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# Predicting fire spread in Western Australian mallee-heath

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## ABSTRACT

The ability to reliably predict whether a fire will sustain itself, and what its resultant rate of spread and intensity will be are key elements in the safe and effective application of prescribed fire in mallee-heath shrublands in Western Australia. A program of experimental burning has been conducted in *Eucalyptus tetragona* mallee-heath at the Stirling Range National Park to identify factors critical to the sustained spread of fire, and to determine the effect of burning conditions on the forward spread rate of fires ignited from a 200 m line source. Fires ignited when the moisture content of the shallow litter beneath the shrub layer was more than 8 per cent (of oven dry weight) typically failed to sustain a continuous flame front and did not spread extensively. However, when the shallow litter layer was below 8 per cent moisture content fire fronts sustained and spread regardless of wind speed. Other indices of fuel dryness, and simple weather variables including air temperature and relative humidity did not satisfactorily discriminate between the fires that spread and those that did not.

Forward spread rates of fires burning in fuels below the critical moisture content threshold was strongly related to wind speed, and spread rates of up to 2500 m $h^{-1}$ were recorded when wind speeds (at 10 m height in the open) were around 25 km $h^{-1}$. Forward spread rates of experimental fires correlated poorly with the Grassland Fire Danger Index from the McArthur Mark 4 meter which forms the basis for fire danger rating in rural areas of Western Australia. Models developed to predict fire behaviour in chaparral shrublands in the United States were of little value for determining whether or not a fire would spread, and consistently under-predicted forward spread rates in mallee-heath.

In mallee-heath it seems that the probability of a fire sustaining must be determined as a preliminary step to predicting the forward rate of spread; the former factor is moisture-dependent while the latter is wind-dependent. To predict fire behaviour in the field situation simple but reliable methods for estimating the moisture content of the shallow litter layer in mallee-heath are required.

## INTRODUCTION

Shrublands are an important and widespread fuel type in southern Western Australia, and despite extensive clearing for agriculture still occupy an area of some 5.5 million hectares (Beard 1984). Mallee-heath is the most common form of shrubland on the southern sandplain which extends between Albany (35° S 118° E) and Israelite Bay (34° S 124° E). Mallee-heath communities are characterized by a stratum of low shrubs up to 1 m or so tall with a scattered overstorey of short, multi-stemmed eucalypts up to 4 m tall. A wide variety of plant species occur in these diverse communities, with *Eucalyptus tetragona* being one of the most common and widespread of the mallee eucalypts present. Extensive tracts of mallee-heath occur on lands managed by the Western Australian Department of Conservation and Land Management (CALM), including the Stirling Range, Fitzgerald River and Cape Arid National Parks, and on adjacent areas of vacant Crown land. Much of this area is relatively remote from population centres and management resources, and often inaccessible because of difficult terrain and limited roading.

Like most of southern Western Australia the south coast is prone to periodic fires. Severe fire weather conditions characterized by extreme high temperatures, low humidity and strong winds occur regularly each summer, particularly in association with the formation of pre-frontal low pressure troughs (Hanstrum *et al.* 1991). Trough movement is commonly accompanied by dry lightning storms which may ignite fires over a widespread area. Air photographs consistently show evidence of extensive fires over the past 50 years, even in areas remote from land clearing and other potential sources of human-caused ignition. More recently, three fires started by lightning burnt over 100 000 ha of the

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Fitzgerald River National Park on a single day in December 1989 (McCaw *et al.* 1992). Further lightning-caused fires burnt some 750 000 ha of CALM estate and vacant Crown land in the Esperance-Norseman area over the summer of 1990-91 (McCaw 1992).

CALM undertakes fire management on lands under its control with the objectives of protecting life and property from damage by wildfire, and maintaining and enhancing environmental values. This latter objective may in some cases necessitate the temporary protection of an area from fire, while in other cases prescribed fire may be used deliberately to regenerate plant communities (McCaw and Gillen 1993). Prior to about 1985 the most common fire management strategy for large reserves in the south coast region was to undertake limited fuel reduction burning within narrow buffer strips located at the interface with neighbouring lands of different tenure. This approach has proved problematic in mallee-heath where slight changes in fuel and weather conditions can lead to dramatic alteration in fire behaviour. If burning conditions are sub-optimal fires do not sustain, leading to inefficient use of resources and ineffective fuel reduction within buffer strips. At the other end of the scale fires which exceed prescribed limits for fire intensity may escape from narrow buffer strips, thus posing a threat to neighbouring lands and potentially endangering personnel at the fireface.

In recent years the feasibility of using aerial ignition to burn strategic strips and mosaics within large unroaded blocks has been investigated and found to have considerable promise as a fire management technique in mallee-heath communities. Successful implementation of this technique depends on a sound understanding of fire behaviour and, in particular, the ability to reliably predict the onset and cessation of sustained fire spread.

In 1989 CALM commenced a study of fire behaviour in mallee-heath, the principal objectives of which were to (1) identify factors critical to the sustained spread of fire, and (2) develop a fire behaviour guide for predicting rate of spread and fire intensity from weather and fuel variables readily measured in the field. The study was based around a program of experimental burning undertaken in the Stirling Range National Park, and involved personnel from CALM's Manjimup Research Centre and South Coast Region. Experimentally-derived data have been supplemented by information gained opportunistically during prescribed burning operations and wildfires. Preliminary results from the study were presented by McCaw (1991). The purpose of this paper is to present updated results from the experimental burning program, and to examine the spread of experimental fires in relation to the Grassland Fire Danger Index from McArthur's Mark 4 meter (1973), and fire spread predictions from two models developed for chaparral shrublands in the United States.

## METHODS

### Experimental Burning

In March 1989 sixteen plots, each 4 ha in area, were demarcated in a uniform area of *E. tetragona* mallee-heath near Two Mile Lake (34° 31"S, 118° 13' E) on the southern boundary of the Stirling Range National Park. The area experiences a mediterranean climate with an annual rainfall of about 470 mm. Plots were located on flat terrain at an elevation of 160 m above sea level in an area that had last been burnt in 1969 by a summer wildfire. Plots were grouped into cells of four, each of which was enclosed within a 100 m wide buffer strip created by scrub-rolling and burning the vegetation; the system of buffer strips permitted experimental fires to be conducted under relatively severe burning conditions without undue risk of escape. Two larger plots (16-50 ha in area) established nearby were also burnt as part of the experimental program.

Mallee eucalypts common throughout the area included *E. tetragona, E. pachyloma,* and *E. marginata.* The shrub layer was species rich with between 50 and 60 species of vascular plants present in a 10 m x 10 m quadrat. Dominant shrubs included species of *Hakea, Dryandra, Isopogon* and *Banksia.* Fuels were assessed on thirty 10 m x 1 m transects distributed across the site which were harvested in four height classes and sorted by size classes into live and dead fractions (for a more detailed account of this procedure see McCaw 1991). The mean fuel load for the site was 12.4 t ha$^{-1}$, consisting of 4.5 t ha$^{-1}$ of litter, 3.1 t ha$^{-1}$ of dead shrub components (<25 mm diameter) and 4.8 t ha$^{-1}$ of live shrub foliage and twigs (<6 mm diameter). The layer of litter on the ground was light and discontinuous, with a projected cover of about 75 per cent.

Weather data recorded during each experimental fire included air temperature, relative humidity, 10 m open wind speed, and global solar radiation. Wind speed was measured using a Unidata anemometer mounted on a 10 m tall Clark mast located 50 m upwind from the side of the plot which was to be ignited. At the time of each fire five replicate samples of four fuel fractions were collected for determination of oven dry moisture content, as follows:

- shallow litter (<10 mm deep) from beneath shrubs,
- deep litter (10-30 mm deep) from beneath mallee clumps,
- elevated dead fuel (<6 mm diameter) from shrubs,
- live foliage from *Dryandra pteridifolia,* a species of low shrub common throughout the study area.

Plots were ignited on the upwind side using a vehicle-mounted flame thrower to light a 200 m long line of fire; ignition was generally completed within a two-minute period. Fires were allowed to spread across the plot with the wind and were contained by the scrub-rolled buffer strips.

Fire spread was measured using buried electronic timers activated by the passage of the flame front, with elapsed times calculated in relation to a master clock started at the commencement of ignition. Reliable timer data were used to prepare fire spread contour diagrams for each plot from which the forward rate of spread of the fire was determined. Spread contours were checked for consistency with the prevailing wind direction during each fire, and compared with low-oblique photographs and visual observation recorded during each burn. Inconsistencies between observed fire behaviour and fire spread contours plotted from timer data resulted in three plots being excluded from some stages of the analysis.

### Comparison with Predictions from Existing Fire Spread Models

The forward rates of spread of fourteen experimental fires were compared with predictions made using three existing fire spread models: the Mark 4 Grassland Fire Danger Meter developed by McArthur (1973); the Rothermel (1972) fire spread model; and the Arizona oak chaparral model of Lindenmuth and Davis (1973). Three fires were excluded from this analysis because forward spread rates could not be reliably determined, and a further fire was excluded because it was in a fuel type that was not representative of the fuels in the remainder of the study area.

Although not developed for predicting fire spread in shrubland fuel types the McArthur Grassland meter is used for fire danger rating in rural areas of Western Australia, including setting of restrictions on prescribed burning. The extent to which calculated fire danger indices reflect the severity of fire behaviour in mallee-heath is therefore an important issue for fire authorities and bush fire brigades working in this fuel type. The Grassland Fire Danger (GFD) index at the time of each experimental fire was calculated from the Mark 4 meter using measured air temperature, relative humidity, 10 m open wind speed and a constant curing factor of 100 per cent. This level of curing was chosen because most large wildfires in mallee-heath have occurred in summer and autumn when pastures and crops were fully cured.

Rates of spread were predicted from the Rothermel model for fuel model 6 using the nomograms provided in Rothermel (1983). This fuel model was selected from Anderson (1982) on the basis of its similar appearance and fuel loading characteristics to mallee-heath.

Variables used to calculate the rate of spread with the Lindenmuth and Davis oak chaparral model were measured air temperature, relative humidity, wind speed, and solar radiation. Foliar moisture content was held constant at 85 per cent which was considered to be a representative value for mature foliage of a range of mallee eucalypts and shrubs (McCaw, unpublished data). No correction was made for chemical coefficient (Davis and Dieterich 1976) as the influence of this factor on fire behaviour in mallee-heath is unknown.

Predictions from the two United States fire models are based on wind speeds measured at 20 feet ( 6.1 m approximately) above the ground. Wind speeds measured at 10 m were adjusted to 6.1 m equivalents using the Applied Meteoroligical Tables of Beer (1990) assuming a roughness length of 0.2 m. In the case of the Rothermel model a standard correction factor of 0.4 was then applied to adjust wind speeds to mid-flame height, as specified for exposed fuel situations by Rothermel (1983, p.33).

## RESULTS

### Factors Critical to the Sustained Spread of Fire

Eighteen experimental fires were ignited over a wide range of burning conditions ranging from cool moist weather in spring and late autumn to hot, dry weather in summer (Table 1).

Data from Plot 3 were excluded at the outset from analysis because this plot contained very sparse fuels that were not representative of the remainder of the site. Most of this plot failed to burn despite the burning conditions at the time of ignition being relatively severe, with an air temperature of 32°C, relative humidity of 40 per cent, wind speed of 17 km $h^{-1}$, and shallow litter moisture content of 7 per cent.

TABLE 1

Summary of weather conditions and fuel moisture during 18 experimental fires in mallee-heath.

Moisture content (MC) data are presented for shallow (SHALLOW) and deep (DEEP) layers of litter fuel, dead elevated fine fuel (DEAD), and live *Dryandra* foliage (LIVE). Weather data are mean values recorded over the duration of experimental fires which was generally less than ten minutes, or over a default period of ten minutes in cases where fires failed to spread.

| VARIABLE | UNIT | MEAN | RANGE |
|---|---|---|---|
| Air temperature | °C | 25 | 20 - 36 |
| Relative humidity | % | 44 | 14 - 63 |
| Wind speed | km $h^{-1}$ | 16.6 | 5 - 25 |
| Solar radiation | W $m^{-2}$ | 606 | 271 - 912 |
| $MC_{SHALLOW}$ | % | 6.6 | 3 - 14 |
| $MC_{DEEP}$ | % | 10.0 | 4 - 32 |
| $MC_{DEAD}$ | % | 9.9 | 6 - 16 |
| $MC_{LIVE}$ | % | 82 | 68 - 90 |

Five of the experimental fires failed to spread following ignition. The characteristic feature of these fires was that the flame front became discontinuous within a short time following ignition (i.e. within one or two minutes) and did not spread any significant distance from the ignition line. Flames only persisted in favourable fuel situations such as the continuous litter beds beneath mallee clumps and patches of low shrubs with a substantial component of elevated dead fuel.

In contrast, a second group of 12 experimental fires was characterized by continuous flame fronts which persisted even in areas where fuels were light and patchy. These fires spread freely across the plot according to the strength and direction of the wind, and in some cases developed rapidly into a crown fire within a minute or so of ignition. The distinction between these and the former group of failed ignitions was clear and individual fires were assigned to one or other category without difficulty.

Exploratory analysis of the factors critical to sustained fire spread was undertaken using scattergrams (Fig. 1) with a range of weather and fuel moisture variables plotted against wind speed. Of the weather variables, air temperature and relative humidity did not clearly discriminate the fires that spread from those that didn't. The probability of a fire sustaining did, however, appear related to solar radiation as no fires sustained when radiation was reduced below 400 W m$^{-2}$ by heavy cloud cover.

Fires which did not spread following ignition were consistently associated with higher moisture contents for each of the dead fuel fractions sampled (Fig. 1). The variable which most clearly distinguished the fires that spread from those that did not was the moisture content of the shallow litter layer. In all cases fires spread when the moisture content of the shallow litter was below 8 per cent. This effect was independent of wind speed across the range of the experimental burning conditions which included wind speeds from 5 - 25 km h$^{-1}$.

## Forward Rate of Spread

Forward rates of spread were determined for nine of the experimental fires with three fires being excluded because timer data were unreliable, or because shifts in wind direction during the course of the fire made it difficult to define a true fire front. One fire conducted under very light winds (<5 km h$^{-1}$ at 10 m) was retained in the analysis despite considerable variability in wind direction. This fire did develop a recognizable front, although the direction of spread was not entirely consistent with the mean wind direction over the course of the fire. In this case the spread of the fire front was determined more by occasional strong gusts than by the average wind condition.

The effect of weather and fuel variables on forward rate of spread was tested for the nine fires remaining in the data set using multiple linear regression, with both raw and transformed data used to determine the equation of best fit. Wind speed was the only variable to have a significant effect on forward spread rate, with the relationship exhibiting a linear form over the range of the experimental data (Fig. 2). The regression equation developed for untransformed data accounted for 59 per cent of variation in rate of spread -

$$FROS = 1.51 + 90.6\ WIND \quad R^2 = 0.59,\ P<0.05$$

where *FROS* is forward rate of spread in m h$^{-1}$ and *WIND* is wind speed in km h$^{-1}$ measured at 10 m height in the open. The tendency for variance to increase with increasing rate of spread was rectified by log transforming rate of spread data, which resulted in an equation of slightly improved fit -

$$lnFROS = 5.64 + 0.09\ WIND \quad R^2 = 0.66,\ P<0.01$$

## Comparison with Predictions from Existing Fire Spread Models

Experimental fires were conducted at GFD indices ranging from 3 (Low) to 23 (Very High); for all but one of the fires the index was below 10. Indices associated with the group of fires that failed to spread following ignition spanned a similar range (3-9) to those associated with the group of fires that did initiate and spread (Fig. 3a). The three fastest spreading experimental fires, which had forward spread rates exceeding 2000 m h$^{-1}$, were associated with GFD indices of 8 or above. However, one of the fires that failed to sustain was ignited at an index of 9. These results suggest that the GFD index is unlikely to prove useful as an indicator of whether or not a fire will initiate and spread. Also, there is unlikely to be a consistent relationship between the GFD index and the rate of forward spread of mallee-heath fires, at least for burning conditions resulting in an index less than 10.

Rates of forward spread predicted for fuel model 6 using the Rothermel fire spread model ranged between 80 m h$^{-1}$ and 760 m h$^{-1}$ (Fig. 3b). Fires that failed to initiate and spread were not consistently associated with low predicted rates of spread. Forward spread rates were positively correlated with predicted spread rates for fuel model 6 but were typically three to four times faster than predicted by the model. For the subset of nine fires that did initiate and spread, predicted and observed spread rates were related by the following linear regression equation:

$$FROS_{OBS} = 94 + 2.97\ FROS_{PRED} \quad R^2 = 0.59,\ P<0.05$$

where $FROS_{OBS}$ is the observed rate of spread in m h$^{-1}$, and $FROS_{PRED}$ is the predicted rate of spread for fuel model 6 in m h$^{-1}$.

The oak-chaparral model predicted forward spread rates ranging from 177 m h$^{-1}$ to 388 m h$^{-1}$ for the fourteen experimental fires and, as with the Rothermel model, there was no consistent association between low predicted rates of spread and failed ignitions (Fig. 3c). Predicted rates of spread bore no relation to, and were consistently much lower than those observed in mallee-heath.

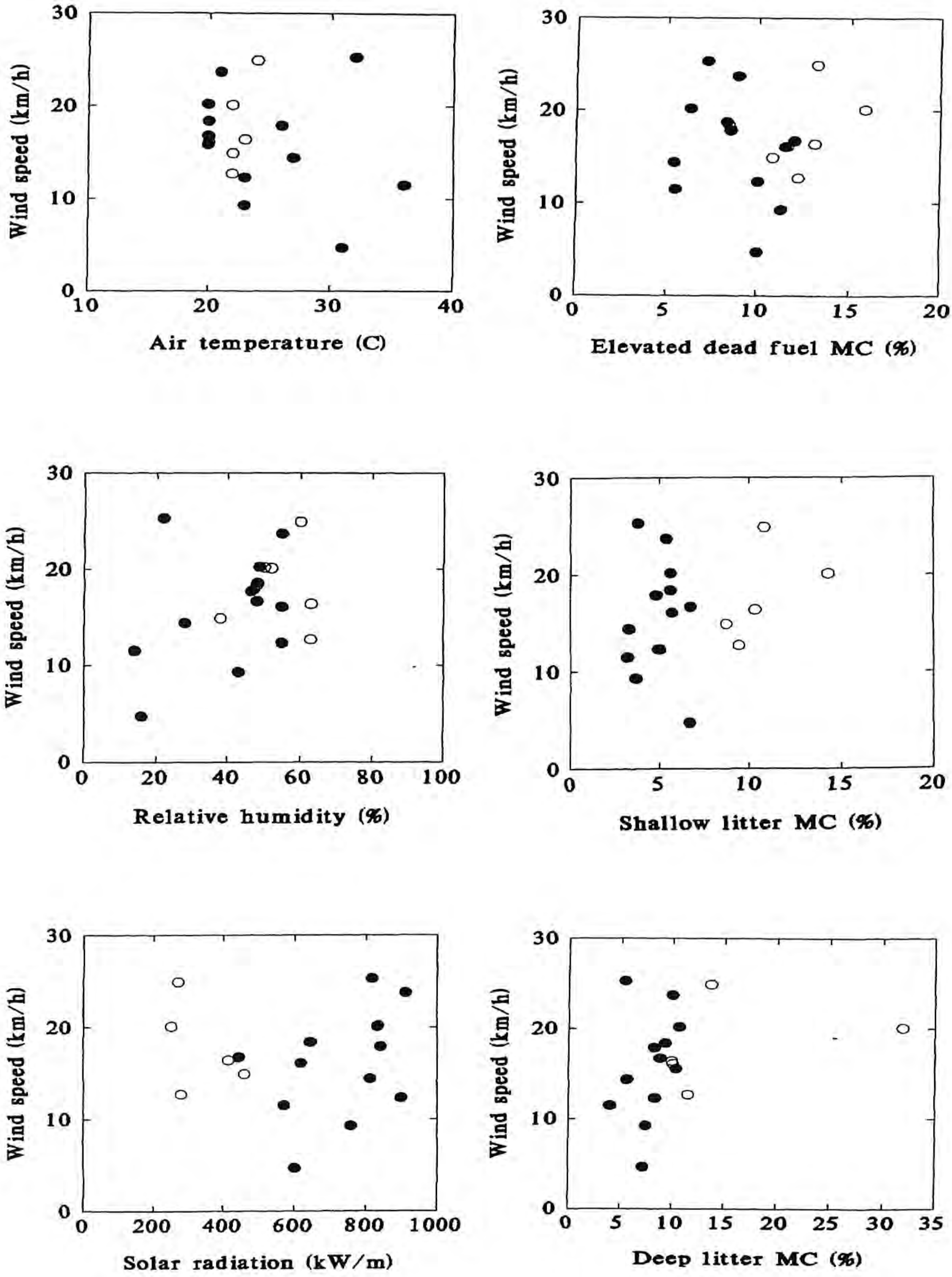

*Figure 1. Scatterplots depicting environmental and fuel moisture variables for 17 experimental fires in mallee-heath. Fires represented by hollow symbols failed to spread following ignition; fires represented by shaded symbols spread freely following ignition.*

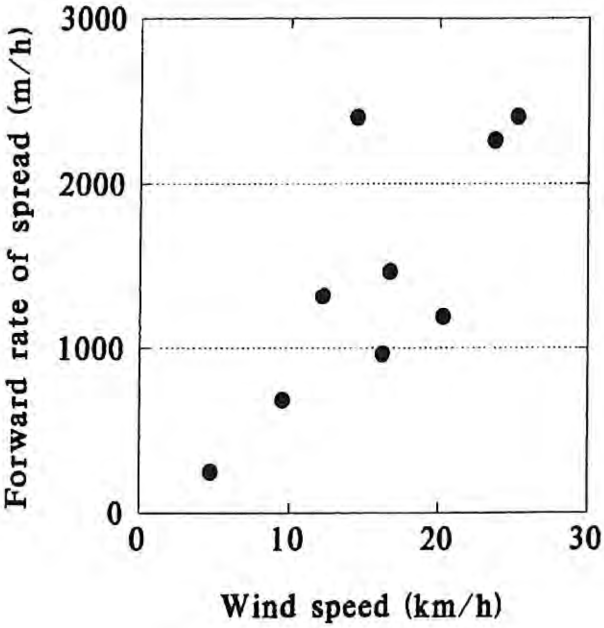

*Figure 2. Forward rate of spread plotted in relation to 10 m open wind speed for 9 experimental fires for which reliable estimates of spread rate were available.*

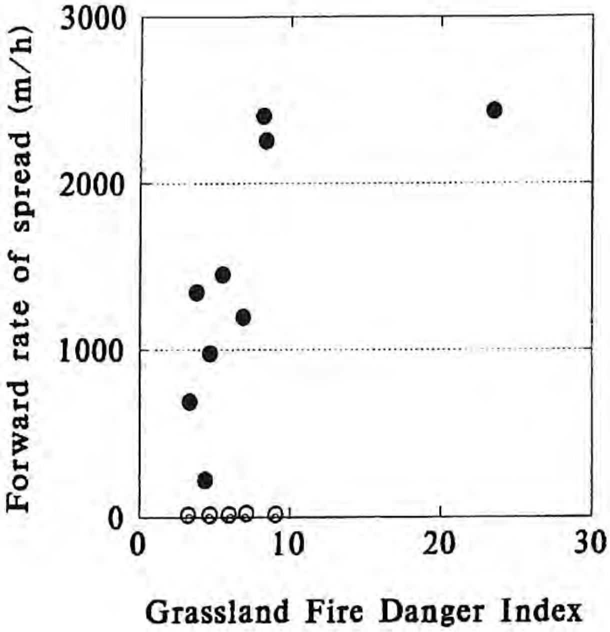

*Figure 3a. Forward rate of spread of selected experimental fires plotted in relation to: the M<sup>c</sup>Arthur Mark 4 Grassland Fire Danger Index.*

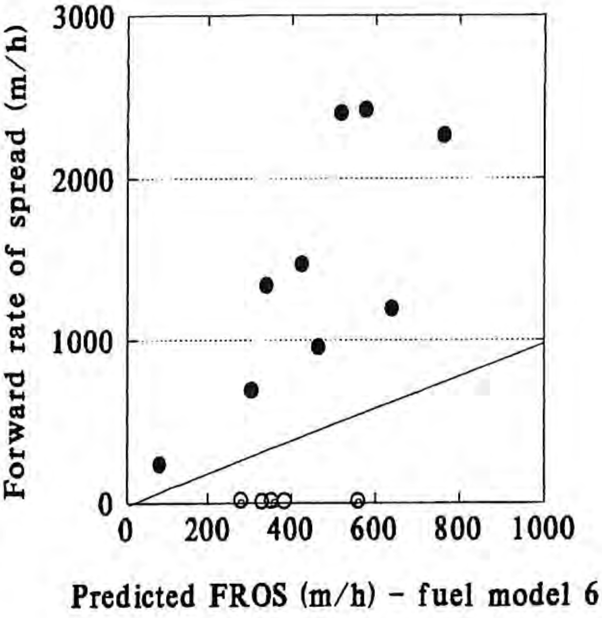

*Figure 3b. Forward rate of spread of selected experimental fires plotted in relation to: rate of spread predicted for Fuel Model 6 using the Rothermel fire spread model.*

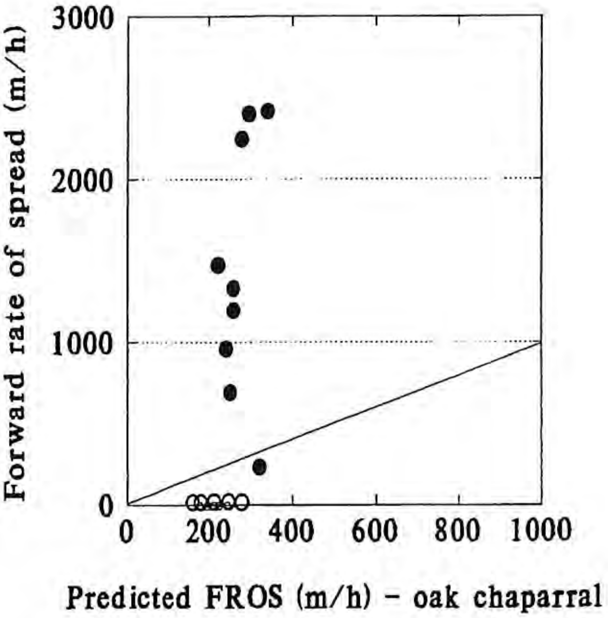

*Figure 3c. Forward rate of spread of selected experimental fires plotted in relation to: rate of spread predicted by the Lindenmuth and Davis oak chaparral model.*

## DISCUSSION

The process of predicting fire spread in mallee-heath would seem to require two distinct steps: firstly, determining whether burning conditions are sufficient for a fire to initiate and spread and, if this is the case, then making a prediction of the forward rate of spread. Evidence from the experimental fires at the Stirling Range indicates that the probability of a fire initiating and spreading in mallee-heath is largely dependent on the level of fine fuel dryness, while wind speed has a dominant effect on the forward spread rate.

Sudden transitions in fire behaviour, apparently linked to slight changes in air temperature, relative humidity and wind speed have been reported to be a characteristic feature of fires in mallee-heath fuel types in southern Western Australia (McCaw *et al.* 1992). The existence of a distinct threshold level of moisture content required for continuous fire spread provides an explanation for this characteristic behaviour. Experimental data indicated that the critical level of fuel dryness required for fire to spread was a moisture content of 8 per cent in the shallow litter layer. Although no data are yet available for fires burning under conditions of strong wind (>20 km $h^{-1}$) with shallow litter in the 8-11 per cent moisture content range, the extent to which strong winds can offset the controlling effect of fuel moisture on fire spread appears to be quite limited in mallee-heath. Threshold moisture contents will almost certainly vary according to the characteristics of the fuel bed, with very dry conditions being necessary for fire spread in highly discontinuous fuels. This was clearly illustrated in the case of Plot 3 where the fire failed to spread following ignition despite a moisture content of 7 per cent in the shallow litter layer.

The observation that burning conditions must reach certain critical threshold before fires will spread continuously has been made for several other discontinuous fuel types including hummock grasslands in the Australian arid zone (Burrows *et al.* 1991; Gill *et al.* 1995), and oak-chaparral shrublands (Lindenmuth and Davis 1973) and pinyon-juniper woodland (Bruner and Klebenow 1979) in the south-western United States. Burrows *et al.* (1991) identified a critical range of wind speed between 12 and 17 km $h^{-1}$ (measured at 2 m height above ground) necessary for fires to spread in spinifex (*Triodia basedowii* and *Plechtrachne schinzii*) hummock grasslands in the Gibson Desert of Western Australia, and reported that this threshold was unaffected by fuel moisture content up to a level of 30 per cent moisture content. The dominant effect of wind on fire spread in hummock grasslands has been attributed to the horizontal discontinuity of the fuel bed which consists of discrete hummocks separated by expanses of bare ground. For fires to spread in such discrete fuels the wind must be sufficiently strong to tilt flames across to the next hummock for long enough to ignite it (Gill *et al.* 1995). Threshold wind speeds for continuous fire spread are therefore likely to vary according to the size, shape, condition and spatial distribution of hummocks (Bradstock and Gill 1993). In the case of oak-chaparral shrubland Lindenmuth and Davis (1973) noted that 'people experienced in Arizona chaparral have always maintained that chaparral either burns fiercely or does not burn at all - no gradation in between'. Experimental burning studies by Lindenmuth and Davis confirmed this rule of thumb and identified a critical rate of spread of about 360 m $h^{-1}$; burning conditions had to be sufficient to generate spread at or above that level before fires would spread across country. Wind was found to be a limiting factor with speeds of around 13 to 15 km $h^{-1}$ (at 10 m height) needed for fires to spread satisfactorily, provided temperature and fuel moisture conditions were favourable. Based on the descriptive account of fuel characteristics in their paper and my own field observations of oak-chaparral it seems that individual oak clumps are relatively discrete and that this fuel type is more discontinous than mallee-heath, probably being intermediate between mallee-heath and hummock grassland. For pinyon-juniper woodland Bruner and Klebenow (1979) found that the likelihood of a fire sustaining could be predicted from a simple score comprising the wind speed, air temperature and percentage vegetation cover; unfortunately the height at which wind speeds were measured was not specified in their paper. While having some application in localized situations this approach has the limitations of not identifying the relative importance of the various factors contributing to the score, and not indicating potential forward rate of spread, and hence fireline intensity.

The Rothermel model showed greater promise than either the McArthur grassland or the oak chaparral model for predicting rate of spread in mallee-heath, although none of the three models tested adequately identified the conditions under which fires would not spread. There may be scope for improving predictions from the Rothermel model by developing a specific fuel model (Burgan and Rothermel 1984) for mallee-heath, and by using an improved technique to estimate mid-flame wind speed (Durre and Beer 1989). The absence of a clear relationship between observed fire behaviour in mallee-heath and the predictions of the oak chaparral model are probably explained by the strictly empirical origins of this model which make it unsuitable for broader application. Differences between mallee-heath and oak chaparral in the relative flammability of live foliage, and in the effects of moisture content and chemical composition on live foliage flammability may be important in this regard.

To predict fire behaviour in the field situation simple but reliable methods for estimating the moisture content of the shallow litter layer in mallee-heath are required. A range of other models for estimating fuel moisture content are available (Viney 1991) and the application of these models in mallee-heath should be evaluated. Direct measurement of fuel moisture content in the field with suitably calibrated grain moisture meters or similar devices provides an alternative method. However, meters currently in use, such as the Marconi, are unsuitable for measuring leaf litter fuels drier than about 10 per cent moisture content and would therefore have limited application in mallee-heath where there is a requirement to accurately measure the moisture content of very dry fuels. New technologies for measuring fuel moisture content in the field should therefore also be investigated as the opportunity arises.

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