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Predicting canopy scorch height in jarrah forests

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ABSTRACT

The height to which foliage is killed by fire (scorch height) is one of the criteria for prescribing control burns and for evaluating the impacts of wildfires in jarrah (*Eucalyptus marginata* Donn ex Smith) forests of Western Australia. Therefore it is important that scorch height can be predicted within limits acceptable to fire managers. This paper reports on the experimental determination of models for making such predictions. Scorch height was found to be a function of fire intensity, flame height and of the season in which the fire burnt. Under cool, moist, spring weather conditions, scorch height was about five times the height of the flames and under dry, warm, summer/autumn weather conditions, scorch height was about nine times the height of flames.

INTRODUCTION

Forest fires kill or damage vegetation by either girdling or incinerating the stem or by incinerating or scorching foliage and buds. Crown or canopy scorch is usually considered to be an undesirable effect of fire, especially in coniferous forests where excessive crown scorch can lead to tree death (e.g. Van Wagner 1970; de Ronde 1983; Johnson 1992) or loss of wood production (Hodgson and Hieslers 1972). For fire-sensitive North American coniferous forests, the degree of crown scorch is widely used to predict mortality (Peterson 1985; Peterson and Ryan 1986; Reinhardt and Ryan 1989; Saveland and Neuenschwander 1990; Swezy and Agee 1991). However, mature jarrah (*Eucalyptus marginata* Donn ex Smith) and marri (*E. calophylla* Lindl.) trees, like many species of *Eucalyptus*, have evolved adaptive traits to recover or regenerate following fire-caused injury (Jacobs 1955; Gill 1975) and quickly replace scorched crowns from epicormic shoots.

In the management of jarrah forests, scorch height, or the height to which foliage and fine branches have experienced a lethal temperature regime, is often used as a criterion for implementing prescribed burns (Sneeuwjagt and Peet 1985). When precribing low intensity fires to reduce fuel levels in uneven-aged forests (trees of mixed ages), the aim is to minimize crown damage by keeping scorch height to less than about 6 m. Scorch above this level can cause long-term crown and stem damage, especially to small saplings where growing tips can be killed back and stem deformities induced. Full crown scorch can cause a temporary reduction of amenity value. Fires of sufficient intensity to cause canopy scorch can temporarily disrupt breeding of birds and arboreal mammals which utilize hollows or feed in the green canopy (Christensen *et al.* 1988; Inions *et al.* 1989). The protection benefits derived from fuel reduction burning can be reduced if the forest canopy is fully scorched. Scorch induces leaf fall which can add up to 5 t ha^{-1} of additional fuel to the forest floor (Luke and McArthur 1978).

In some circumstances, however, the objective of prescribed burning is to fully scorch the forest canopy. This may be required to maximize regeneration by creating 'ashbed' and by stimulating a massive and synchronized release of canopy stored seed (Cremer 1965; Henry and Florence 1966; Christensen 1971; Burrows *et al.* 1989), to induce a positive growth response from established trees following crown replacement (Kimber 1978), or to interrupt the life cycle of forest pests such as jarrah leaf miner (Abbott *et al.* 1993). Prescribed burns to regenerate or eradicate specific understorey species usually require fires of sufficient intensity to cause full crown scorch (Shea *et al.* 1979; Christensen 1982; Burrows 1985).

Whatever the purpose of prescribed burning, it is essential that jarrah forest fire managers be able to predict the extent of crown scorch. Sneeuwjagt and Peet (1985) present a table for predicting the maximum scorch height to jarrah during low intensity spring fires from predicted rates of spread and total available fuel quantities. During autumn conditions, scorch height is estimated to be 1.8 times greater than the predicted spring scorch height. The table presented by Sneeuwjagt and Peet (1985) applies to a narrow range of burning conditions which is adequate for low intensity fuel reduction fires where rates of spread are less than about 70 m h^{-1} and scorch heights are less than about 12 m. A rule of thumb used in south-eastern Australian eucalypt forests is that scorch height is about six times flame height (Luke and McArthur 1978). Hoare (1985) used flame height to assess and predict the biological effects of fire in tropical eucalypt woodland and found scorch height to be about 4 times flame height.

During a forest fire, vegetation above the flames is affected by a rising plume of hot air, and live leaves and fine twigs are scorched and killed when heated above temperatures of about 60-70 °C for very short durations (Kayll 1968; Methven 1971; Ryan 1982; Cheney *et al.* 1992; Gill 1995). Thomas (1963), using dimensional analysis, derived a relationship between temperature rise above ambient, fire intensity and the height above ground for no-wind situations and Van Wagner (1973) used this relationship as a basis for determining the height at which lethal temperatures were experienced (scorch height). He also introduced the idea that, under the influence of wind, the plume follows an angled path up into the vegetation. His relationship between scorch height and fire intensity was developed from 13 small experimental fires in Canadian forest types with theoretical adjustments to scorch for ambient temperature and wind speed; the theory being that scorch height is directly related to ambient temperature and inversely related to wind speed, other things being equal. Thus the acute physical impact of fire is a function of the amount and rate of heat release (intensity) and of factors affecting heat transfer (ambient temperature and wind speed). Van Wagner's (1973) equations are shown below (in the units of this study).

$$h_s = 0.148(I)^{2/3}$$

$$h_s = [4.4713(I)^{2}/3]/(60-T)$$

$$h_s = \frac{0.742(I)^{7/6}}{[0.0256(I) + (0.278U)^3]^{1/2}(60-T)} \quad \text{(van Wagner 1973)}$$

Where:
h_s = scorch height (m),
I = fire intensity (kW m^{-1}) (Byram 1959),
U = wind speed (km h^{-1} in the forest at 1-2 m),
T = ambient temperature (°C).

Van Wagner's models have been widely used to predict crown scorch and tree mortality in North American conifer forests (e.g., Rothermel and Deeming 1980; Kercher and Axelrod 1984). Cheney *et al.* (1992) developed a semi-physical model based on Van Wagner's model to predict scorch height from low intensity fires in *E. sieberi* regrowth forests in New South Wales. They found that most variation in scorch height (55 per cent) could be explained by flame height, followed by intensity and rate of spread. As fuel quantity was considered to be more or less constant during their experimental fires, they presented another model for predicting scorch height from rate of spread (R), and ambient temperature (T):

$$S_h = 2.9263(R^{0.5})(e^{0.0537T})$$

$$R^2 = 0.63 \quad \text{(Cheney } et\ al. \text{ 1992)}$$

To develop a physical model of scorch height, Cheney *et al.* (1992) measured radiation and air temperature in the crown scorch zone above low intensity prescribed fires in *Eucalyptus sieberi* regrowth forests. They used these measurements and Van Wagner's plume theory to model plume temperatures above fire and combined this with a model describing the thermal response of *E. sieberi* leaves to produce a model to predict scorch height.

None of the physical models described have been validated for jarrah forests and the scorch tables presented by Sneeuwjagt and Peet (1985) are limited in that they apply only to low intensity fires. This study evaluates these models for use in jarrah forests and develops specific empirical models for predicting scorch height in jarrah forests over a wide range of burning conditions.

METHODS

The study was carried out in conjunction with jarrah forest fire behaviour experiments conducted over summer and early autumn (January, February and March) in 1979 and 1980. Details of these experiments are described by Burrows (1994). Experimental fires were set in forty 2 ha plots which were last burnt 7 years prior to this experiment. The quantity of dead leaves, twigs, bark and floral parts < 6 mm in diameter on the forest floor (litter fuel) was measured before and after each experimental fire in a series of 20 m x 4 m sub-plots (30-40 per 2 ha plot). Litter fuel depth was measured at ten locations within each sub-plot and a relationship between litter depth and fuel quantity was used to determine litter fuel quantity (Burrows 1994). Fire rate of spread was measured by timing the spread of flames through the sub-plots, and visual estimates of flame height and length were made by experienced observers. Calibrated wooden pegs situated in the plots aided the visual assessment of flame dimensions. A portable weather station set at 1.5 m above the forest floor in an adjacent plot some 50 m from the plot to be burnt recorded ambient air temperature, relative humidity and wind speed and direction during each experimental fire.

Mean scorch heights within the sub-plots were measured about 5-6 weeks after fire using either a height stick for scorch ≤2 m or a clinometer for scorch >2 m. Mean scorch heights were regressed with mean fire behaviour parameters (rate of spread, flame height, flame length and fire intensity) obtained for each sub-plot. Scorch height measurement was limited by the maximum height of the vegetation at each sample point. In many cases, the entire vegetation profile was scorched indicating that the potential scorch height exceeded the height of the vegetation used to measure scorch height. Therefore, only data where scorch height was less than canopy height were used in analysis.

Additional scorch height data were acquired from Peet (1966 unpublished data archived at the CALM Manjimup Research Station Archive File 22/06.2). Peet's data were obtained during small, low intensity fires set in jarrah forests in spring 1966 when conditions were cool and moist. Unfortunately, we were unable to reliably match Peet's historical scorch height and fire behaviour records with the weather records. Therefore, seasonal data (spring and summer/autumn) were analysed separately because of seasonal differences in weather conditions during the fires, fuel moisture content and tree physiology.

RESULTS AND DISCUSSION

Scorch Height and Semi-physical Models

Observed scorch heights are graphed, with scorch heights predicted by Van Wagner's (1973) model using fire intensity, ambient air temperature and wind speed, in Figure 1. When applied to jarrah forests, Van Wagner's model consistently under predicted scorch height. The scorch model derived by Cheney *et al.* (1992) using fire intensity, wind speed and ambient temperature, also under predicted at low scorch levels and showed poor predictive capacity at high fire intensities. Differences in forest type, fuel characteristics and methods of calculating fire intensity probably explain the poor performance of these models. Cheney (1990) has discussed the limitations of using Byram's (1959) fire intensity to compare fires burning in different fuel types. Correction factors to improve the predictability of the Van Wagner model were generated by regressing observed scorch height with predictions, as shown in Figure 1. Regression analysis solving for coefficient values ('k' values) using Van Wagner's equation form did not improve the R^2 values or the error statistics. The best-fit equation using the form given by Van Wagner (1973) is:

$$S_h = 1.49 \frac{0.742(I)^{7/6}}{(60-T)[0.0256(I) + (0.278U)^3]^{1/2}} + 1.06 \quad R^2=0.65$$

Where:

S_h = scorch height in jarrah forests (m),

I = fire intensity (kW m^{-1}),

T = ambient air temperature (°C),

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

Scorch Height and Fire Behaviour Variables

Of the fire behaviour variables, flame height, flame length and Byram's (1959) fire intensity showed strongest correlation with scorch height. This is not surprising as these descriptors reflect the amount and rate of heat release for a given fuel type (Cheney 1990). There is considerable variation in scorch height not explained by the relationships in Table 1, reflecting the inherent variability and difficulty of measurement of scorch height, the behaviour of fire, fuels and meteorological conditions. In some instances, tilting of the convection column would have resulted in inaccuracies when matching scorch height with the appropriate fuel and fire behaviour variables which gave rise to the scorch, further adding to the unexplained variation in scorch height.

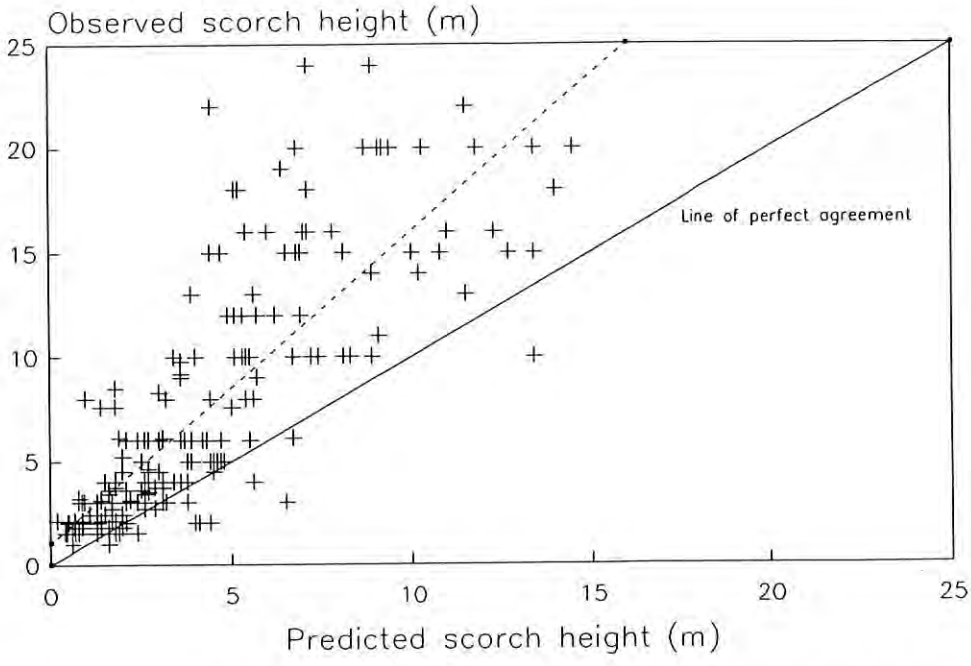

Figure 1. Scorch heights observed following fires in jarrah forests, with scorch heights predicted by Van Wagner's (1973) equation.

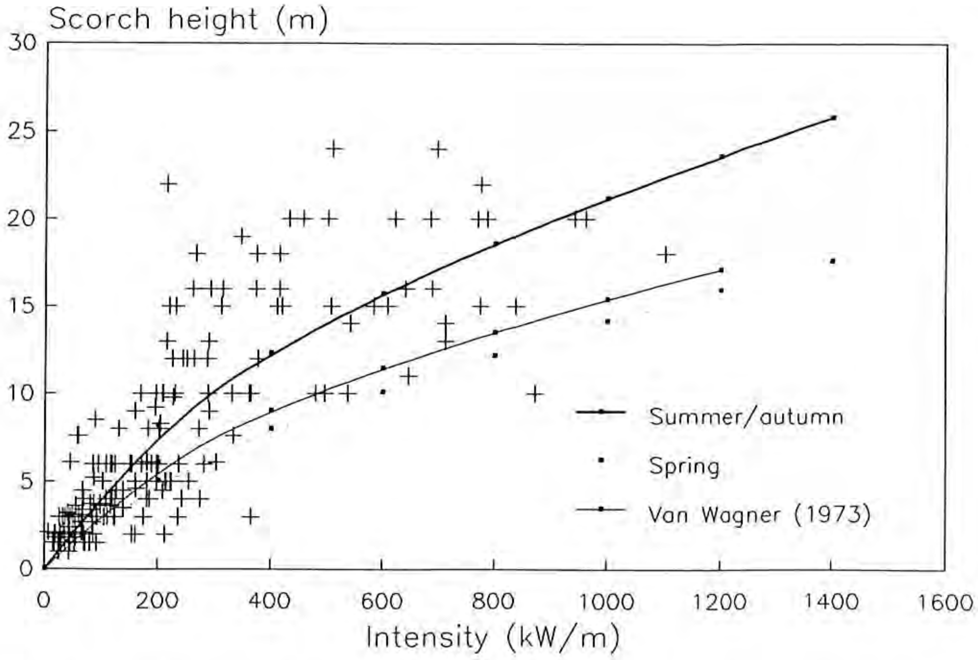

Figure 4. Scorch heights during jarrah forest fires in spring and summer/autumn are graphed with Byram's (1959) fire intensity. Scorch height predicted using Van Wagner's (1973) equation is also graphed for comparison. Regression equations are shown in Table 1.

wildfires. A strategy for achieving this is to implement low intensity fires in spring under cool weather conditions when fuels are moist. This operation successfully achieves fuel reduction while minimizing canopy damage, especially in regrowth forests. Current prescriptions require scorch height to be less than 6 m which also minimizes the impact on flora (especially small trees), fauna and visual qualities (e.g. see Burrows and Friend *in press*). Using the relationships contained in Table 1, this can be achieved by prescribing fires with flame heights less than about 1 m in spring (cool, moist conditions) and less than about 0.5 m in summer/autumn (warm, dry conditions), or maintaining fire intensities below about 250 kW m^{-1}. For a standard jarrah forest fuel with about 8.0 t ha^{-1} of available fine fuel, headfire rates of spread should not exceed about 65 m h^{-1}.

Fires burning under warm and dry conditions in summer or autumn cause significantly higher crown scorch than spring fires with similar flame heights. Where the aim is to fully scorch the forest canopy with prescribed fire, then this is best achieved with the minimum fire intensity needed to fully scorch the canopy to ensure that the fire can be controlled and does not cause excessive damage to other forest values. From the relationships in Table 1, the minimum flame height to achieve full canopy scorch to a mature jarrah forest (top height 20-25 m) under warm, dry summer/autumn conditions is about 2-3 m, which is equivalent to a fire intensity of about 1000-1200 kW m^{-1}.

CONCLUSIONS

Scorch height is a useful and meaningful criterion for setting limits to the intensity of prescribed burns and for assessing the potential severity of wildfires. An ability to predict scorch height is important for planning and implementing fire management activities.

None of the existing scorch models adequately predicts scorch height over the range of fire conditions likely to be experienced in the jarrah forest. This study developed new relationships enabling scorch height in jarrah forest fires to be predicted, within reasonable limits, from readily measured fire behaviour variables such as flame height, flame length and fire intensity. The strong seasonal differences between these relationships is probably owing to seasonal variation in (1) weather conditions, (2) plant physiology and (3) fuels available for burning.

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