PREDICTING BLOW-UP FIRES IN THE JARRAH FOREST

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SUMMARY

Fuel reduction burning in the jarrah *(Eucalyptus marginata)* forest has dramatically reduced the incidence of severe wildfires. Modern forest fire fighters in Western Australia are rarely confronted with explosive fires associated with very heavy fuels and severe fire weather conditions. However, any fire burning in dry conditions has the potential for rapid and violent build-up in intensity, or rate of spread, threatening the lives of unwary fire fighters.

Forest fires behave according to reasonably well understood physical laws. If fire fighters understand these interactions they will be better able to anticipate lethal situations. This paper discusses a number of characteristics of fire and the fire environment which may cause unexpectedly severe fire behaviour (blow-up) in the jarrah forest, and provides guidelines for fire fighters to evaluate potentially dangerous fire situations.

INTRODUCTION

Experienced fire fighters expect fires burning under heavy fuel and severe weather conditions to display violent behaviour. The dangers of such fires are obvious, and precautions and suppression strategies are implemented accordingly. However it has often been small fires burning under seemingly mild conditions which have, for no apparent reason, escalated in behaviour, and endangered the lives of fire fighters. Such an incident occurred recently at Boyicup, in jarrah forest east of Manjimup. It was later reported: "To a man, they all admit that the fire behaviour experienced in the period of the fire explosion was totally unpredicted, and the worst they had experienced. Fire fighters found it difficult to understand why this fire explosion occurred." (Sneeuwjagt, 1982).

When Forests Department suppression crews arrived at the Boyicup Wildfire, fire behaviour was mild with a rate of spread of 40 - 60 m hr^{-1}. The fire danger index (F.D.I.) was 63, and the predicted rate of spread (Sneeuwjagt & Peet, 1976) was 133 m hr^{-1}. Unexpectedly, the fire accelerated to an estimated 3 000 m hr^{-1} with 20 m high flames. The lives of several fire fighters were threatened. Effective training and quick action prevented a fatality.

Fire behaviour is not an independent phenomenon, but obeys certain physical laws. The fire behaviour exhibited in the Boyicup wildfire was considered unusual because changes in the conditions influencing the fire's behaviour were either not anticipated, or were severely underestimated. Expectations of how a fire should behave are based largely on experience, and to a lesser extent, on fire behaviour guides. Forest fire behaviour is a very complicated phenomenon which is governed by the highly variable properties of fuel, weather, and topography. An understanding and evaluation of these factors, and their contribution to the development of blow-up fires, is essential in enabling fire fighters to recognize and avoid dangerous situations.

FUEL FACTORS CONTRIBUTING TO BLOW-UP FIRES

Low Fuel Moisture Content

When generally favourable burning conditions exist, there is always the potential for a fire to blow-up. Most blow-up fires have occurred when fuels are dry (≤ 6% moisture content oven dry weight [o.d.w.]), and when the Soil Dryness Index (S.D.I.) (Mount, 1972) is high (>1 200). Fuel moisture content is the most significant factor affecting the combustion rate, rate of spread, amount of fuel available for burning, ease of ignition, radiation efficiency, crowning and spotting potential. When fuel moisture content falls below about 6 per cent (relative humidity <25% - 30%) very slight increases in fuel load, windspeed, slope, or changes in fuel structure and arrangement, can cause severe changes in fire behaviour (Fig. 1).

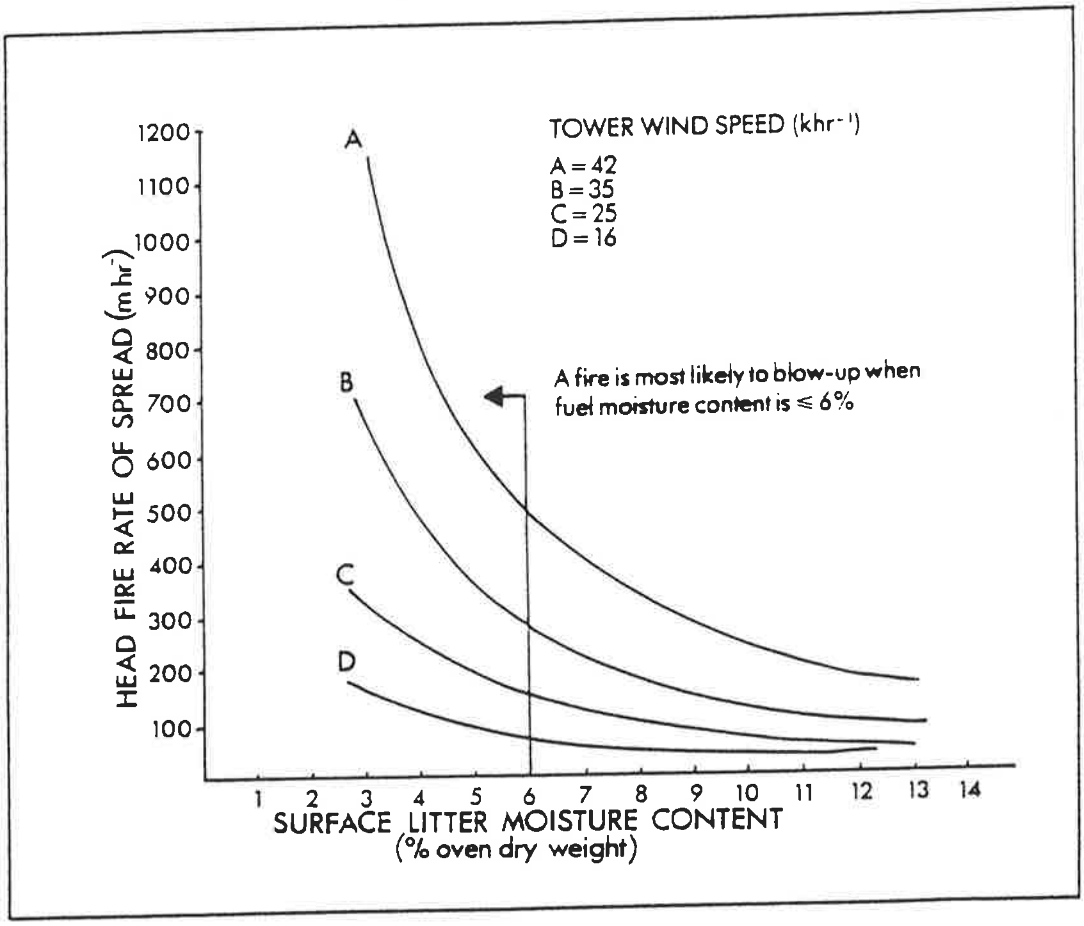

FIGURE 1: The effect of fuel moisture and windspeed on head fire rate of spread for fires burning in jarrah leaf litter (after Sneeuwjagt & Peet, 1976).

The moisture content of dead fuels, such as leaf litter, is regulated by air temperature and relative humidity (r.h.). Rainless periods, with high temperatures and low (<30%) relative humidity, produce very dry fuels. Fine litter and trash fuels respond to diurnal fluctuations in r.h. (Fig. 2). Most fuel moisture prediction systems are based on equilibrium moisture content, and so will underestimate fuel moisture early in the day when r.h. is falling, and overestimate later in the day when r.h. starts to rise. Forest Fire Behaviour Tables for Western Australia (Sneeuwjagt & Peet, 1976) predict the fuel moisture content of leaf litter, but under dry conditions the moisture content of well aerated trash (dead vegetation) may be considerably lower. Surface leaf litter moisture content rarely reaches equilibrium with atmospheric conditions, and lags by about 2 hours. The slow gain of moisture by litter fuels, and rapid increases in relative humidity, can lead to serious underestimations of fire behaviour, especially in areas influenced by sea breezes. It is therefore safest to assume minimum fuel moisture content for at lease 2 -3 hours after the sea breeze has come in.

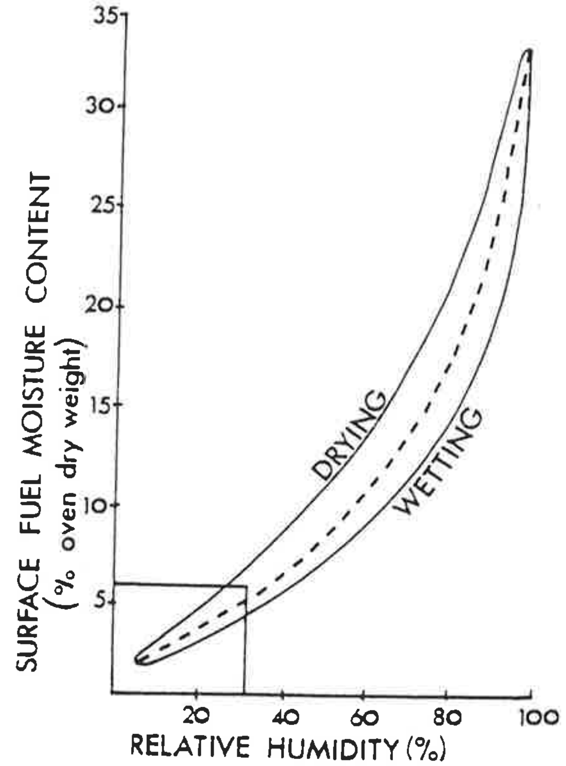

FIGURE 2: Wetting and drying curves for eucalypt leaf litter (Luke & McArthur, 1978). Low Relative Humidity (r.h.) means low fuel moisture. Beware when r.h. drops below 30%.

The diurnal trend of temperature and r.h. is very important in relation to moisture gain overnight. If the overnight temperature remains high and the r.h. low, there will be very little moisture uptake by litter fuels, and fires can display unexpectedly severe behaviour in the morning. Most major wildfires in Australia, including the 1961 Dwellingup fires, have been preceded by very dry overnight conditions. Figure 3 illustrates normal and abnormal overnight conditions. These conditions can be measured using a thermohydrograph.

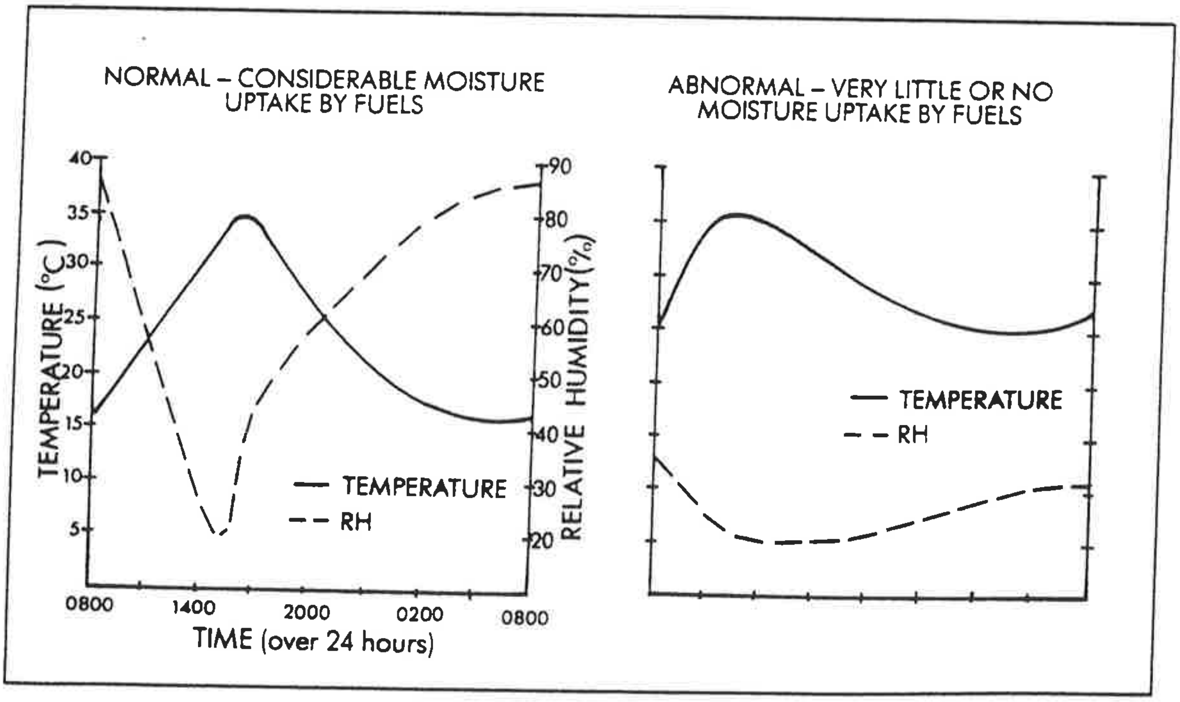

FIGURE 3: Normal and abnormal diurnal temperature and relative humidity traces. Dry overnight conditions have been associated with blow-up fires.

The dramatic increase in rate of spread with fuel dryness is illustrated for jarrah litter fuels in Figure 1. Other fuel arrays, such as dense scrub, are more loosely compacted than the leaf litter bed. Consequently, these fuel types may not show a marked increase in the rate of spread until the fine fuel moisture content falls below 6 - 8%, and the Soil Dryness Index is high (>1 200).

Fuel moisture content can be directly determined by the oven drying technique, or using instruments such as the Marconi Moisture Meter. The Forest Fire Behaviour Tables for Western Australia (Sneeuwjagt & Peet, 1976) provide guides for predicting surface, and profile fuel moisture contents, based on rainfall, temperature and r.h. These predictions are most useful in the immediate vicinity of the weather station. Fuels are generally drier in the east and north of the jarrah forest due to climatic variation.

FUEL TYPE

Fuel type refers to the physical and chemical arrangement of living and dead vegetation which will affect its combustion rate. The Forest Fire Behaviour Tables for Western Australia (Sneeuwjagt & Peet, 1976) enable the prediction of the average likely headfire rate of spread, for fires in jarrah forest, burning in a predominantly leaf litter fuel type. For much of the upland jarrah forest, this fuel type dominates fire behaviour. Fuel type differs vastly from lower slopes to flats, and creek beds. Tables 1 & 2 contain examples of the properties of the different fuel types encountered in the range of the jarrah forest.

TABLE 1

Common vegetation fuel types found in the Sunklands area of the jarrah forest range

VEGETATION FUEL TYPE	GENERAL DESCRIPTION
1	Found on lateritic ridges. Species may include *Acacia browniana, Leucopogon verticillatus, Hovea elliptica, Bossiaea ornata.*
2	Sandy swamps. Includes *Melaleuca preissiana, Beaufortia sparsa, Agonis linearifolia.*
3	Found in creek systems. Includes *Agonis linearifolia, Astartea fascicularis, Banksia littoralis, Eucalyptus patens, E. megacarpa.*
4	Usually found on flats with deep grey sands. Species may include *Leptospermum ellipticum, Hibbertia hypercoides, Melaleuca thymoides, Adenanthos barbigera, Anarthria prolifera, Petrophile linearis, Acacia mooreana.*
5	Loamy sands with clay close to the surface. Includes *Banksia littoralis, Xanthorrhoea preissii, Kingia australis, Hypocalymma stricta.*
6	Loamy, well drained site. Includes *Acacia obovata, Acacia varia, Hibbertia quadricolor, Pultenea drummondii.*
7	Midslope, shallow sand over gravel. Includes *Burtonia conferta, Hibbertia pachyrrhiza, Hovea trisperma, Xylomelium occidentalis, Persoonia longifolia, Alocasuarina fraseriana.*

TABLE 2

Structure of common fuel types found in the Sunklands area of the jarrah forest range

	FUEL TYPE (7-10 YEARS SINCE LAST BURNT)						
	LEAF LITTER ONLY	VEGETATION TYPE 1	VEGETATION TYPE 2	VEGETATION TYPE 3	VEGETATION TYPE 4	VEGETATION TYPE 5	VEGETATION TYPE 6
TOTAL FUEL LOAD T/HA	7-8	2-3	7-8	12-15	9-10	5-7	3-4
APPROX. DEPTH OF FUEL (MM)	15	900	900	1800	1400	1100	1000
SURFACE AREA-TO-VOLUME/ RATIO	72	32	31	24	24	30	24
POROSITY cm^3/cm^2	.41	117	19	12	10	68	43
FUEL PARTICLE SPACING (CM)	-	11.5	2.9	2.1	2.2	6.8	4.8
PACKING	.098	$1.72x10^{-4}$	$8.4x10^{-4}$	$3.0x10^{-3}$	$1.80x10^{-3}$	$5.4x10^{-4}$	$6.4x10^{-5}$

Scrub fuels commonly found on some upland sites, creeks, and flats are similar in structure to grass fuels, and even though they consist largely of live vegetation, have been observed to burn ferociously under dry conditions. Research into the behaviour of fires burning in a range of jarrah forest fuel types is continuing. Scrub fuel types only comprise some 10-30% by area of the jarrah forest, but have been associated with many blow-up situations. Often the transition from upland litter fuels to the scrub fuels of flats and creek systems is very sudden. Equally sudden will be the change in behaviour of fires burning across these site changes. Fire fighters should be wary of fires burning towards creeks and flats, and can expect severe fire behaviour when conditions are dry. Slope changes and increased windspeeds on these sites will contribute to increased fire activity. This is discussed in a later section. Figure 4 illustrates the relationship between fuel properties, combustion rate, and rate of spread, and highlights the difference between leaf litter fuels and scrub fuels.

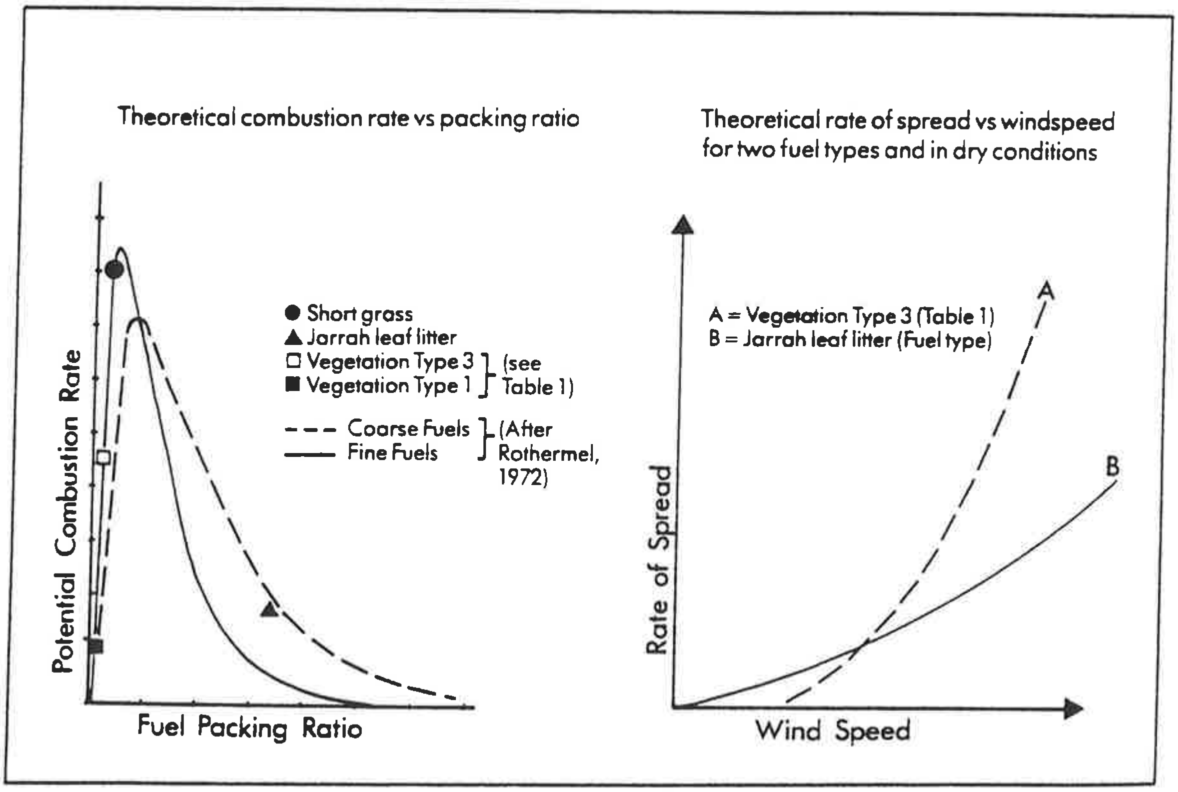

FIGURE 4: The influence of fuel arrangement and particle size on fire behaviour.

FUEL QUANTITY

Fire rate of spread varies directly with the quantity of fuel available for burning. Fire energy output, or intensity (Byram, 1959), is dependent on the amount and rate at which fuels are consumed. Doubling the available fuel load effectively increases energy output, or intensity, fourfold. Total fuel weights for the various jarrah fuel types are shown in Table 2. The available fuel weight will vary with burning conditions, and increases as the fire danger index number increases. It is not adequate to treat scrub fuel weights in the same fashion as litter fuel weights when predicting head fire rates of spread. For instance, dry grass fuels rarely exceed 4 - 5 tonnes/ha, but burn many times faster than the equivalent load of eucalypt litter. Within each of the fuel types shown in Table 2, fuel quantity will not change sufficiently to dramatically change a fire's behaviour. However, fuels can change dramatically if the fire jumps roads or breaks, and burns in forest of a different fuel age, or which contains logging debris. There may be situations where large pockets of heavy fuels exist in recently burnt forest. The fire fighter must continually observe and assess surrounding fuels, and anticipate any changes in fire behaviour.

Creeks and swamps in the jarrah forest do not usually burn in mild hazard reduction burns, and may remain unburnt for many years. Despite appearances there is rarely more than 12 - 15 tonnes/ha of fuel in these areas, but the well-aerated trash, fuel particle size, loose packing, and the continuity of these fuels assures that they will burn ferociously and considerably faster than the equivalent weight of leaf litter fuel.

WEATHER FACTORS CONTRIBUTING TO BLOW-UP FIRES

Wind

Wind is the most variable and difficult to predict of the weather factors affecting fire behaviour. Wind at the fire front will be affected by the topography, the vegetation, local heating and cooling, the fire's size, and the presence of other fires. Spot forecasting techniques for wind speed and direction are not sophisticated enough to account for these variations, and there is no substitute for a local knowledge of wind behaviour. The importance of the effect of wind on fire behaviour is shown in Figure 1, *and is the primary cause of blow-up fires in the jarrah forest.*

Fuel arrangement, particle size, packing ratio, and moisture content will influence the degree to which wind affects fire behaviour. In the initial stages of a fire burning in dry eucalypt litter fuel under light to moderate winds, the energy of the convection column may be greater than that of the windfield. The fire will burn mildly in a roughly circular shape (Fig. 5). As the fire area, or wind speed, or fuel type changes, the convection column may be bent by the windfield. Flames will then lean over the unburnt fuel bed, and the fire will assume a roughly elliptical shape with a well defined, and often fast spreading headfire (Fig. 5).

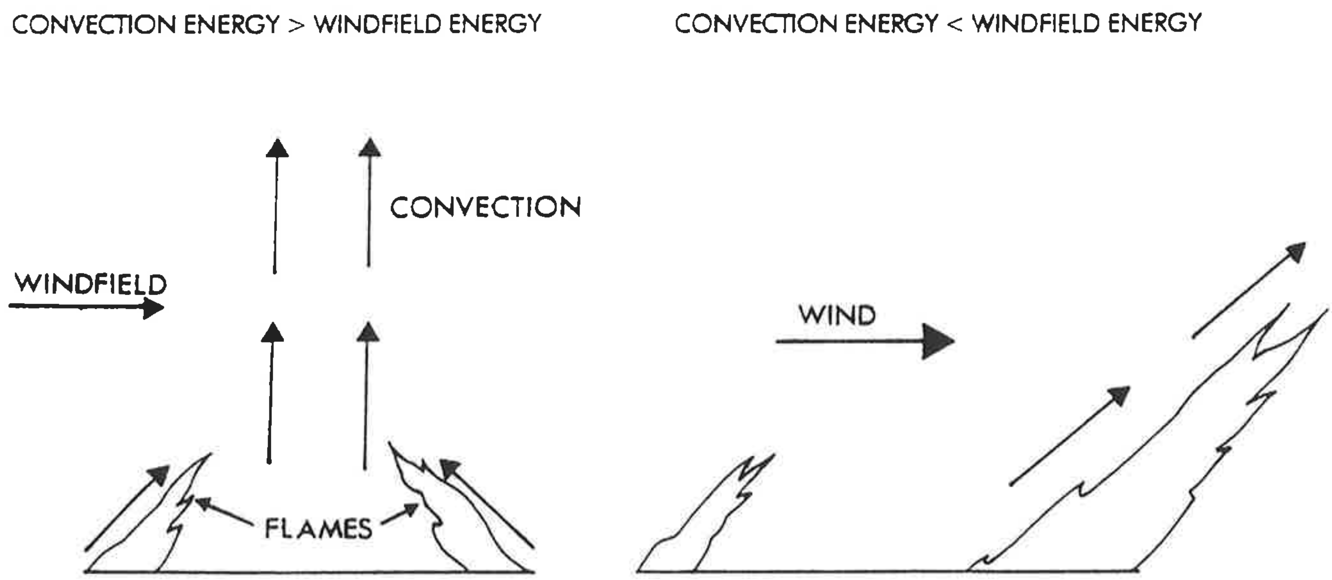

FIGURE 5: Flame angle and the interaction between the convection column and the windfield.

Loosely arranged well-aerated fine fuels, such as scrub or grass, will respond much faster to wind changes than the more compacted and coarser litter fuels. Coarse fuels modify the windfield more than fine, flash fuels. Forecast windspeed refers to the average wind speed over a time interval of between one and two hours. During this time there will be lulls and gusts which will affect fire behaviour accordingly. The wind may also change direction, but if such wind shifts are not great, and are not sustained for any length of time, then the fire will not display lasting dangerous behaviour. Changes in wind speed and direction can be large enough and long enough to cause considerable escalation in fire behaviour.

Vegetation

Vegetation provides a friction surface to wind, and strongly influences its speed and turbulance. Although wind speed in the upper atmosphere can affect a fire's behaviour, it is the wind speed at the flame front which largely determines the ground fire behaviour. The degree to which wind speed is reduced by vegetation is a function of the height and structure of the vegetation. For most upland jarrah sites, the wind speed at 1.5 m above the forest floor ("Forest windspeed") will be the order of one third to one quarter that experienced in the "free" air above the canopy, or at 10 m above ground and in the open ("Tower Windspeed") (Sneeuwjagt & Peet, 1976). However, on lower slopes and flats where there are fewer trees, or adjacent to roads and fire breaks, the wind speed may be one half or three quarters that of the "Tower Windspeed". Fire fighters can expect fire behaviour to escalate on or near these sites. In the jarrah forest an increase in wind speed as the vegetation changes is accompanied by changes in fuel type (see Tables 1 and 2) which will further dramatically change the fire's behaviour. The rate of spread may increase four or five fold (Fig.6).

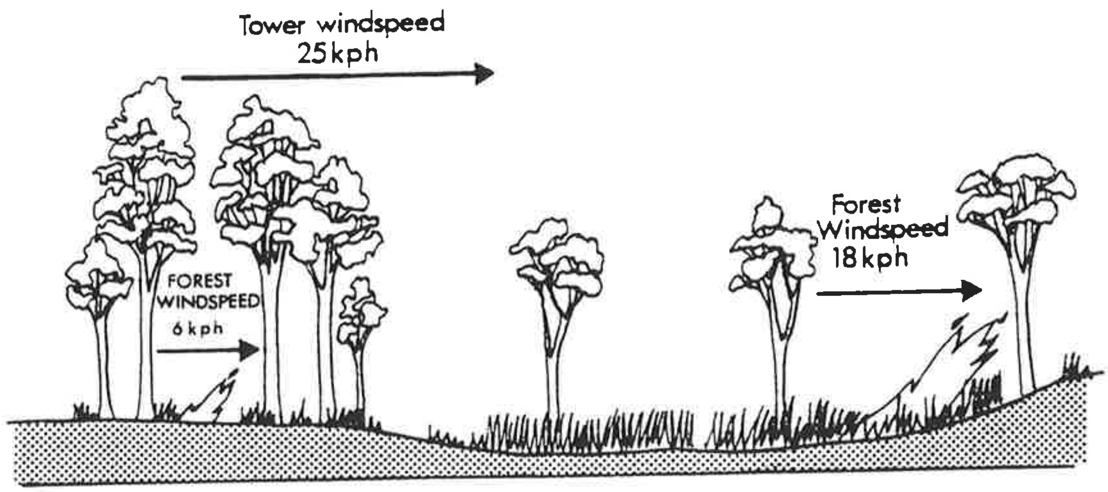

FIGURE 6: The influence of vegetation structure on wind speed at flame height. Increase in wind speed associated with low forest and poor canopy cover can cause increased fire activity.

The removal of vegetation by the fire can result in a reduction in wind impedance and stronger winds at the fire front, particularly when the entire vegetation profile is defoliated.

Topography

With the exception of the Darling Scarp, the jarrah forest occurs mostly on flat or undulating terrain, dissected by creeks and valley systems. These slight topographic changes can produce local changes in the windfield.

Large scale eddies in the windfield near the Darling Scarp often occur in summer, either at night, or in the early morning when fresh easterly winds blow. Figures 7 and 8 show what are thought to be the most common wind patterns during the night, and in the early morning (Allan Scott, personal communication*).

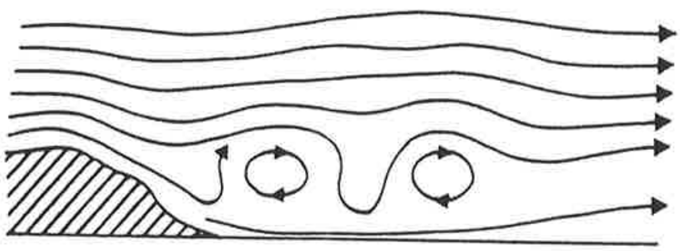

FIGURE 7: Probable airflow pattern over the Darling Scarp during the night.

* Allan Scott, Officer of The Bureau of Meterorology, Perth, W.A.

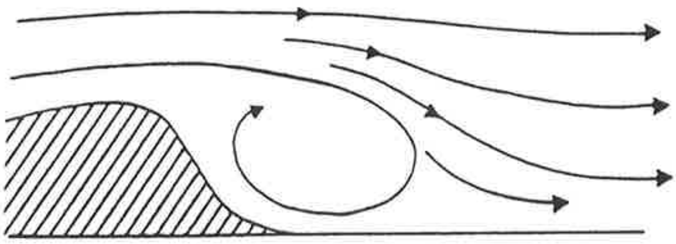

FIGURE 8: Well developed rotor or reverse airflow over a steep section of the Darling Scarp. Most likely to occur in the early morning, and can cause fire control problems.

At times, strong downslope winds, which blow in the lee of the Scarp, are increased by katabatic effects. The shape of the Scarp (or similar topography) can influence wind strength. For example, where valleys lead out from the scarp onto the coastal plain, stronger winds usually occur due to funnelling. Steep slopes are likely to promote the formation of rotor or reverse flow (as shown in Fig. 8), and can cause highly erratic fire behaviour.

In a stable atmosphere, the wind speed around hills is likely to increase around the sides of the hill and over the crest. Parallel ridges and valleys nearby may alter wind speed and direction, when the wind is not blowing parallel to them. The wind will tend to be diverted towards the orientation of the ridges. When the wind is parallel to the ridges, an increase in speed is likely through the valleys. Figure 9 shows the relationship between the wind speed measured on various slopes, and the wind speed measured at 2.0 m over poorly forested land. These data demonstrate that small topographic features can produce significant wind changes, and should be paid due attention by fire fighters.

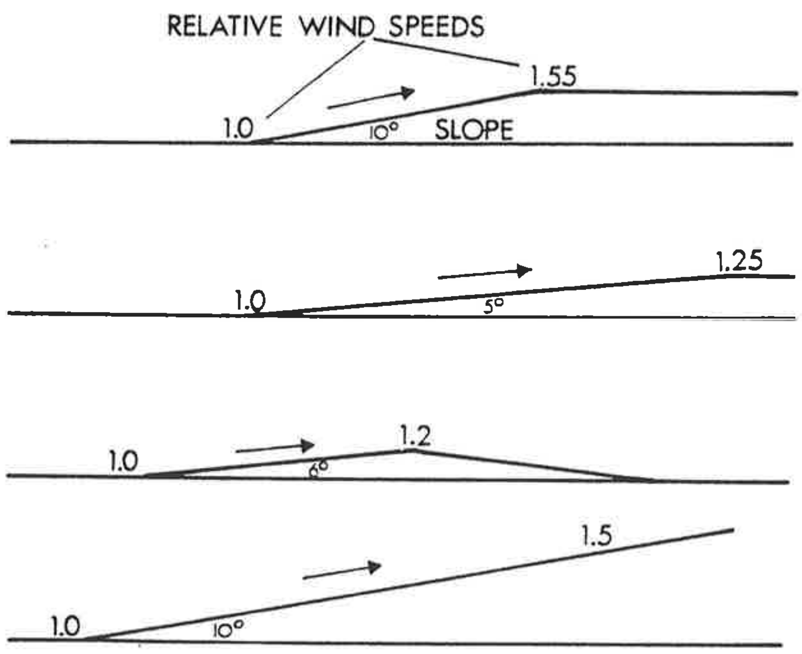

FIGURE 9: Wind speed changes on slopes adjacent to flat terrain.

Localized and topographically induced wind changes can cause erratic changes in fire behaviour, but these may be relatively short lived once the fire has burnt out of the offending topography. Fire fighters should determine the speed and direction of the gradient wind, clear of topographical influences. Gradient wind speed and direction will determine the overall fire direction and behaviour in the event of a blow-up.

Diurnal Wind Variation

Variations in wind speed and direction occur during most days, especially during the warm, dry summer months. Land and sea breezes are obvious daily wind variations, but areas beyond the influence of these winds also experience wind variations. A common summer's day wind pattern is a fresh easterly in the late evening and early morning, which weakens as kthe land surface warms. The timing and magnitude of diurnal wind variations, including land and sea breezes, changes throughout the jarrah forest range, and can best be anticipated from experience. Cool southerly or south-westerly sea breezes can come in suddenly beneath the gradient wind. At high altitudes the smoke plume will continue to be influenced by the gradient wind, and fire fighters may not be given sufficient warning of the wind change at ground level.

To aid in predicting the onset of sea breezes, fire controllers should continually request wind speed and direction information from observers located south, or south-west, of where fire control activities are taking place.

Atmospheric Stability

Fires are affected by atmospheric stability, which may either encourage, or suppress, the vertical air motion generated by the fire (convection). The convectional circulation thus established is affected by the stability of the air. A stable atmosphere (lapse rate $<10^{\circ}$C per 1,000 m rise in altitude) tends to suppress the rise of convection columns. Neutral and unstable atmospheres (lapse rate $\geq 10^{\circ}$C per 1,000 m) induce the vertical motion of the convection column, which in turn increases the indraft into the fire at low levels. Surface winds tend to be turbulent and gusty when the atmosphere is unstable, thus causing erratic fire behaviour. Strong winds aloft may descend to the surface in the afternoon. The rapid development of towering convection columns, combined with upper level winds, promotes intense and long distance spotting. Unstable conditions are often associated with the passage of a cold front, and may persist on the day after a cool change. A clear atmosphere with good visibility, cumulus type cloud development, gusty winds, dust whirls, and smoke columns which rise to great heights, is indicative of unstable conditions. Visible indicators of a stable atmosphere are steady winds, poor visibility at lower levels due to accumulation of smoke and haze, smoke columns which drift apart after a limited rise, lack of vertical motion of the convection column, and stratus type clouds. Spotter aircraft can take atmospheric soundings of air temperature while engaged on normal circuits to confirm atmospheric stability.

Diurnal changes in surface heating and cooling produce changes in atmospheric stability, from night temperature inversions to unstable conditions during the day. An inversion exists when atmospheric temperature increases with altitude. The effect of an inversion is to restrict the vertical motion of convection columns, since inversions are very stable. Smoke, dust, or haze may be trapped below a low level inversion. During typical light wind, fair weather periods, radiation cooling at night forms a stable inversion near the surface, which deepens until just before sunrise. As the surface is heated, a shallow super adiabatic layer is formed, and steadily deepens during the day. The low level night inversion will suppress the rise of the convection column, thus suppressing fire behaviour. However, as the inversion dissipates, and the atmosphere becomes unstable, the fire's behaviour will become more erratic.

If the daytime inversion is weak or shallow, it may be pierced by the convection column. If the air above the inversion is unstable, piercing the inversion may act on the fire as if a damper were opened, and the fire will flare up.

Upper Atmospheric Winds

If there are strong winds high in the atmosphere during the morning, these may descend to the surface when vertical mixing occurs during the day. Likewise, the wind speed and direction at high levels, as indicated by the type of clouds and their speed of movement, or from measurements, may also occur on the surface later in the day. Vertical mixing often occurs with the formation of a trough of low pressure inland from the west coast. East of the trough the morning winds are north-east, but as the trough moves inland during the afternoon the north-west winds in the upper atmosphere (1,000 m above sea level) can be mixed down to the surface. These winds are driven by the winds above, and they often reach gale force very quickly. This situation produces conditions which make fire control very difficult. It is not always possible to predict trough movement, and the extent of vertical mixing, but sometimes high stratus cloud streaming in from the north west may indicate strong winds at ground level later in the day. Fire fighters at the fire front should continually observe the direction of the smoke in the convection column. This indicates the prevailing wind conditions. Changes in smoke direction will often indicate a change in wind direction at the surface within 10 - 20 minutes. Just prior to change the fire may abate, and fire fighters may observe an eerie lull, with smoke, embers and ash streaming overhead. This is a sign of danger. The fire is about to change direction, and will run in the direction of the overhead smoke. Fire fighters should evacuate the area immediately, and be wary of increased fire activity and increased spotting. A flank fire which suddenly becomes a head fire is often more severe than the original head fire. The new fire front may be considerably longer, and thus generate far more energy than the original.

Fire Interaction

Numerous fires scattered over an area, as often occur from spotting, sometimes produce violent fire behaviour. A number of large fires in close proximity may be drawn together to form one conflagration. This phenomenon is most pronounced in heavy fuels, and conditions of high fire danger. Under these conditions back burning can be a dangerous practice. The back burn and wildfire can be drawn together so violently that large whirlwinds, crown and spot fires create tremendous difficulties for fire fighters.

The sphere of a fire's influence on the windfield will vary according to the fire intensity, fire size and ambient wind conditions. Small fires (5 - 10 ha) burning under dry conditions (<6% moisture content) and in seven year old jarrah fuels (7 - 8 tonnes/ha) have been observed to "draw" backfires lit 150 m downwind of the fires. The "backfire" reached a rate of spread of 480 m hr^{-1}, and localized crown fires were observed. The violent eruption in behaviour as a result of backfiring produced a shower of embers and numerous hop-overs. During recent experimental fires, an anemometer placed in a protected area some 200 m downwind of a fire, burning in heavy fuels in a jarrah creek system, recorded indraft fire winds up to 27 kph. Prior to the fire's approach, winds were steady at 5 kph (at 2 m above the forest floor). Research is continuing into fire interaction, but fire fighters should be wary of lighting backfires in heavy fuels (> 8 t/ha) when fuel moisture content is ≤ 6% (i.e. r.h. is ≤ 30%). The same phenomenon can create a dangerous situation if fire fighters are caught between a headfire, and a series of seemingly small and harmless spot fires downwind of the main fire.

CONCLUSIONS

Weather forecasting provides an overall evaluation of fire weather conditions, but it is the personal responsibility of every fire fighter to continually observe weather conditions at the site of the fire. Fire fighters must be trained to anticipate wind shifts due to local influences, and to expect changes in fire behaviour in different fuel types. Fires are most likely to blow-up when fuels are dry (⩽6%), on days of high temperature and low r.h. Flats, creeks, and areas of heavy fuel accumulation are places where fires are likely to blow-up. Fire fighters must always be aware of the direction of the prevailing wind, and be alert to wind shifts. They should learn to position themselves so that they are not threatened by sudden changes in fire behaviour.

ACKNOWLEDGEMENTS

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