggerated under conditions of high fuel quantity and high wind speeds as fires would not have reached a quasi steady state. Alexander (1982) suggested reducing the total fuel quantity consumed in the flaming zone in these situations, but did not provide details on how this should be done.

To examine the relationship between flame size and fire intensity for jarrah litter fuels, fire intensity was calculated two ways by deriving two measures of fuel quantity consumed in the flaming zone.

Method 1: The first calculation was based on the generally accepted premise that almost all fuel less than 6 mm in diameter is consumed in the flaming zone. Thus, intensity was calculated from the fuel quantity consumed (w_C)(t ha^{-1}), determined from total fuel quantity (W) less residue after combustion (r) and rate of spread (r_F) (m h^{-1}). Thus:

$$I = (W-r)*r_F*0.516,$$

where I = intensity (kW m^{-1}), W = total fuel < 6 mm diameter (t ha^{-1}), r = fuel residue (t ha^{-1}) and r_F = rate of spread (m h^{-1}).

The quantity of fuel residue (material remaining on the fire table after all combustion had ceased) was a function of the total fuel quantity and wind speed. The proportion of the total fuel quantity consumed by all forms of combustion (total quantity on the table minus residue/total quantity) was dependent on the headfire rate of spread (therefore wind speed and fuel moisture content). When rate of spread exceeded about 60 m h^{-1}, the proportion of fuel consumed was more or less constant at about 85 per cent of the total fuel quantity.

Method 2: This estimate of intensity (I) is based on calculating the quantity of fuel actually consumed in the flaming zone using flame residence time, flame depth and the combustion rate of litter fuel particles described by Burrows (1994).

$$(1) \qquad W_{FZ} = D*K*(W*0.1)$$

where W_{FZ} = weight of potential fuel in the combustion zone (kg), D = flame depth (m), K = the width of the fire table (2 m in this case), W = total fuel quantity (t ha^{-1}) (*0.1 converts t ha^{-1} to kg m^{-2}).

$$(2) \qquad C_{CZ} = W_{CZ}*(t_r*C_R)$$

where C_{CZ} = the actual weight of fuel consumed in the flaming zone (kg), t_r = flame residence time (s), C_R = fuel combustion rate (0.017 kg s^{-1} kg^{-1} of initial fuel; from Burrows 1994).

Therefore,

$$(3) \qquad I_{FZ} = (C_{CZ}/(D*2))*(r_F/3600)*18700$$

where I_{FZ} = flaming zone intensity (Kw m^{-1}), D*2 area of fuelbed flaming (D = flame depth, 2 m = width of fire table) (m^2), r_F = rate of spread (m h^{-1}) (divided by 3600 = m s^{-1}), 18700 = heat yield (Kj kg^{-1}).

Intensities calculated using both methods were quite different but related to flame length reasonably well, as shown in Figure 11. Byram's equation is also graphed for comparison. The best fit regressions of fire intensity with flame length for the two methods were:

$$\text{Method 1: } I = 912.8(L)^{1.373} \qquad \text{(Equation 7)}$$

$$\text{Method 2: } I = 265.1(L)^{1.745} \qquad \text{(Equation 8)}$$

Flame Residence and Fuel Burn-out Time

It was difficult to measure the residence time of headfire flames from the thermocouple traces alone. Thermocouple temperature rose sharply as flames approached the sensors, but the decay curve was gradual. The 'event markers' on the thermocouple chart print-out, which were based on visual observations, provided better estimates of residence time.

Flame residence time was a function of fuel quantity as graphed in Figure 12. The poor relationship for headfires reflects the variability of the quantity of fuel consumed in the flaming zone, particularly at high wind speeds, and the

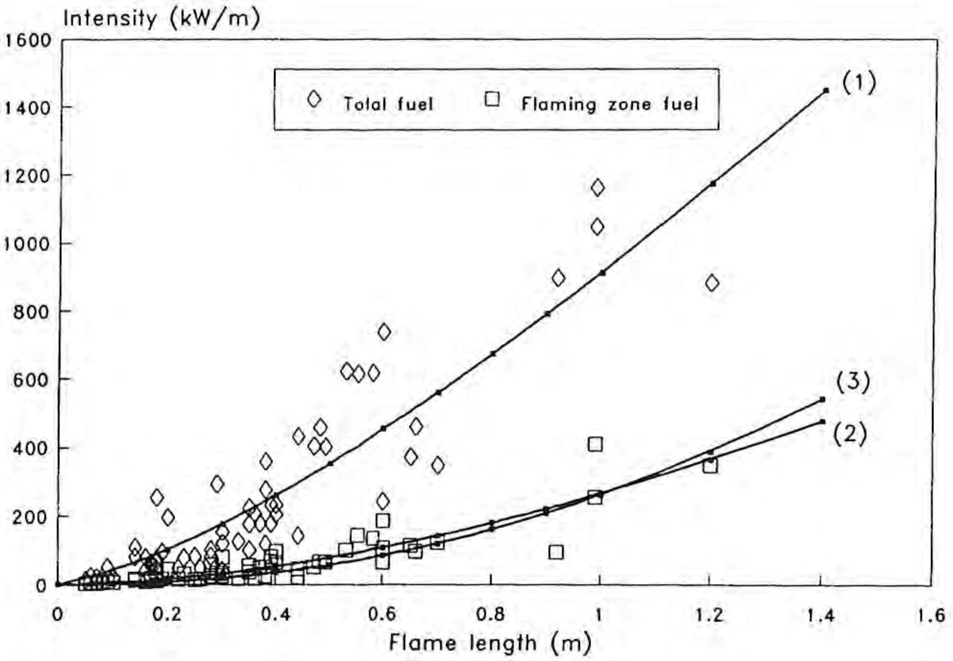

Figure 11. Fire intensity (I) with flame length (FL). Fire intensity is calculated using (1) total fuel consumed by all combustion phases ($I = 912(FL)^{1.37}$) and (2) using an estimate of fuel consumed in the flaming zone ($I = 265.1(FL)^{1.74}$). Byram's (1959) relationship (3) is also graphed ($I = 259.8(FL)^{2.174}$).

difficulty of determining leading and trailing edges of flames. A better relationship was determined for the more stable and well defined backfire flames. Anderson (1964) found that residence time peaked when white pine and ponderosa pine fuels were in the moisture content range of 8–10 per cent, but no such trend was apparent during this study.

Burn-out time, the time taken for all combustion, was also dependent on fuel quantity, although wind speed accounted for 8 per cent of the variation in the case of headfires (Fig. 13). At low fuel quantities, burn-out time was similar for headfires and backfires. However, heavy and deep fuels continued to smoulder for up to 20 minutes after the passage of backfire flames.

Slope and Rate of Spread

The effect of slope (S) on rate of spread under zero wind

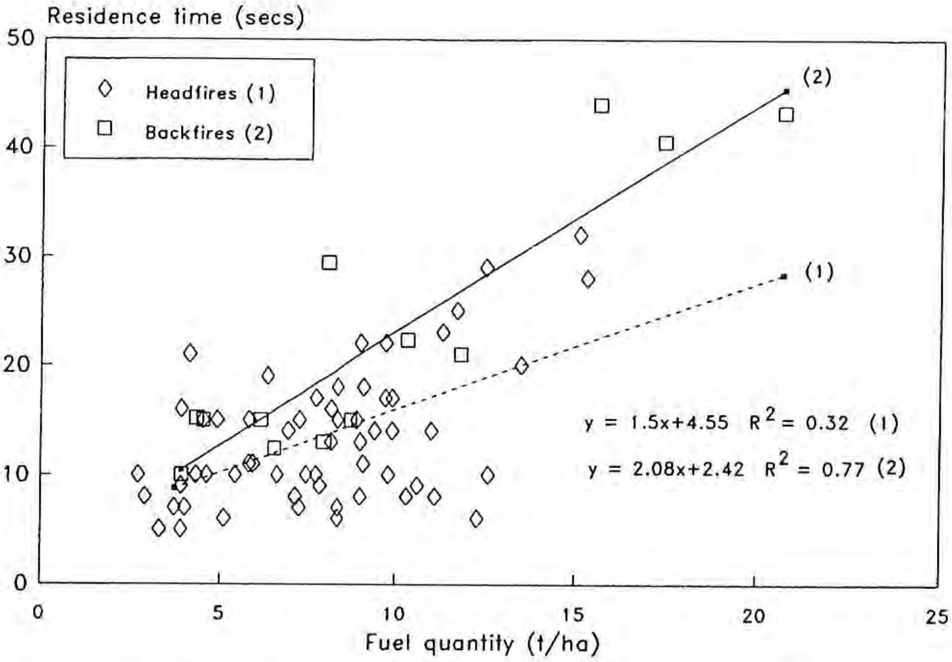

Figure 12. Flame residence time with fuel quantity consumed for headfires (1) and backfires (2).

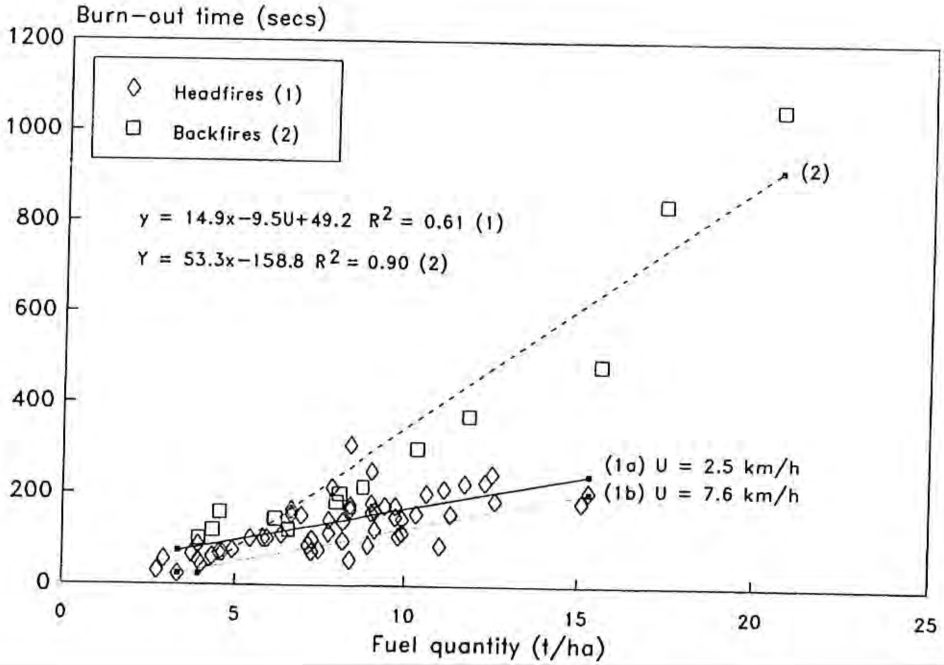

Figure 13. Burn-out time with the quantity of fuel consumed for headfires (1) and backfires (2).

conditions and for uniform jarrah litter fuel is shown in Figure 14. Positive slope had a strong positive influence on rate of spread whereas negative slope had a weak but noticeable negative effect. The best equation for predicting rate of spread from slope under these conditions was an exponential of the form:

$$r_F = 12.36 * e^{(0.0687 * S)} \qquad \text{(Equation 9)}$$

(0.44) (0.0068) (parameter standard errors)

Flame angles in relation to the fuel bed (i.e. 90° minus slope) for fires burning on the inclined (sloped) table and a selection of wind-driven fires burning on the flat table (controlling for fuel moisture content and fuel quantity) are graphed with rate of spread in Figure 15. The relationship between slope-induced flame angle and rate of spread is similar to the relationship between wind-induced flame angle and rate of spread.

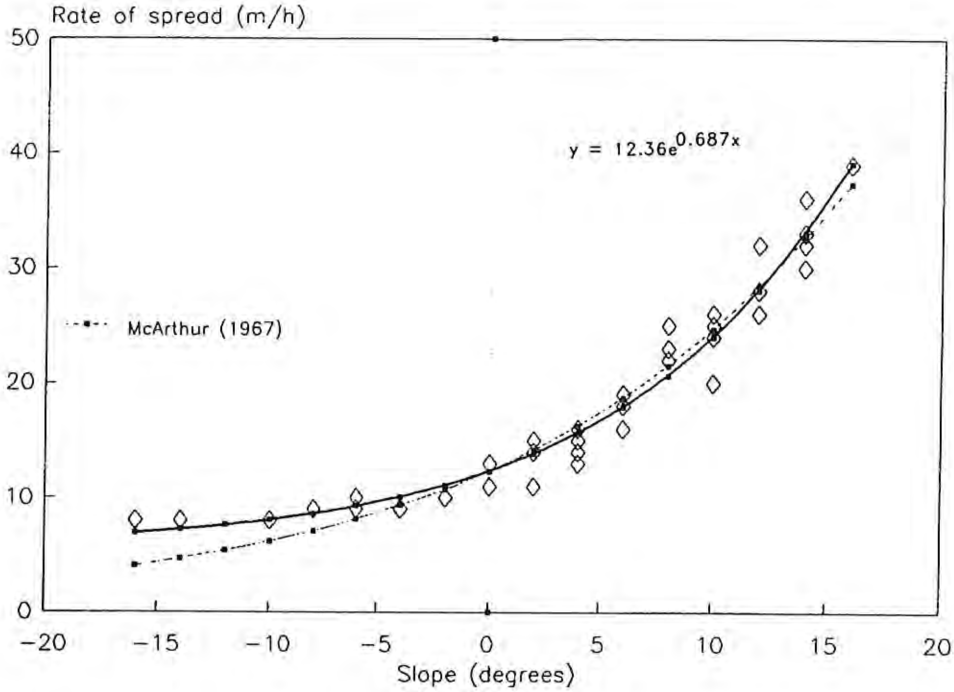

Figure 14. The effect of slope on rate of spread (zero wind).

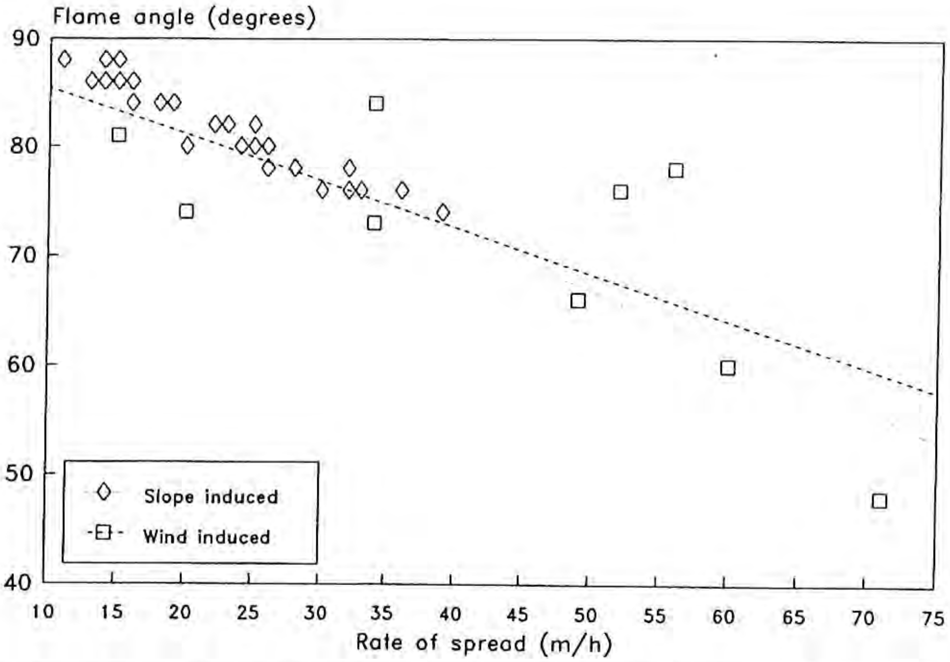

Figure 15. The relationship between flame angle and rate of spread is similar for slope-induced flame angle and for wind-induced flame angle.

Wind Speed and Fire Shape

Fires lit from a point source in uniform jarrah litter fuels on the large laboratory table burnt in a roughly elliptical to double ellipse shape under the influence of wind provided by fans. After an extensive examination of fire shape data for a range of fuel types from a range of sources, Alexander (1985) derived a single empirical relationship between fire shape (length-to-width ratio) and wind speed at standard exposure

$$L/W = 1.0+0.00120*WIND^{2.154} \quad \text{(Alexander 1985)}$$

Data obtained by this study were fitted to this equation form and the best fit equation relating fire length-to-width ratio (L/W) and wind speed (U) at 20 cm (0.2 m) above the litter bed was;

$$L/W = 1.0+0.0236(U)^{2.114} \quad \text{(Equation 10)}$$

$$(0.010) \quad (0.247) \quad \text{(parameter standard errors)}$$

Equation 10 is graphed in Figure 16 along with data from three jarrah forest wildfires (Underwood *et al.* 1985; McCaw *et al.* 1992). The wildfire data were not used in the regression analysis. Wind speeds for the wildfire data are estimated wind speeds at 1.5 m above the forest floor based on wind reduction models for jarrah forest (Sneeuwjagt and Peet 1985).

DISCUSSION

Rate of spread and fuel quantity

Fire behaviour models developed in the field (e.g. McArthur 1962; Sneeuwjagt and Peet 1985; Forestry Canada 1989) form the basis of forest fire behaviour prediction in Australia and Canada and assume a direct relationship between headfire rate of spread and fuel quantity. There is no reported statistical evidence to support this relationship for Australian forest fuels but McAlpine (1995) found a weak and indiscernible relationship for several Canadian fuel types. He questioned whether the relationship should be incorporated into the Canadian fire behaviour prediction system. This is discussed further in relation to field experiments described by Burrows (this volume). For the experimental fires described by this study, the rate of spread of wind driven fires was found to be independent of the quantity of fuel *per se* on the fire table, but the rate of spread of backfires and zero wind fires was directly related to fuel quantity.

Studies of the effect of fuel quantity on rate of spread are limited and the findings are conflicting. The difficulty of measuring the fuel contributing to the fire spread process probably accounts for this. Fang and Steward (1969) found that fuel quantity had no effect on spread rate in artificial fuel beds. Similarly, Fons (1946) and Fons *et al.* (1962) showed that the rate of spread of laboratory fires was dependent on fuel compactness and fuel density, but was independent of the quantity of fuel per unit area. Steward (1974) reported that rate of spread was independent of 'fuel loading density' (fuel quantity) for laboratory fires burning in shredded newspaper and poplar wood shavings and in still air. However, he proposed that this would not be the case for wind-driven fires. Carrier *et al.* (1991) theorized that rate of spread was inversely related to fuel quantity. This was later demonstrated in the

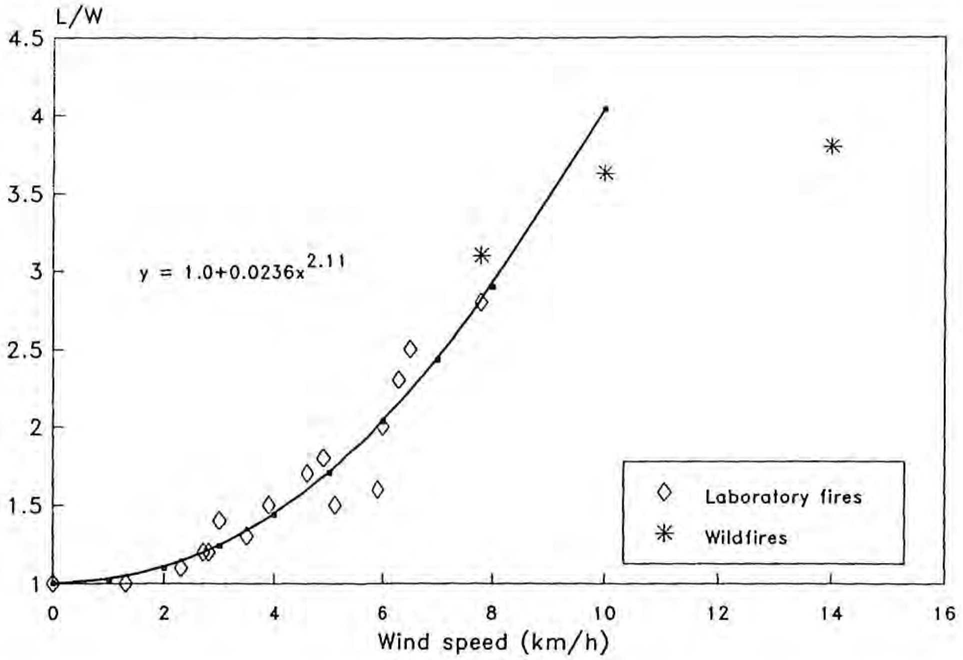

Figure 16. Fire shape (width-to-length ratio – L/W) as a function of wind speed. Data from three documented wildfires are also graphed for comparison with laboratory fires. Wildfire data are from Underwood et al. *(1985) and McCaw* et al. *(1992).*

laboratory by Wolff *et al.* (1991). However, their findings are questionable as fuel quantity was increased by increasing bulk density and packing ratio.

Rothermel (1972) incorporated fuel quantity (loading) in fire spread equations to determine packing ratio and reaction intensity. Reaction intensity and energy release rate (Rothermel and Anderson 1966; Rothermel 1971; Rothermel 1972; Frandsen and Rothermel 1972) depend on the rate of fuel consumption in the active flaming zone. That is, the fuel contributing to that portion of fire line intensity that is driving the fire. Clearly, fuel loading and fuel contributing to fire spread are different measures for well compacted and relatively coarse fuels such as eucalypt litter. The amount of fuel burning in the flaming zone and the amount of fuel per unit area are similar quantities for fuel arrays which are well aerated and consist of fine particles, such as the artificial cribs etc. studied by Fons *et al.* (1962), Byram *et al.* (1966), Anderson and Rothermel (1966), Thomas (1967), Anderson (1969), Steward (1971).

A lack of understanding of the fundamental physical and chemical processes of combustion and fire spread limits a theoretical interpretation of the effect of fuel quantity on rate of spread, especially for wind-driven fires. There is general agreement in the literature on the way in which fuel properties such as particle size and packing influence rate of spread (e.g. Fons 1946; Beaufait 1965; Anderson *et al.* 1966; Murphy *et al.* 1966; Rothermel and Anderson 1966; Byram *et al.* 1966; Rothermel 1972; Albini 1980; Vines 1981; Albini 1982; Nelson and Adkins 1987; Anderson 1990). However, there is no general agreement on the processes involved. For example, Van Wagner (1967) recognized discrepancies in the mechanisms of heat transfer between laboratory studies using wooden cribs (e.g. Thomas 1965, Byram *et al.* 1966) and those using pine needles (e.g. Beaufait 1965; Rothermel and Anderson 1966). Radiation from flames above the fuel bed was found to be unimportant in the crib studies but appeared to be the main mechanism of fire spread in the needle bed studies. Thomas *et al.* (1961), Fons *et al.* (1962), Thomas (1970) argued that flames extending above the fuel bed were not sufficiently thick to be very emissive and that heat radiated through the fuel bed was more important. Consequently, rate of spread depended on bulk density and not on the quantity of fuel per unit area (Fons *et al.* 1962). Albini (1985) modelled fire spread using radiation as the propagating heat flux, but Steward (1971) and Frandsen and Andrews (1979), using a mathematical modelling approach, concluded that convective heating through the depth of the fuel bed was important.

Nelson and Adkins (1987) reported that the 'key process in the spread of the wildland fuel is horizontal displacement of flame at the fuel surface by a convection mechanism related to wind speed'. Cheney (1990b) proposed the concept of fire spreading across the fuel bed surface and down into the fuel bed. Interaction between the ambient wind field and flame convection, flame contact, and the concepts proposed by Cheney (1990b) and Nelson and Adkins (1987) helps to explain the behaviour of laboratory fires burning in a jarrah litter fuel bed.

Fires burning under zero wind conditions burnt slowly with erect, stable and discrete flames. Rate of spread was controlled by fuel quantity and moisture content and the flames burnt more or less uniformly through the fuel bed with radiation within the fuel bed presumably being the primary spread mechanism. The spread ratio (ratio of forward rate of spread-to-vertical (downwards) spread rate) was close to 3. When wind was applied, the flames were tilted, but only tilted significantly to affect rate of spread above a wind speed 'threshold'. The 'threshold' varied between 1–3 km h^{-1} depending on fuel quantity (and probably moisture content but this could not be demonstrated here). At high wind speeds (3.0–8.0 km h^{-1}), flames spread rapidly across the surface of the fuel bed and slowly down into the fuel bed and the spread ratio was high (40–60). This could be interpreted as direct flame contact with the fuel bed surface and forced convection of hot and burning gasses through the fuel bed at the combustion interface being the primary mechanism for flame spread which increased linearly with wind speed. With increasing fuel bed depth, hence increased fuel quantity, an increasing proportion of the fuel at depth was consumed in the secondary (flickering) and residual (glowing and smouldering) combustion phases (terminology after Alexander 1982) behind the trailing edge of the flame. Secondary and residual combustion is unlikely to contribute positively to fire spread and theoretically would act to retard spread by shifting the convective centre upwind. In shallow, light fuels (4–5 t ha^{-1}) under high wind speeds (6–8 km h^{-1}), the relatively small flames were blown almost flat onto the fuel bed which was consequently ignited by flame contact. Most of the fuel was consumed in the flaming zone.

The high fire spread ratio (horizontal versus vertical) for wind-driven fires reflects the physical nature of jarrah litter fuel beds. In well-aerated fuel beds there is a greater rate of vertical consumption of fuel. Frandsen and Schuette (1978) burning excelsior in the laboratory, clearly demonstrated an inverse relationship between packing ratio and the downward burning rate and reported slow vertical rates of spread and low rates of fuel weight loss for well compacted fuel (i.e. packing ratio = 0.065). Compared with wood cribs and other artificial fuel beds, the leaf litter fuels studied here could be considered as compacted, or poorly aerated, with a packing ratio of 0.06–0.08. Using an equation developed by Rothermel (1972) the optimum packing ratio for the litter fuel studied here is about 0.006. It was very likely that the packing ratio varied through the vertical profile of the fuel bed, increasing with distance downwards from the fuel bed surface. The well-compacted nature of jarrah forest litter fuel resulted in a slow rate of vertical or downward consumption of fuel, even though the wind-driven flames spread rapidly across the better aerated fuel bed surface. In this laboratory study, forward rate of spread was therefore found to be independent of the quantity of fuel per unit area.

Rate of Spread and Wind Speed

Wind speed has long been proven to be the most important environmental factor affecting fire rate of spread, both in laboratory and field studies (see reviews by Beer 1991a, 1991b; Pitts 1991; Carrier *et al.* 1991). The precise mechanism of how and why wind speed directly affects rate of spread is not well understood. In general terms, it is probably a result of increased oxygenation, better mixing of combustion gasses, increased pre-heating of the fuel bed owing to lowering of the flame angle and flame contact with the fuel bed (e.g. Fons 1946; Thomas 1967; Luke and McArthur 1978; Cheney 1981; Chandler *et al.* 1983; Nelson and Adkins 1987).

Wind-driven fires in jarrah forests typically progress in surges. This has been observed in other fuel types (e.g. Wade and Ward 1973). Fluctuations in spread rate observed in the field are usually owing to the gustiness of wind (Albini 1982; Alexander *et al.* 1991) and interaction between ambient wind field and the convection column. In the latter situation, the flames are blown over the unburnt fuel bed, igniting it by direct contact. Fire spreads rapidly across the fuel bed surface (top 15–20 mm) resulting in long, deep flames. A point is reached when the flame is sufficiently deep and the convection energy in the flaming zone is greater than the ambient wind field, and the flames stand nearly vertically. This is characterized by tall, erect and noisy flames which may result in localized crowning and torching. When the fuel bed has burnt down and the convection column loses energy, the wind field again dominates and drives the flames forward.

Fire spread and wind speed data reported by other workers studying both artificial and natural fuel beds in the laboratory have derived either exponential or power equation forms relating rate of spread and wind speed (e.g. Anderson and Rothermel 1966; Byram *et al.* 1966; and review by Pitts 1991). However, Byram *et al.* (1964) reported a linear relationship for wood cribs constructed from 6.4 mm square sticks, suggesting that the form of the relationship is probably a function of fuel particle size.

A feature of the relationship between fire spread and wind speed which lends itself to a non-linear equation form is the low rate of increase in rate of spread at low (sub-threshold) wind speeds compared with the higher rate of increase at higher wind speeds. Over the range of the experimental data reported by this and other laboratory fire studies, the choice of equation form may not be critical. However, when predicting fire rate of spread beyond this range the equation form will be highly significant. For example, using either linear Equation 2 or non-linear Equation 10 from Table 3 above to predict headfire rate of spread over the range of experimental conditions will result in similar predictions. However, for a wind speed of 10 km h^{-1}, the equations predict vastly different rates of spread. Because of a lack of understanding of the fundamental processes of combustion and fire spread, it is difficult to select the equation form which is conceptually correct from experimental data sets which represent a narrow range of potential conditions. However, based on the data presented here, a power equation form best fitted the entire range of wind speeds and a linear form was best for wind speeds >3.0 km h^{-1}.

Rate of Spread and Fuel Moisture Content

Fuel moisture content has long been recognized as an important factor affecting ignition and fire spread (Gisborne 1928). The precise nature of the relationship varies from one fuel type to another but the decrease in rate of spread with increased moisture content is conventional wisdom among fire managers and researchers. The physical processes of the influence of moisture on fire spread are reasonably well understood and have been addressed in the literature (e.g. Fons 1946; Davis *et al.* 1959; Anderson and Rothermel 1966; Pompe and Vines 1966; Anderson 1969; Brown and Davis 1973; Luke and McArthur 1978; Vines 1981; Gill *et al.* 1981; Chandler *et al.* 1983; Artsybashev 1984). Albini (1980) has proposed a useful theoretical model which deals with the concept that a limiting value of moisture content can be related to the structural properties of the fuel bed. This was later demonstrated by Wilson (1985).

Fuel moisture content influences rate of spread and quantity of fuel consumed so affects flame dimensions. Anderson (1964, 1968), studying ponderosa pine and white pine needle beds, showed that flame depth and fuel moisture content were related by a maxima function. Laboratory studies by Rothermel and Anderson (1966) showed that flame depth increased with increasing wind speed but the vertical depth of burn decreased. This was visually apparent here and probably explains why wind speed, and not fuel quantity, influenced flame depth. The high packing ratio of jarrah litter fuel resulted in slow downward consumption of fuel, so at high wind speeds combustion rate per unit area (energy release rate) was lower than at low wind speeds, even though the total energy release rate was greater. This phenomenon has been reported by Rothermel and Anderson (1966) for other fuel types studied in the laboratory.

Backfire Rate of Spread

The backfires studied here were of low intensity (<150 kW m^{-1}), slow spreading and the flames were small and stable, so could be readily studied in the laboratory without concern for scale. Unlike wind-driven fires, there were little or no secondary or residual combustion phases and the compact backfire flames burnt deep into the fuel bed, the entire fuel profile being consumed in the flaming zone.

The benign characteristics of backfires, in terms of control difficulty and potential to cause damage to the natural and built environment, probably explain why relatively little attention has been given to modelling their behaviour. Past studies aimed to assist with the development of mathematical models of fire spread (Thomas *et al.* 1963; Anderson 1964). However, the backfire is an integral part of the structure, geometry and symmetry of a fire spreading from a point source in a continuous fuel bed, and is the antitheses of the headfire.

Fire behaviour changes dramatically around the perimeter of a wind-driven fire from the slow, low intensity backfire to the often fast, intense headfire (Catchpole *et al.* 1982; Catchpole *et al.* 1992). Understanding the processes of backfire spread and the transition in fire behaviour towards the headfire is likely to provide greater understanding of fire spread and fire shape. Backfires are often used to control wildfires (Burrows 1986) and to achieve a range of prescribed burning objectives, so an ability to predict the effect of different fuel quantities on backfire behaviour will aid suppression planning and the application of fires for ecological reasons.

Although backfires were slow moving and stable, their spread rate increased linearly with increasing quantity of fuel. This finding is in contrast to that of headfires reported above. Significantly, flames became deeper, more erect (vertical) and longer with increasing fuel quantity and fuel depth. These relationships also held for fires burning under zero wind conditions, although the zero wind fires spread faster for a given fuel quantity than did backfires burning into wind.

Anderson (1964), working in pine fuels, found that fire rate of spread did not increase when fuel depth exceeded three inches (75 mm). The maximum fuel bed depth studied here was 45 mm, and there was no indication of spread rate saturating. Van Wagner (1967) established a strong curvilinear relationship between backfire rate of spread and fuel moisture content, but suggested that, in theory, fuel quantity should not affect rate of spread. Fang and Steward (1969) reported that the rate of spread of fires burning in wood shavings was unaffected by fuel loading density. Similarly, rates of spread in two artificial fuels studied by Steward (1974) were not influenced by fuel quantity or fuel depth. Beaufait (1965) and McAlpine (1988) reported consistent spread rates for backfires in pine needle fuels over a range of wind speeds whereas Murphy *et al.* (1966) found that backfire rate of spread increased with increasing wind speed, although these studies used an artificial non-porous fuel. Ward (1971) found that the rate of spread of backfires burning in *Pinus pinaster* needles was constant, regardless of wind speed and slope (all else being equal).

Assuming backfire rate of spread to be constant or negligible, is common when modelling fire shape (Van Wagner 1969; Potter *et al.* 1979; Anderson 1983; Alexander 1983; Alexander 1985). This assumption is probably reasonable at high headfire rates of spread, but inaccuracies in modelling fire shape and dimension will become more significant at lower spread rates (Alexander 1985).

The difference between fires burning under zero wind and burning into a constant wind of 4.6 km h^{-1} in this study was the position of the flame in relation to the fuel bed. Under zero wind conditions, the flame was near vertical, but a flame burning into the wind was tilted over the burnt fuel bed. The inverse relationship between flame angle and fuel quantity (when wind speed is constant at 4.6 km h^{-1}) demonstrates the interaction between flame convection and the ambient wind field. At high fuel quantities (>15 t ha^{-1}), flames burning into the wind were nearly vertical. Thus, the wind had little effect on flame attitude when backfires were burning in deep, heavy fuels (fuel depth and fuel quantity were strongly correlated). The point at which a backfire behaves as though it is burning under zero wind (hence likely to spread faster) will depend on the conditions of fuel quantity and ambient wind speed, *ceterus paribus*. For a given wind speed, there is a threshold fuel quantity, below which the wind field will dominate flame convection, causing the flame to tilt over the burnt fuel bed. This threshold obviously increases with increasing wind speed. Other factors (held constant during backfires studied here) such as fuel moisture content and slope probably influence this relationship.

Rothermel and Anderson (1966) developed mathematical models explaining flame tilt as a function of the relative magnitude of the fire and wind forces. The magnitude of fire forces was found to be a function of the combustion rate per unit area of fire. If this is large then the flames will not be tilted and rate of spread will be low. Rothermel and Anderson (1966) found that the energy release rate was dependent on wind speed, such that low or no wind resulted in high energy release per unit area of burning fuel. Therefore, flames are more erect and rate of spread is low. This theory helps to explain the behaviour of backfires studied here. The energy release rate of a fire burning into wind was a function of the fuel quantity. Vertical depth of burn (into the fuel bed) increases with decreasing wind speed (Rothermel and Anderson 1966), so is probably near maximum for fires burning in zero wind and for backfires. Therefore, increasing fuel quantity produced a higher energy release rate per unit area of combustion and more erect, taller flames.

In this study, the length and depth of backfire flames related well to the rate of fire spread in jarrah litter fuel and supports findings in other fuel types (Byram *et al.* 1966; Rothermel and Anderson 1966; McArthur and Cheney 1966; Thomas 1967; McArthur 1968). Radiation flux from a flame is a function of its size (Anderson 1968; Packham and Pompe 1971). Backfires burning in jarrah leaf litter produced relatively small flames which leant away from the unburnt fuel bed. Thermocouple traces showed that the temperature of thermocouples on the fuel bed surface ahead of the advancing flames did not rise significantly until the flames were very close.

This is consistent with other findings (Rothermel and Anderson 1966; Fang and Steward 1969; Frandsen 1973) and with the conclusion that relatively low level radiation is the primary source of heat transfer to unburnt fuel during backfires, which therefore spread very slowly. Interestingly, the relationship between pre-heat distance and fuel quantity (therefore rate of spread) saturated at a fuel quantity of about 12 t ha^{-1}. This is approaching the quantity at which flames tended to 90°.

Headfire Flame Dimensions

Flame size was a function of wind speed, (or rate of spread) and fuel quantity, or more precisely, the quantity of fuel involved in the combustion zone. Rate of spread and flame depth were independent of fuel quantity and were largely dependent on wind speed. This evidence suggests that increasing flame size is primarily an effect of increasing rate of spread and not a cause. That is, large flames and associated radiation output are a consequence of fast spreading fires and of more fuel being consumed, not the cause. Wind forced the flames through and across the fuel bed, involving more fuel in the combustion zone and generating larger flames and higher intensities. Increased radiation falling on the fuel bed surface will obviously lead to more rapid pre-heating. When flames were erect (near 90°), that is, when the convection column dominated the wind field, fires spread very slowly. The wind speed necessary to tilt the flames over the fuel bed increased with fuel quantity (Fig. 10) as convection energy is directly related to the quantity of fuel being consumed in the flaming zone (Byram 1959). There was no significant increase in rate of spread until flames were tilted more acutely than about 80° which required a wind speed of 2–4 km h^{-1} depending on fuel quantity (Fig. 10).

Fire Intensity

Using w_c (Method 1) to calculate intensity resulted in very high values for a given flame length compared with using C_{cz} (Method 2), which produced values similar to those of Byram (1959) (Fig. 12 (7–13)). Method 1 assumes that all heat is released in the flaming zone, which was clearly not the case. This is consistent with the discussion above and with Cheney's (1990b) fire spread concept that not all fuel contributes equally to the intensity of a wind-driven fire. The difficulty of accurately determining fuel consumed in the flaming zone severely limits the usefulness of intensity as a universal descriptor of fire behaviour. Simply measuring the total quantity of fine fuel burnt and using this to calculate fire intensity results in an over-estimate of fire intensity because a significant and variable (and difficult to measure) proportion of the fuel is burnt behind the flaming zone. The magnitude of over-estimation should be constant for a given fuel type so relationships between intensity and fire behaviour or impact will be meaningful for that fuel type. Cheney (1990b) showed that it was inappropriate to compare and characterize fires burning in different fuel types using intensity alone. Calculating fuel consumed in the flaming zone, as described above, and using this to calculate intensity provides a more meaningful estimate of intensity but is cumbersome and depends on knowing flame depth and residence time.

For a given fuel complex, flame size is the ultimate measure of energy output so alternatively, fire intensity can be estimated from flame length. For jarrah forest fires in predominantly litter bed fuels Equation 8 relating fire intensity and flame length should be used to estimate fire intensity. Flame length can be predicted from Equation 3 but the relationships between flame dimensions and fire intensity reported in this study apply only to fuel beds with similar characteristics to those for which the relationships were developed.

Rate of Spread and Slope

The relationship between rate of spread and slope (Equation 9) is similar to the equation developed by Noble *et al.* (1980) using data taken from McArthur's fire behaviour meters (McArthur 1966, 1967 and 1973). Van Wagner (1977) compared data on the effect of slope on rate of spread from five published sources and found that all were reasonably similar. He derived an upslope equation from a subjective average line drawn through data from the five sources but cautioned that relationships derived in the laboratory may not be valid in the field owing to differences of scale. The behaviour of fire burning upslope is strongly affected by the degree of slope whereas fire burning downhill is less sensitive to slope (Equation 9, McArthur 1967 and Van Wagner 1977). Some fire behaviour models (e.g. Rothermel 1972), assume that fires burning downhill behave as if on level terrain, but as noted by Van Wagner (1988) it is important to understand how negative slope affects rate of spread for accurate fire growth modelling. Van Wagner (1988) reported that spread rate decreased with increasing negative slope by 64 per cent for a slope of –22° which is similar to the findings reported here. On the other hand, Ward (1971), working with maritime pine (*Pinus pinaster*) litter bed fuel in the laboratory, found that rate of spread downslope was constant, regardless of the degree of negative slope.

As with other studies, the slope-rate of spread experiments reported here were conducted in the absence of wind. Where wind and slope are aligned, the Forest Fire Behaviour Tables and the McArthur Forest Fire Danger Meter assume the effects to be additive, but there are no procedures for determining rate of spread when slope and wind are not aligned. Other models (e.g. Rothermel 1972, 1983) determine the resultant of two spread vectors; one for slope (zero wind) and one for wind. Albini (1976) vectorized slope only and used the vector aligned with wind to correct rate of spread. The shortcomings of these approaches have been reviewed by McAlpine *et al.* (1991) who have proposed a new procedure for resolving slope-wind interactions. They present a model that converts slope to an equivalent wind speed, which is then used in vector analysis with actual wind speed to determine rate of spread. The relationship between flame angle and rate of spread graphed in Figure 15 held regardless of whether flame angle was wind induced or slope induced. Slope has an effect on fire spread similar to that of wind in that it changes flame angle with respect to the fuel bed. This finding supports the notion of treating slope as an equivalent wind speed.

Fire Shape and Wind Speed

An ability to predict fire shape has important ramifications for planning both wildfire suppression strategies and prescribed burns. For a given fuel, the rate of growth and the shape of a spreading fire is largely a function of wind speed, providing direction is constant and the terrain uniform (see Anderson 1983; Alexander 1985). Under these conditions, fires burning in more or less continuous fuels will eventually burn in an approximately elliptical shape (e.g. Curry and Fons 1938; Fons 1946; McArthur 1966; Van Wagner 1969; Anderson *et al.* 1982). The shape of an ellipse can be conveniently expressed by its length-to-width ratio, as used by Pirsko (1961), McArthur (1966) and Cheney (1981). A comprehensive review of ellipse properties in relation to fire spread has been prepared by Alexander (1985). Equation 10 relates fire shape in the laboratory with wind speed at 20 cm above the fuel bed. Alexander's (1985) equation was derived from field data and uses a standard exposure wind speed (at 10 m in clear air). Therefore, it is difficult to make direct comparisons, but a comparison of regression coefficients reveals that Equation 10, developed here, is not as curved as Alexander's (1985) equation.

There is ample experimental and anecdotal evidence demonstrating the acceleration of fire spread from a point source (e.g. Peet 1967; McArthur 1967; Cheney and Barry 1969; McAlpine 1988). The rate of 'distortion' of fire shape, from an initial circular shape to the final elliptical shape, under the influence of wind has been reported by McAlpine (1988, 1989), studying laboratory fires and Weber (1989a, 1989b) has made useful advances in the understanding and modelling of fire acceleration from a point source. The relationship between fire shape and wind speed graphed in Figure 16 assumes that a steady state was reached. The limited field data for jarrah fires suggests that the relationship developed from small scale laboratory studies holds reasonably well for the field situation. This is surprising as field observations indicate that rate of spread could take from 10–70 minutes to stabilize. It is possible then, that final fire shape stabilizes relatively quickly, even though fires may still be accelerating.

Peet (1967) developed a linear relationship between the rate of spread of flank fires and head fires for small, mild fires burning in jarrah forest litter fuels. In the field, the fires burnt in an ovoid shape. Peet (1967) reported that, up to a head fire rate of spread of about 80 m h^{-1} (4 feet min^{-1}), the L/W ratio did not exceed about 1.30 (measured from Figure 4, Peet 1967). As wind data were not provided by Peet, it is not possible to make direct comparisons with the laboratory results reported here. Green *et al.* (1983) tested the adequacy of several geometric shapes, including elliptical, double elliptical, ovoid shapes and even rectangles, and found that all provided good approximations to actual fire shapes. They concluded that little gain could be made by attempting to fit complicated shape models to fire spread patterns. Green (1983) reported that, while an ellipse was adequate for modelling shape in continuous fuels, it was not adequate for patchy fuels. Fires burning in patchy, light hummock grassland fuels have poor back and flank fire development and burnt in straight lines or 'fingers' (Burrows *et al.* 1991).

CONCLUDING DISCUSSION

Fire behaviour in eucalypt fuels has been traditionally studied in the field. These studies represent the first attempt at examining the behaviour of eucalypt litter fires in the partially controlled laboratory environment. Laboratory studies are limited by the scale of the fires and by the extent to which conditions of fuel and wind in the laboratory reflect those in the real world. However, important relationships were studied and described with a degree of control which is impossible to achieve in the field. Important findings emerging from these laboratory experiments in relation to the behaviour of fire in jarrah litter are:

(1) Even under partially controlled laboratory conditions, combustion and fire spread are highly sensitive and highly variable phenomena.

(2) Rate of spread of wind-driven fires was independent of fuel quantity and most variation was explained by wind speed and fuel moisture content. However, backfire rate of spread was directly related to fuel quantity such that doubling fuel quantity caused a doubling of rate of spread.

(3) At wind speeds below about 3 km h^{-1}, flames were near vertical and fires spread slowly depending on fuel quantity. Above this speed, flames were tilted and fires spread rapidly across the fuel bed surface and slowly down through the fuel bed. Flame size was determined by rate of spread and fuel quantity. Flame contact appeared to be the primary spread mechanism.

(4) Over the entire range of wind speeds (0.0–7.6 km h^{-1}), the best equation form relating wind speed and rate of spread was a power function. For wind speeds above 3 km h^{-1}, the best form was a linear one.

(5) The quantity of fuel consumed in the flaming zone of fires fanned by strong winds was not equal to fuel quantity per unit area and was impossible to measure, making precise calculation of fire intensity impossible.

(6) Headfires would not spread when fuel moisture content exceeded about 21 per cent odw and when fuel quantity was less than about 3.5 t ha^{-1}.

(7) The effect of slope on rate of spread was similar to that reported by other workers. Slope affects rate of spread in a similar manner to wind speed, by changing the orientation of the flames.

(8) The relationship between fire shape and wind speed developed in the laboratory appears to hold for field conditions.

(9) In reviewing wind-aided fire spread theory, Carrier *et al.* (1991) cite a number of authors who emphasized the long length of fire run required to achieve a steady state of faster spreading fires in the laboratory. It is highly likely that the faster spreading laboratory fires reported here (wind speed = 7.6 km h^{-1}) had not reached a steady state, highlighting a serious limitation of the laboratory for studying fire

behaviour. The larger scale field experiments reported in this volume provide an opportunity to test the fire behaviour models developed from these laboratory studies and to compare the two techniques for predicting fire behaviour.

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