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Time dependence of temperature above wildland fires

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ABSTRACT

A statistical description is presented for the time dependence of temperature at various heights above a moving wildland fire. The model was developed using nonlinear least-squares curve fitting on experimental data from fires in shrubland fuel complexes and is based on classical theory with empirical modifications (where necessary) to suit the fuel types being studied. Relative to a stationary observation point which is overtaken by a spreading fire, the temperature-time history can be partitioned into two distinct regions:

(i) As the fire approaches, the rapid temperature rise above ambient is modelled by a Gaussian curve, having only one free parameter β to describe its steepness. Maximum temperature rise in measured data generally occur within 60 seconds.

(ii) As the fire recedes, the temperature falls comparatively slowly, with the fastest rate determined by simple Newtonian cooling (again described by one free parameter, γ. In practice, residual burning in larger components of the fuel bed results in a long 'tail' so that γ becomes an effective value.

Fire effects upon vegetation are discussed and a means of comparing lethal exposure experiments in the laboratory with wildland fire temperature-time curves is detailed.

INTRODUCTION

In studying the ecological impact of wildfires, it is desirable that the temperatures to which plants are subjected and the durations of those temperatures are known. In a related paper, Weber *et al.* (this publication) present a model for the variation of maximum temperature with height above ground for free-burning wildland fires. This new study considers the time dependence of the temperature rise, for any height above a given point on the ground, as a firefront approaches, passes over and then recedes. In particular, the time at temperature, for any given temperature rise ΔT, has a major impact on the survival probability of vegetation. Martin *et al.* (1969) have presented temperature lethality curves for leaves and seeds. We later relate our findings to theirs and detail a method for determining lethal temperature exposures, a long-standing problem.

MATHEMATICAL THEORY

Temperature Rise

From inspection of many sets of experimental data, the temperature at a given height rises abruptly from ambient to a maximum value, naturally suggesting a plume-like, Gaussian-shaped dependence as suitable and appropriate given the level of accuracy inherent in thermocouple data. This is supported by the theory of Yih (1969), who modelled the temperature rise ΔT for a large height z above and for a horizontal distance x away from the plume due to a stationary line source of heat

$$\Delta T = kI^{2/3} / z \exp(-x^2/\alpha^2 z^2) \qquad (1)$$

where k is a proportionality constant, I is the line fire intensity and x is the horizontal distance. A large height is necessary as the theory of Yih (1969) assumes a line heat source. The quantity α is an entrainment constant approximately equal to 0.16 (Lee and Emmons 1961). A wildland fire moving at a constant rate of spread U approximates a line source at position x=Ut so that we may recast equation (1) as

$$\Delta T = A / z \exp(-t^2/\beta^2 z^2) \qquad (2)$$

where $\beta = \alpha/U$, $A = k\, I^{2/3}$ and t = 0 at the time of maximum temperature. (Note that this equation with t=0 gives ΔT_{max} versus height and has been used by Thomas (1963) and Van Wagner (1973).) Thus t is negative prior to the arrival of the firefront.

Temperature Fall

From simple Newtonian theory, the cooling rate of a hot object is proportional to its temperature elevation above ambient

$$dT/dt = -\gamma\,(T - T_a) \qquad (3)$$

where γ is a constant for a given fuel. Integration of equation (3) yields the following expression for ΔT as a function of time

$$\Delta T = B \exp(-\gamma\, t) \qquad (4)$$

The obvious boundary condition is that B is equal to ΔT_{max} and thus B = A/z necessarily, where A/z was defined for the temperature rise. This behaviour should apply exactly to fires where the combustion residence time is negligible. From a fluid-mechanical analysis of the cooling phase, assuming idealized Newtonian cooling; a value for γ of order 0.1 is obtained. As seen later, this is much greater than the fitted values and is thus equivalent to much faster cooling than occurs in practice. Real wildland fires leave in their wake a trail of partially-combusted fuel, from smouldering ash through glowing coals to actively flaming logs. Therefore, γ obtained from a least-squares fit to data from such fires will be an effective cooling constant.

FITTING EXPERIMENTAL DATA

Temperature-time Dependence

A series of experiments has been performed in Ku-ring-gai Chase National Park, near Sydney, and at the CSIRO Kapalga Experimental Station in Kakadu National Park, Northern Territory. The Ku-ring-gai fuels were shrubby and varying in depth from 0.5 m to about 2 m (Weber *et al.* this publication), while the Kakadu vegetation consisted of mainly long dry grass, an intermittent shrubby understorey and eucalypts to about 15 m maximum height, Moore *et al.* (this publication).

Data from seven Ku-ring-gai fires and 20 Kakadu fires, obtained over a three-year period, were analysed. The temperature data were obtained from arrays of shielded Type K (chromel-alumel) thermocouples which were mounted on an aluminium mast and spaced between ground level and 9 m. For details of the Ku-ring-gai experiments the reader is referred to Bradstock and Auld (1994). In this paper we present only results at the 3.5 m and 6.0 m level above ground where the 1/z plume theory is more likely to apply and the moving fire appears more like a line source, so that equation (2) should be valid. Figures 1 and 2 show the results of fitting equations (2) and (3) to one of the Ku-ring-gai fires at 3.5 m and 6.0 m above ground level respectively. Both curves were constrained to pass through ΔT_{max}. Note the rapid rise in temperature to maximum (within 60 seconds) after the fire's onset, followed by a long, slow fall in temperature over more than 300 seconds following maximum temperature. However, at large positive values of time, temperatures tend to remain elevated above those predicted by the Newtonian cooling model. This behaviour is reflected in the fitted values for the cooling parameter which were 0.013 and 0.009 at the 3.5 m and 6.0 m levels respectively. These are an order of magnitude smaller than the theoretical Newtonian value of about 0.1. The fluctuations in ΔT which occur during cool-down probably correspond to small-scale flaring of fuel elements and also to slow fluid-mechanical pulsations connected with air entrainment.

Figures 3 and 4 depict the temperature-time history for a Kakadu fire, again for 3.5 m and 6.0 m above ground level. The scaling is quite different to that of the Ku-ring-gai fire yet the same qualitative behaviour is evident. Note that, as in Figure 2, the model *under-predicts* the decline in temperature as it is unable to accommodate prolonged smouldering or persistent localized combustion after the firefront has passed. The fitted value of γ was 0.016 at 3.5 m and 0.013 at 6.0 m. In both fires the fit around the peak is very good.

Total Time-above-temperature

The simple approach to predicting thermal death of plant materials in fires would be to take the length of exposure above certain temperatures and compare the results with those from constant temperature exposure in a furnace or water bath. Given experimental temperature data or fitted curves such as those in Figures 1 to 4, the total time for which a given value of ΔT is exceeded may be read directly off the graph. However, with a little algebra, we may express time above ΔT as a function of ΔT as follows:

From equation (2) the time above ΔT during which the temperature is rising is

$$t_r = \beta z\,(\ln(A/z\,\Delta T))^{1/2} \qquad (5)$$

From equation (4) the time above ΔT during which the temperature is falling is

$$t_f = (1/\gamma)\ln(A/z\,\Delta T) \qquad (6)$$

Therefore the total time above ΔT is

$$t_{tot} = \beta z\,(\ln(A/z\,DT))^{1/2} + (1/\gamma)\ln(A/z\,\Delta T) \qquad (7)$$

Fitted values of A, β and γ were inserted into equation (7) and the resulting curves are shown in Figures 5 to 8.

It is also possible to obtain an estimate of time above ΔT directly from the thermocouple data. This is fraught with problems as it requires an interpolation (by eye) between data points. However, in order to evaluate our method of fitting temperature-time curves, it seemed appropriate to compare the two methods of finding time above ΔT. Hence the data points on Figures 5 to 8, which exhibit the same trend as the curve from equation (7).

USING TIME ABOVE T TO ESTIMATE DEATH OF VEGETATION

Laboratory measurements of temperature-time exposures which cause leaf death usually come from bathing the sample in a constant temperature and measuring the time till death. This is not a true representation of the temperature exposure in a fire, due to many factors, including the variability in thermal environment associated with wildland fires and the different thermal properties of water and air, but, for obvious reasons, is the convenient experiment to perform. It provides curves like those in Martin *et al.* (1969), characterized by the equation

$$\ln t_d = a - b\,T, \tag{8}$$

where t_d is the time to death at an exposure temperature T.

A way in which these laboratory curves might be used together with our temperature-time relationship (equation (7)), to predict leaf death and other fire effects is given below. It is the heat flux and the ability of the vegetation to dissipate heat that governs the temperature rise of a sample. However, the flux is difficult (if not impossible) to estimate for a given fire, at a given height and time, even with temperature information. Hence, in the absence of detailed understanding of the fluid mechanics, we are forced into considering only the temperature information available to us.

We first notice that the lethal time at a constant temperature, T_{const}, will be more than the lethal time at a varying temperature, $T_{var}(t)$, where the minimum is always equal to, or greater than, T_{const}. It is then clear that we can perform a direct comparison of the time above a given temperature curve from a fire, with the death curves found in the laboratory. This provides a bound on the effects of the fire on vegetation. Namely, if the time-temperature curve is ever at a higher temperature than the death curve then the vegetation being considered will perish. However, if the death curve is always above the time-temperature curve we cannot be certain of the fate of the vegetation. These possibilities are shown together on Figure 9.

A better method to determine the fate of the vegetation, particularly in this uncertain zone, consists of the following. Divide the time-temperature curve into discrete temperature ranges and determine the time spent within a particular range. The ratio of this calculated time to the laboratory measured time to death at a representative time in the same range is then determined. This allows for both the heating and cooling phases that the vegetation is subjected to. If we assume additivity of these exposures then the sum of these ratios will give an indication of the likelihood of death. Mathematically this can be expressed as a death number, D,

$$D = \Sigma_i\, t(T_{i-1}<T<T_i) \,/\, t_d(T_i^*) \tag{9}$$

where $t(T_{i-1}<T<T_i)$ is the time spent in the temperature range (T_{i-1},T_i) and $t_d(T_i^*)$ is the laboratory-measured time to death of a representative temperature (T_i^*) in the range (T_{i-1},T_i). If the sum of these ratios, the death number, (D) is greater than 1, then death is likely, and if the sum is less than 1, then the vegetation is likely to survive. Of course, for values near 1, the outcome is still uncertain. The larger the number/closer together the discrete temperature ranges considered, and hence the narrower the temperature range, the more accurate this method will be. In the limit as the width of the temperature range tends to zero equation (9) can be rewritten

$$D = -\int_{\tau=T_a}^{\tau=T_{max}} \left((1/t_d) * dt(\tau)/d\tau \right) d\tau \tag{10}$$

which, using the model for the external temperature (equation (7)) and the model of Martin *et al.* (1969) for the time to death (equation (8)), gives the death number as

$$D = (\beta z/2 + 1/\gamma)\, e^{-a} \int_{\tau=T_a}^{\tau=T_{max}} e^{b\tau} / (\tau - T_a)\, d\tau \tag{11}$$

What is needed are the laboratory-measured time to death of the vegetation (leaves, fruit, stem) for as many different temperatures as possible to determine $t_d(T)$ and the external temperature profile either from experiments or the model detailed previously.

The fires considered here both have a maximum temperature well above 60°C and hence leaf scorch will occur at the heights in question. The effects of the fire exposure on the fruits and stems could be determined using the method outlined above. Unfortunately, at present the data needed to use equation (9) or to fit to the model of Martin *et al.* (1969) (equation (8)) to find $t_d(T)$ is not available in the literature. Recently Mercer *et al.* (1994) have used the model outlined here as the external temperature input to their model for the temperature exposure of seeds in woody fruits.

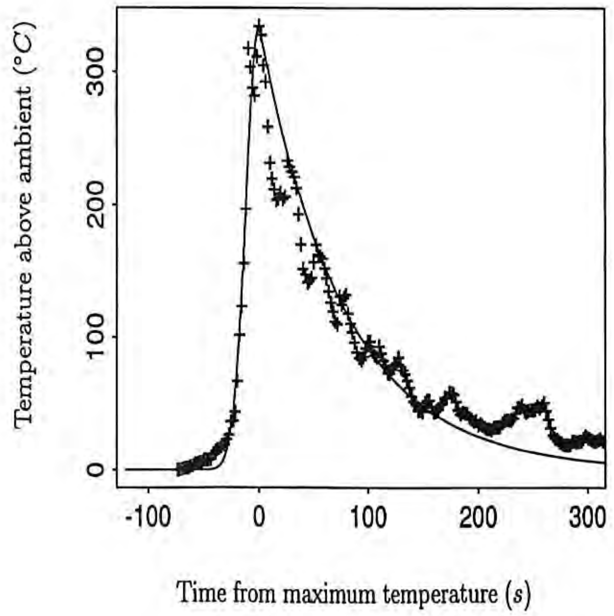


Figure 1. Temperature-time curve and data for the Ku-ring-gai fire at 3.5 m.

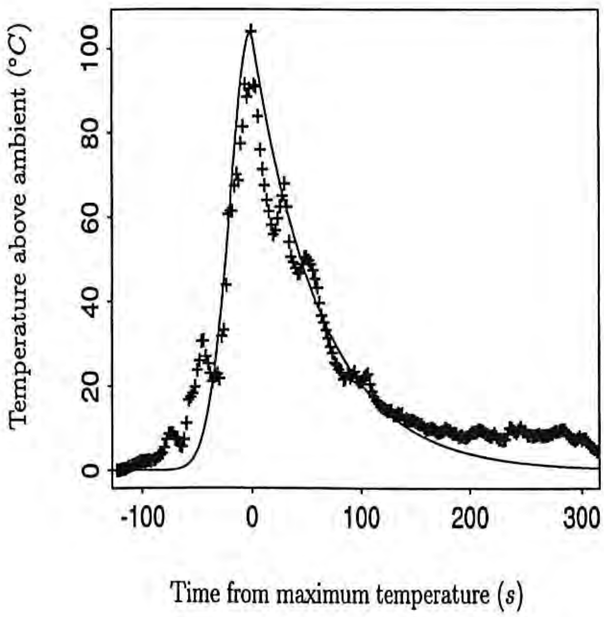


Figure 3. Temperature-time curve and data for the Kakadu fire at 3.5 m.

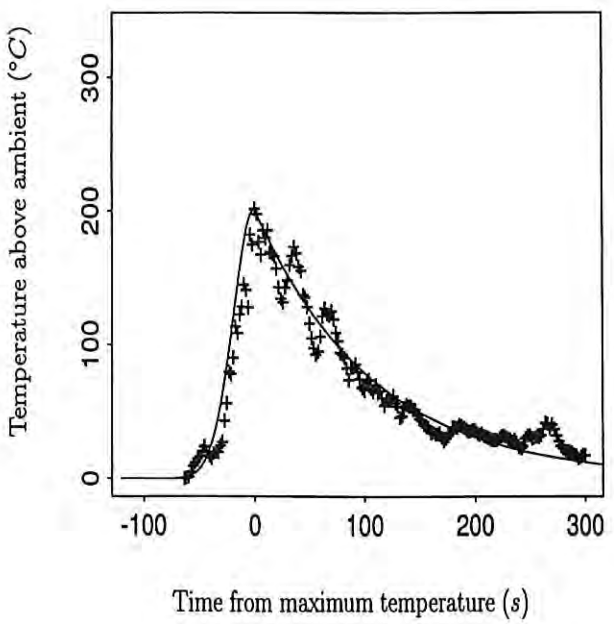
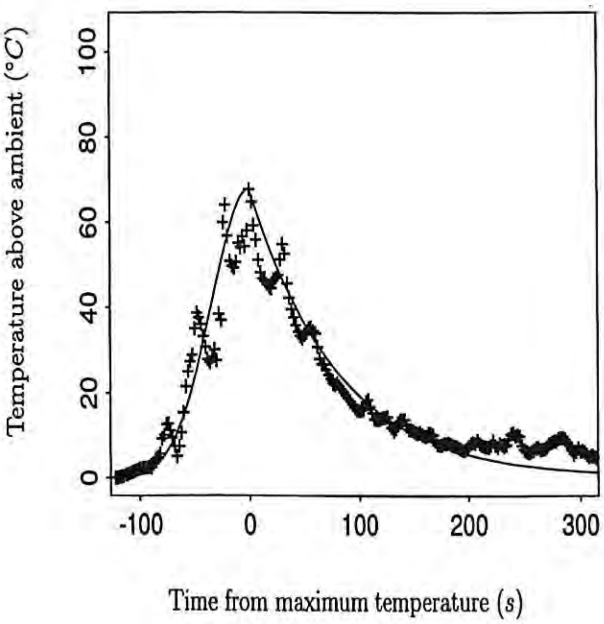


Figure 2. Temperature-time curve and data for the Ku-ring-gai fire at 6.0 m.



Figuer 4. Temperature-time curve and data for the Kakadu fire at 6.0 m.

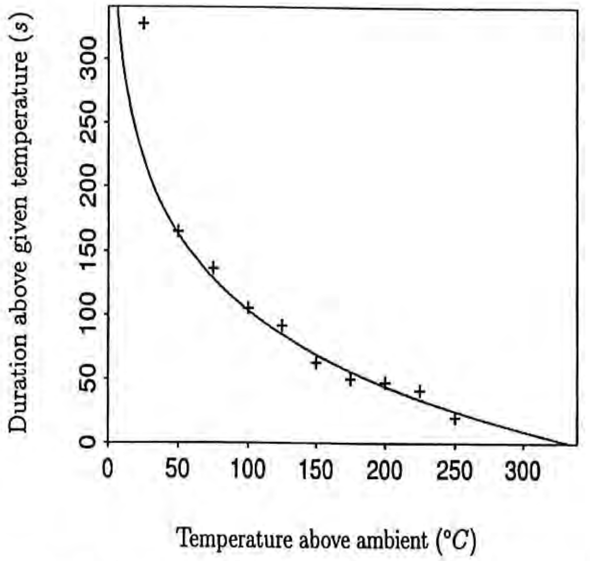


Figure 5. Duration of the fire above a given temperature for the Ku-ring-gai fire at 3.5 m.

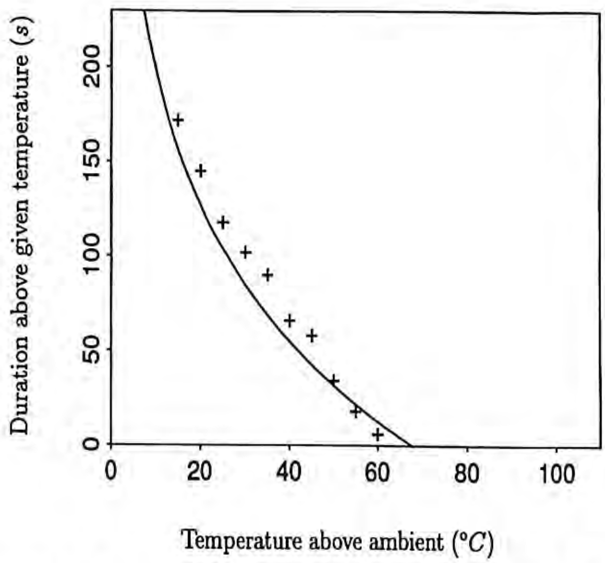


Figure 8. Duration of the fire above a given temperature for the Kakadu fire at 6.0 m.

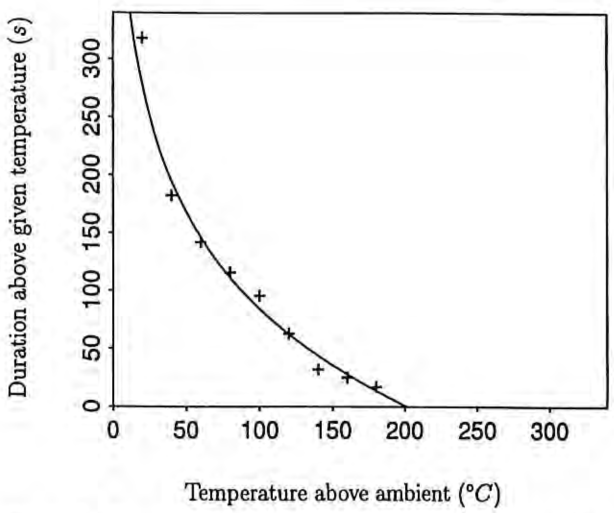
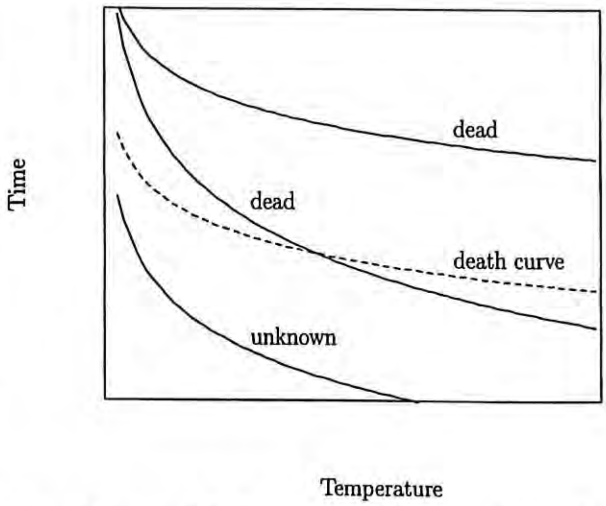


Figure 6. Duration of the fire above a given temperature for the Ku-ring-gai fire at 6.0 m.



Figuer 9. A typical death curve for vegetation and some of the possibilities for the time-temperature curves and the resultant effect on the vegetation.

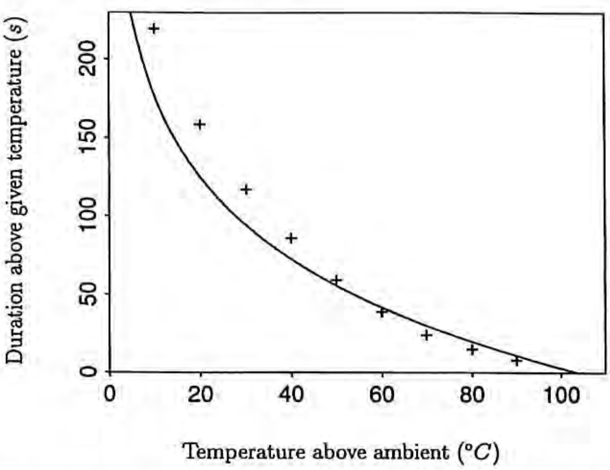


Figure 7. Duration of the fire above a given temperature for the Kakadu fire at 3.5 m.

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