# Do eucalypt forest fires burn faster and hotter in older fuels? – implications for hazard reduction burning.

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## Abstract

Fire behaviour guides developed for open eucalypt forests in Australia have used fine fuel load as the principal fuel variable for predicting rate of spread and difficulty of suppression. This approach has the merit of simplicity in operational use, and allows fire behaviour predictions to be linked to models of fuel accumulation that are based on time since the last fire. There has been a growing awareness amongst fire researchers and practitioners of the importance of other fuel attributes including the quantity and arrangement of understorey shrubs, and the condition of bark on standing trees. While it has been possible to describe and measure these fuel variables there has been no means of applying this information to make quantitative fire behaviour predictions.

Project Vesta is an experimental study designed to quantify age-related changes in fuel attributes and fire behaviour in dry eucalypt forests typical of southern Australia. Experimental fires were conducted during dry summer conditions at two sites with understorey fuels ranging in age from 2 to 22 years since fire. New fire behaviour models have been developed that predict rate of spread and difficulty of suppression according to wind speed, fuel moisture content and variables that reflect the abundance and condition of leaf litter, understorey fuels and bark. These models predict that under conditions of high to very high fire danger the rate of spread and intensity of fire are strongly correlated with fuel age for a period of at least 15 years after fire. In forests dominated by trees with fibrous bark the spotting potential and difficulty of suppression may continue to increase for considerably longer periods after fire because of the accumulation of bark on stems. For this reason predictions of fire behaviour based solely on fine fuel loading will tend to under-estimate potential fire behaviour in forests that have been unburnt for some time.

The improved understanding of relationships between fuel age and potential fire behaviour in dry eucalypt forests gained from Project Vesta provides a better basis to assess the benefits of various fuel management alternatives that may be employed to reduce difficulty of fire suppression and protect assets from damage during high intensity wildfires.

## Introduction

Fuel load is the principal fuel characteristic used in Australian forest fire danger rating systems to predict fire behaviour within a particular forest type. Fire behaviour guides for eucalypt forests were first developed in the early 1960's by Alan McArthur of the Commonwealth Forestry and Timber Bureau (1962, 1967) and George Peet of the Western Australian Forests Department (1965). Both fire behaviour guides predict that the rate of forward spread (R) is directly proportional to weight of fine fuel (w) according to a simple linear relationship of the form:

$$R = aw$$

where a is a constant defined for the particular fuel type (McArthur 1962, Peet 1965).

Experimental evidence for this relationship between rate of spread and fuel load came from measurements of small experimental fires lit in open eucalypt forests with fuels comprised of leaf litter and occasional low shrubs. Fire were generally ignited at a point source and allowed to develop for periods of up to one hour or so.

Later editions of the Forest Fire Behaviour Tables for Western Australia (Sneeuwjagt and Peet 1985) allowed for the condition and density of understorey shrubs to be taken into account when estimating the available fuel quantity, but retained the assumption that rate of spread depended directly on fuel load.

Fire intensity is defined as the rate of heat released per unit length of fire front (Byram 1959), and is calculated by the following equation:

$$I = HwR$$

where I = fire intensity (kW $m^{-1}$),
H = the heat yield of combustion of the fuel (kJ $kg^{-1}$),
w = weight of fuel consumed (kg $m^{-2}$) and,
R = rate of forward spread of the fire front (m $s^{-1}$).

Fire intensity is a useful practical measure of the difficulty of suppression of a forest fire and is positively correlated with flame length, and with the spotting distance of firebrands transported ahead of the flame front (Ellis 2000).

The relationship between fuel load, rate of spread and fire intensity has provided a simple but powerful argument in support of the practice of fuel reduction burning in eucalypt forests. If the rate of spread is directly proportional to fuel weight, then halving the fuel weight also halves the rate of spread and reduces the intensity of the fire by a factor of four (McArthur 1962). In the simplest case of a freshly burnt area the logic of this proposition is self-evident: where there is no fuel there can be no fire. However, it may be less evident in situations where the vegetation consists of a number of potentially flammable components that may or may not become involved in combustion according to the severity of the burning conditions. Examples of these potential fuels include shrubs, tree canopies and bark on the stems of standing trees. Techniques for rating the relative hazard of these fuels have been developed (McCarthy et al. 1999) but such ratings have not readily been used for making quantitative predictions with existing fire behaviour models.

The relationship between fuel weight and rate of spread has been questioned on several grounds including:

- absence of statistical validation for the findings of McArthur (1962, 1967) and Peet (1965)
- the results of subsequent experimental burning studies in forest (Burrows 1999) and grassland (Cheney et al. 1993) which failed to demonstrate a relationship between these two variables;
- reports of severe fire behaviour in recently burnt areas, particularly during conditions of Extreme fire danger (Bradstock and Scott 1995, Meredith 1996).

In 1995, the Western Australian Department of Conservation and Land Management and CSIRO Forestry and Forest Products Bushfire Research and Management Group embarked on an experimental program (Project Vesta) that was designed to address the effect of age-related fuel characteristics on fire behaviour in eucalypt forests. The purpose of this paper is to describe how the key findings of Project Vesta can inform the debate about the effectiveness of hazard reduction burning for wildfire control.

**The Project Vesta experiments**

During the summers of 1998, 1999 and 2001 experimental fires were lit at two sites in the Jarrah forest of south-west Western Australia. The experimental site at McCorkhill block 20 km west of Nannup had a shrubby understorey dominated by Agonis parviceps which grows to a maximum height of about 2 m. In areas unburnt for 8 years or more this understorey can become sufficiently dense to restrict wind speed in the forest, and can provide a ladder fuel that increases flame length. In contrast, the site at Dee Vee Road 30 km north of Collie had a sparse understorey of Bossiaea ornata which rarely exceeds a height of 0.5 m. At each site a number of replicate plots were established in areas of forest unburnt for between 2 and 22 years. Plots were 200 m x 200 m in size and were separated by bulldozed tracks.

Fuel and vegetation characteristics were assessed at up to 32 sample points in each plot. Five fuel strata were recognised, as follows:

- overstorey canopy and bark,
- intermediate canopy and bark,
- elevated shrubs,
- a near-surface fuel layer comprised of twigs, bark suspended leaves and low shrubs,
- surface litter.

Fuel characteristics assessed at each point included the depth, cover and loading of surface litter and near-surface fuel, and the height of elevated fuel. Each fuel strata was described by a fuel hazard score following the concept of McCarthy et al. (1999). Fuel hazard was rated against a set of standard descriptions that reflected increasing potential flammability on a scale from 1-4. A percent cover score was also assigned to each fuel stratum. Samples of surface litter and near-surface fuel were harvested and oven dried to determine loadings in t $ha^{-1}$. Sampling intensity was designed to estimate the mean surface fuel loading with a standard error of less than ± 15 per cent. Elevated shrub fuels were also harvested from a small number of quadrats in each fuel age to determine loadings of live and dead material <6 mm diameter. Bark consumption was determined from measurements of the reduction in bark thickness and the height of charring on the stems of ten Jarrah trees in each plot.

Wind speed was measured during each fire using four sensitive cup anemometers suspended from portable aluminium towers at a height of 5 m above ground. For each plot, four towers were placed at 40 m intervals in a line in the forest upwind of the plot to be burnt. The distance between the anemometers and the ignition line was generally about 40 m. Wind speed was also measured using an anemometer mounted 30 m above ground in a forest clearing within 1 km of the experimental plots. For the purpose of fire spread analysis wind speeds from these instruments were combined into 10-minute means.

Experimental fires were conducted under dry summer conditions of moderate to high forest fire danger. On each burn day fires were ignited simultaneously in plots of each fuel age (5 ages at McCorkhill, 4 ages at Dee Vee). Ignition lines 120 m long were lit with drip torches on the upwind edge of each plot, working outwards from the centre point of the ignition line to complete the lighting operation in two minutes. Observers described the behaviour of each fire as it spread through the plot and recorded the rate of spread using tags and electronic timers. Fire behaviour ranged from slow-spreading surface fires to high intensity fires (7000 kW $m^{-1}$) with sporadic crowning activity. Eleven sets of experiments were conducted at McCorkhill, and 12 sets at Dee Vee making a total of 104 fires.

## Changes in fuel characteristics with increasing time since fire

At both sites surface and near-surface fuel loads increased for at least 15 years after fire, with about 75 per cent of the fuel load accumulating within the first 10 years. Surface fuel loadings stabilised at 12-15 t $ha^{-1}$, and the combined loading of surface and near-surface fuels at 15-17 t $ha^{-1}$. This pattern of accumulation is consistent with models previously developed for Jarrah forest litter by Peet (1971) and Burrows (1994). Surface fuel hazard scores increased rapidly during the first six years after fire and then continued to increase slowly for a further ten years. Litter cover was almost continuous after six years and changed little thereafter. Near-surface fuel hazard and percent cover scores rose more slowly than did those for surface fuels, but increased for at least 15 years after fire. Near-surface fuel height also increased for at least ten years after fire.

At the McCorkhill site the height of the elevated fuel stratum increased steadily with time since fire and attained a mean of 1.5 m at an age of 15 years. In contrast, the height of the elevated fuel stratum at Dee Vee was independent of time since fire, with 2-year-old and 20-year-old fuels both having a mean height of 0.5 m. Despite the large difference in fuel height between McCorkhill and Dee Vee, loadings of elevated fine fuel were similar for the two sites (1-2 t $ha^{-1}$) and were small in comparison with surface fuel loadings. The per cent cover of elevated fuel stabilised at a constant level within 5 years after fire. Elevated fuel hazard scores increased for at least 10 years after fire at both sites, with the McCorkhill site stabilising at a level about one half score higher than the Dee Vee site.

Jarrah has a fibrous bark (stringybark) that extends over the entire stem to the fine branches, and varies in condition according to the previous fire history of the stand. Jarrah stems in stands subject to low-intensity fuel reduction burning are often lightly charred to a height of a few metres, while stands recently burnt by intense wildfires may be heavily charred to the full height of the trees (30-35 m). Where fire has been absent for 20 years or more Jarrah bark is brown to grey in colour and may become fissured to a depth of 2-3 cm. Bark hazard scores on both overstorey and intermediate canopy trees increased with time since fire. This was accompanied by a progressive increase in bark thickness to 30 mm or more on trees in the oldest fuel ages at each site. The season and intensity of past fires appeared to have an important influence on bark thickness with trees in the 19-year-old fuels at Dee Vee having considerably thicker bark than trees in 16-year-old fuels at McCorkhill. Experimental fires in the summer of 1983 are likely to have removed all combustible bark on the trees at McCorkhill (Burrows et al. 2001), whereas at Dee Vee a regime of low intensity spring fires would have allowed bark to accumulate above a height of 1 m on the stem.

**Fuel characteristics and fire spread**

Rate of spread data from experimental fires were reduced to a zero slope equivalent using the slope function of McArthur (1967), and were standardised to a surface litter moisture content of 7 percent using the function of Burrows (1999). In some case wind speed data exhibited a post-ignition increase that was not detectable in the observations made some distance away from fires at the 30 m tower. This effect was more evident in older fuels and higher intensity fires, and persisted for up to an hour after ignition. It is likely that the enhanced wind speed was due to a change in convective activity around experimental fire plots after ignition. Wind speed data measured at each experimental plot were adjusted to a pre-fire equivalent value using a function that related the proportional increase in speed to fire intensity.

Following standardisation, the rate of spread data showed a strong relationship with wind speed. For a given wind speed the fires at McCorkhill tended to spread faster than those at Dee Vee, suggesting that differences in fuel characteristics between the two sites affected rate of spread. When stratified by wind speed classes, rate of spread data showed a positive relationship with surface fuel load although correlations were mostly <0.5, and the effect of surface fuel load was not evident in all wind speed classes.

A range of other fuel variables were screened using the same approach, including variables derived from the product of hazard scores, percent cover scores, and fuel height. Several of the derived fuel variables were strongly correlated (>0.7) with rate of spread across all wind speed classes and were superior to variables based on a single attribute of the fuel. Derived variables strongly correlated with rate of spread included:

- product of near-surface fuel height and hazard score,
- product of near-surface fuel height and percent cover score,
- product of elevated fuel height and hazard score,
- product of elevated fuel height and percent cover score.

Bark hazard scores and percent cover scores for the intermediate and overstorey strata were not strongly correlated with rate of spread. However, bark loss and char height on Jarrah trees were correlated with fire intensity and the pre-fire thickness of the bark. Linear regression equations fitted to intensity and pre-fire bark thickness explained at least 60 per cent of the variation in bark loss. Estimates of the quantity of bark fuel consumed in a typical Jarrah forest stand ranged from 1-2 t $ha^{-1}$ for fires up to 1000 kW $m^{-1}$, and 6-8 t $ha^{-1}$ for fires of 6000 kW $m^{-1}$.

**Discussion**

Project Vesta experiments have confirmed that the rate of spread of fires in open eucalypt forest is affected by a variety of fuel characteristics which change as the age of the fuel increases. Some characteristics of the fuel stabilise within six years after fire and do not change appreciably in older fuels. This was the case for percent cover of surface litter and elevated fuel, and for elevated fuel height at Dee Vee. However, other fuel characteristics continue to change for at least 10-15 years after fire as was observed for near-surface fuel hazard and cover, elevated fuel hazard, and near-surface fuel height. Elevated fuel height also continued to increase with time since fire at McCorkhill where the forest had a shrubby understorey. The amount of bark on standing trees that is potentially available as fuel also increased with time since fire. This is partly because the trees have thicker bark, and also because fires in older fuels tend to be more intense and result in higher char on the stem. Bark may contribute half as much fuel again as is there is in the surface and near-surface fuel strata. The higher level of bark consumption in older fuels also has a significant influence on the density of firebrands transported downwind of the flaming zone (Ellis – this conference).

These findings support McArthur's proposition that the difficulty of suppression is greater in older fuels not only because of the heavier fuel loadings and higher fire intensities, but also because the fires may spread faster. The Project Vesta experiments showed that surface fuel loading was correlated with rate of spread under some situations, but also demonstrated that other fuel variables can provide better explanatory power for modelling rate of spread. Variables that combine different characteristics of the fuel, such as height and hazard score, provide an opportunity to develop fire behaviour models that can be applied across a range of forest types, rather than being specific to a particular type. We consider that in selecting variables for inclusion in a fire behaviour model, weighting should be given to practical issues of field assessment as well as to statistical considerations. For this reason we favour measures of fuel height and fuel hazard score instead of percent cover which can be difficult to assess consistently amongst different observers. Project Vesta findings add weight to the view that visually-based fuel hazard rating systems have potential to replace more labour intensive methods of fuel assessment.

## Conclusions

Project Vesta has confirmed that the potential intensity and rate of spread of fires in open eucalypt forests is directly related to the time since last fire. The intensity and difficulty of suppression of fires will increase for at least 15 years after fire because of changes taking place in the characteristics of surface, near-surface and elevated fuel strata. In forests dominated by trees with fibrous bark the spotting potential and difficulty of suppression may continue to increase for considerably longer periods after fire as bark continues to accumulate on trees. For this reason predictions of fire behaviour based solely on the loading of fine surface fuels will tend to under-estimate potential fire behaviour in forests that have been unburnt for some time.

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