CALMScience Supplement 4: 83-88 (1995)

Quantifying bushfires for ecology using two electronic devices and biological indicators

P. H. R. MOORE[1], A. M. GILL[1] AND R. KOHNERT[1]

[1] CSIRO Division of Plant Industry, GPO Box 1600, Canberra 2601, ACT.

ABSTRACT

The main fire input to models concerned with the ecological impact of fires on biota or soils is temperature, either as a critical instantaneous value or as a time sequence. An instrumented system for measuring temperature-time curves in fires is described. Based on shielded mineral-insulated thermocouples and a data logger, it has proven to be effective, rugged, reliable and portable in a wide range of vegetation types. This system is relatively expensive. To obtain more extensive coverage of fires, less expensively, and to also measure rates of spread of fires, a 'temperature-residence-time meter' (TRTM) has been developed. This meter records the times that temperatures persist over a chosen value. By analysing 106 temperature-time curves from near ground level during fires in woodlands and forests at Kakadu National Park, we have found that the durations of chosen high temperatures were statistically intercorrelated ($r>0.82$) but that the times to reach peak temperatures from 60°C (a measure of flame residence time) were poorly correlated with these durations ($r>0.40$). Both electronic devices have widespread application for studies of fire ecology. Selected botanical attributes may be used as post-hoc indicators of fire properties.

INTRODUCTION

While ecological effects of fires are the result of the interactions between ecosystem properties and fire regimes, immediate impacts of fires can be related to the severity of fires as measured by, for example, fire intensity. While fire intensity - a measure of rate of heat release - is a most useful measure of fires for ecological purposes, it is a correlative measure rather than an explanatory one. Explanatory models of immediate fire effects invariably use fire-induced temperatures as inputs. Why this is important is indicated by various temperature thresholds *approximating* critical levels for various processes to achieve particular significance:

- 60°C, denaturation of proteins, hydrated-cell death;
- 100°C, boiling point of water, temperature of thermal arrest, desiccation of tissues;
- 300°C, ignition temperature, decomposition of plant materials, charring of tissues;
- 500°C mineralization of organic matter.

In all cases, these thresholds vary somewhat and are affected by duration of exposure. In leaf-scorch models, an instantaneous value of temperature for leaf death has often been used (e.g. Van Wagner 1973) or assumed, while a model of bark death in *Eucalyptus* (Gill *et al.* 1986) used a 60°C temperature of cell death and the time the external bark temperature persisted above 100°C as inputs. Mercer *et al.* (1993) used a lethal temperature of 70°C for seeds (after Bradstock *et al.* 1993) and various forms of external time-temperature curves as inputs to a model for predicting the impact of fires on survival of seeds in woody fruits. In a soil model, Aston and Gill (1976) used a temperature-time curve at the surface as an input.

Measuring temperature-time curves at various positions in the fire or plume is important for the provision of suitable inputs to ecological models. Here we describe a means of measuring the temperature-time profile during fires. As well, we describe an instrument which measures periods of time its sensor experiences above-threshold temperatures while recording the times of arrival and departure of the fire. The times of arrival of fires at a number of sensors can be used to measure rates of spread of fires. Rate of spread is a critical component of intensity measurement. The profiling system allows intensive sets of measurements to be taken while the cheaper instrument measuring durations of elevated temperatures can be used to measure variation across landscapes. Interpreting fire conditions can be aided also by measuring biological attributes which are discussed below.

TEMPERATURE-TIME PROFILES

The temperature-time profiling system first developed by the authors during 1988 is an effective, rugged, portable, minimal cost, reliable system which is easily and quickly put in place in the field. It uses thermocouple sensors displayed in vertical and horizontal arrays connected to a buried data logger. The thermocouples chosen for routine use were stainless-steel sheathed, mineral-insulated, chromel-alumel thermocouples (Type K, from 'Pyrosales Australia') 1.5 mm outside diameter encasing insulated wires of 0.25 mm diameter. The system has been used successfully in fires with intensities up to nearly 20 000 kW m^{-1}. Using this system, temperatures have been measured during fires in heathlands, mallee, temperate forests and tropical woodlands.

Thermocouples, unlike paints or crayons, give the time course of temperatures. Gill and Knight (1991) pointed out that temperature measurement by thermocouple, strictly speaking, gives a 'thermocouple temperature' rather than a 'fire temperature' because there are likely to be non-equilibrium exchanges of heat taking place between fire and thermocouple. Using the same equipment each time allows legitimate comparisons to be made. However, caution in interpretation is needed when comparing temperatures from different sets of equipment.

A typical temperature-time curve produced from the instrument is depicted in Figure 1: it shows the usual rapid rise in temperature as the fire reaches the thermocouple and the slower decline in temperature associated with the passing of the flames. The example is from a height of about 10 cm but the usual deployment of the 9 thermocouples in the vertical direction is from near ground level to a height of 9 m.

The temperature-time profiling system has now been used for five years in Australian vegetation types. The system used has similarities to those used overseas by Bidwell and Engle (1990), and Jacoby *et al.* (1992). However, these instruments recorded temperatures up to only 3 m.

The temperature-time profiling system provides high quality data for a single profile in the fire but, as the system requires a data logger and computer, it is relatively expensive. Because fire attributes often vary widely from point to point within a fire, additional measurements that can be taken over a wider area and less expensively, would be useful. The temperature-residence-time meter (TRTM), described below, is a novel instrument that partly achieves this objective.

THE TEMPERATURE-RESIDENCE-TIME METER

'Residence time' is one time measure in the time-dependent weight-loss curve for fuel, a curve which reflects the heat generation rate of the fire. 'Residence time' has been defined as the period of flaming combustion (Cheney 1981). However, as mentioned above, ecological studies may be concerned with times above certain temperatures, if not the details of the temperature-time curve, and these temperatures may be influenced by charring combustion and residual heat in the environment. Rothermel and Deeming (1980) suggested that the flame-residence time is equal to the time from initial temperature rise to the time of 'definite drop' following attainment of peak temperature whereas the temperature-residence times are longer (Fig.1). The TRTM's measure the time registered by the thermocouples above a certain defined temperature as well as rates of spread of fires.

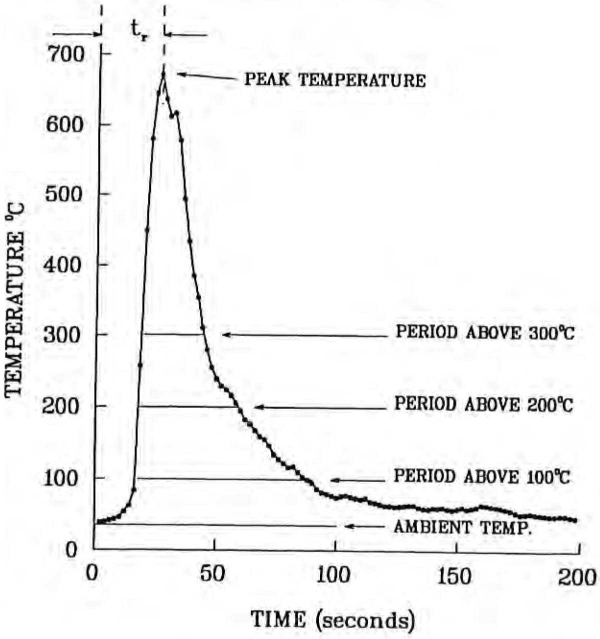

Figure 1. A typical temperature-time curve for surface fires. 'Time' is the elapsed time from the first rise above ambient. t_r *is the flame residence time (Rothermel and Deeming 1980).*

The TRTM, is a small instrument that is buried in soil with a thermocouple sensor exposed above ground in the path of a fire; it records the times of fire arrival at, and departure from, the sensor. The prototype was developed in 1988. By having three or more meters laid out in triangles (Simard *et al.*1984), rates of spread can be calculated from the arrival times of the fire at the apices of the triangles.

The fire meter is comprised of a small plastic box (12 cm *x* 6.5 cm *x* 4 cm.) incorporating a digital stopwatch and electronic circuits, a connector for a detachable thermocouple, and external electronic contacts (for batch battery charging of meters in a 'holding box' and for synchronizing the starting and resetting of all meters). The detachable thermocouple consists of 1 m of thermocouple wire on a 60 cm lead of thermocouple extension wire.

The meter is triggered (on or off) by a thermocouple-generated voltage equivalent to an approximate thermocouple temperature of 200°C. This thermocouple temperature was chosen as being high enough to avoid triggering the meter in air and appropriate to indicate the presence of flames when placed 10 cm above the ground. The threshold level is 'approximate' because '200°C' really represents the difference in temperature between the exposed thermocouple and the cold junction buried in the soil; the error due to variation in soil, and cold-junction, temperature is relatively small. The threshold temperature can be adjusted to the user's specifications.

The thermocouples chosen for routine use were the same as those used for the temperature-time-profiling system. They were effective, rugged and reliable. Fused bare-wire thermocouples of the same 0.25 mm diameter continually broke down, short circuited or turned the instruments off prematurely (due to their sensitivity to cooler-air pulses within the fire as the flames died down). A finer-drawn version of the sheathed thermocouple with a 1 mm outer diameter was found to be satisfactory in terms of ruggedness and reliability on most occasions but there were more breakdowns with this than with the larger-diameter version. Because of the detachable nature of the thermocouples, users can choose the thermocouple most appropriate to their particular needs.

TRTM is a reliable, relatively inexpensive, portable, reusable instrument suitable for grass and litter fires of intensities up to at least 18 000 kW m^{-1}.

We have analysed 106 temperature-time curves from thermocouples placed 5 to 10 cm above ground during fires in woodlands and forests in Kakadu National Park. The durations of temperatures above 60, 100, 200, 300 and 400°C were all intercorrelated with statistically significant correlation co-efficients between 0.82 and 0.96. The period from the time the thermocouple reached 60°C to the time it reached peak temperature - a measure of flame-residence time - was highly significantly correlated with the other times recorded above but with the relatively low correlation coefficients between 0.40 and 0.54. Thus, there is a trend indicated between 'flame residence time' and 'temperature residence time' but prediction of one from the other on the basis of these measurements is inappropriate.

For rate of spread measurement, the TRTM, is a development of the instrument reported by Blank and Simard (1983). The latter workers used a piece of solder to sense the fire (by melting). TRTM may be reused without sensor replacement, is easier to read, and has greater reliability and sensitivity than Blank and Simard's instrument; it is more expensive but still of a reasonable cost.

FIRE INTENSITY AND TEMPERATURE

Fire intensity has become a standard variable to measure in studies of fire ecology so it is of interest to examine the relationship between intensity and temperature. Intensity is a measure of the rate of heat release per length of fire-line (fire-line intensity, I_B, Byram 1959) or burning area (reaction intensity, I_R, Rothermel 1972).

$$I_R=I_B.d$$

where d is the flame depth.

$$I_B=H.w.r$$

where I_B is the intensity in kW m^{-1}, H is the heat of combustion in kj kg^{-1}, w is the fuel loading in kg m^{-2} and r is the rate of spread in m sec^{-1}.

Current theory links intensity, I, and peak temperature of the temperature-time curve, T_m, at different heights, z, but only in the plume well above flames (Yih 1952; Van Wagner 1973):

$$T_m - T_a = k(I^{0.67}/z)$$

where T_a is the ambient temperature and k is a constant. Recent work by Weber *et al.* (1993) examines the problem of extending equations to the prediction of temperatures in the flaming zone. The relationships in the equation above appear to have limited value for ecological studies because of their applicability to the plume of the fire only and because temperature duration is not predicted. However, in the above-mentioned studies by the authors at Kakadu National Park, correlations between peak temperatures and durations of temperature above 60, 100, 200, 300 and 400°C in the 106 curves analysed were statistically significant with correlation coefficients between 0.64 and 0.82.

BIOLOGICAL INDICATORS OF TEMPERATURES

Post-hoc indicators of fire severities for ecological studies are useful because fires may occur unexpectedly in study areas and intensity limits to fire control (Luke and McArthur 1978) may limit experimentation. The 'indicators' can be the items of interest to the ecologist but to put the situation into a management context may require a knowledge of the links between fire properties and the 'indicators' themselves. Common indicators are height of leaf scorch (Fig.2) while less commonly considered are thickness-profiles of bark lost from smooth-barked trees (Fig.3; Gill 1981) and heights of leaf char (Fig.4). Diameters of live stems consumed by fire at different heights provides another indicator (Fig.5). When considering biological indicators it is important to remember that, apart from the fire itself, immediate prefire tissue temperatures and moisture contents and species effects may be important in determining the observed results.

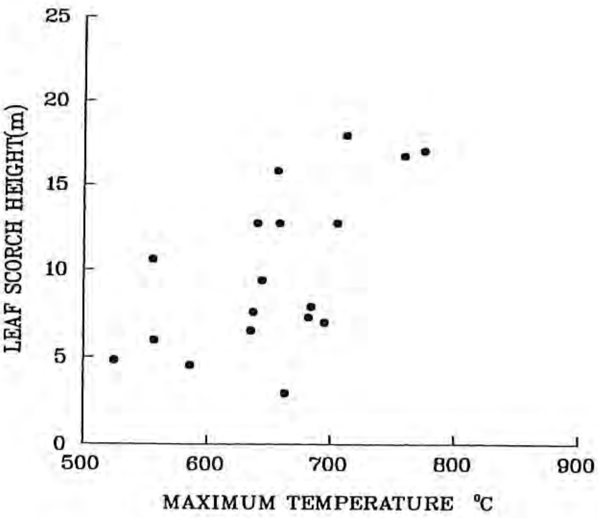

Figure 2. Maximum height of leaf scorch as a function of maximum temperature reached in temperature-time profiles during fires at Kakadu National Park in 1990-1991.

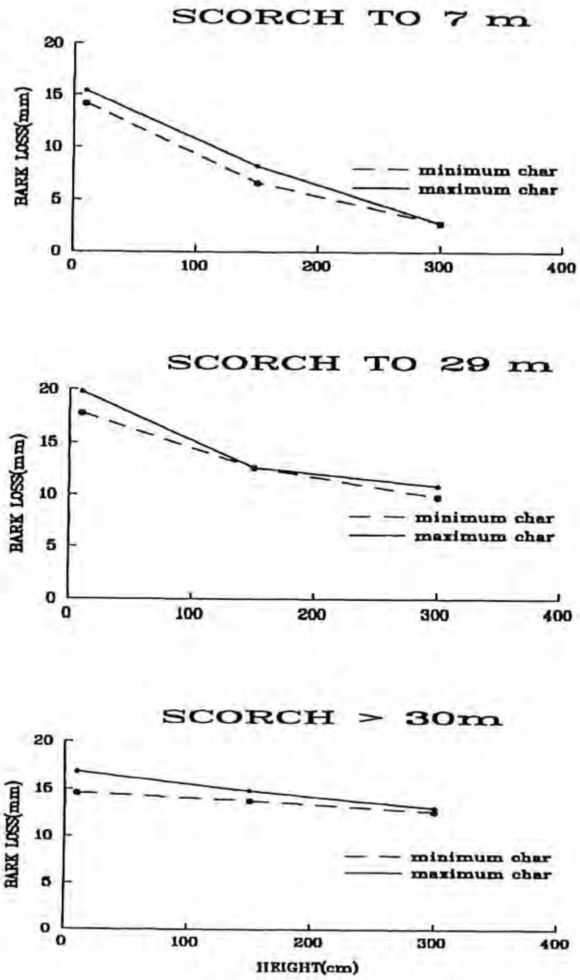

Figure 3. Thicknesses of decorticated bark as a function of sample height on mature smooth-barked trees following fires. The examples, all from south-eastern Australia, were chosen to show bark losses in fires producing a range of scorch heights.

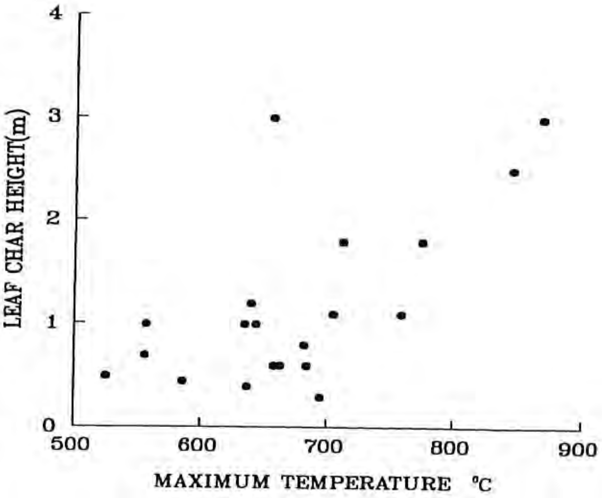

Figure 4. Maximum heights of leaf charring as a function of maximum temperature reached in temperature-time profiles during fires at Kakadu National Park in 1990-1991.

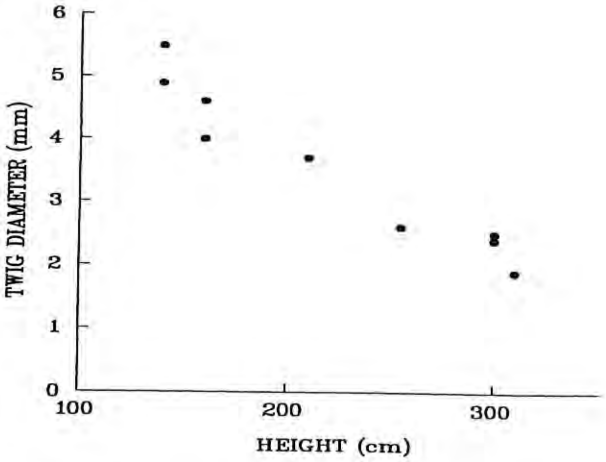

Figure 5. Diameters of live stems, twigs or branches of mallee eucalypts consumed by fire at various heights during fires at Yathong Nature Reserve, New South Wales, December 1991.

CONCLUSIONS

Two useful instruments with widespread application have been described and thoroughly tested. The temperature-time-profiling system measures profiles of temperatures for the duration of the fire. The temperature-residence-time meter measures the times of arrival and departure of a fire at a thermocouple sensor and records the duration of exposure of the sensor above a threshold value. From triangulated TRTM measurements, the rate of spread of a fire can be measured. The authors have found the instruments to be rugged, reliable, portable and effective. In the absence of such instruments, biological indicators may be used but their study is in it's infancy.

ACKNOWLEDGEMENTS

We would like to thank Dr R.Bradstock and Dr G.Mercer for their comments on a draft manuscript. Mr Bruce Condon generously assisted with the design of the electronics for the TRTM.

REFERENCES

Aston, A.R. and Gill, A.M. (1976). Coupled soil moisture, heat and water vapour transfers under simulated fire conditions. *Australian Journal of Soil Research* **14**, 55-66.

Bidwell, T.G. and Engle, D.M. (1990). Behavior of headfires and backfires on tallgrass prairie. *US Department of Agriculture Forest Service General Technical Report* SE-69, 344-350.

Blank, R.W. and Simard, A.J. (1983). An electronic timer for measuring spread rates of wildland fires. *US Department of Agriculture Forest Service Research Note* NC-304, 4p.

Bradstock, R.A., Gill, A.M., Hastings, S.M. and Moore, P.H.R. (1994). Survival of serotinous seedbanks during bushfires; comparative studies of *Hakea* species from southeastern Australia. *Australian Journal of Ecology* **19**, 276-282.

Byram, G.M. (1959). Combustion of Forest Fuels. In: Davis, K.P. (Ed.). *Forest Fire: Control and Use.* McGraw Hill, New York. pp. 61-89.

Cheney, N.P. (1981). Fire behaviour. In: Gill, A.M., Groves, R.H. and Noble, I.R. (Eds). *Fire and the Australian Biota.* Australian Academy of Science, Canberra. pp. 151-175.

Gill, A.M. (1981). Coping with fire. In: Pate, J.S. and McComb, A.J. (Eds). *The Biology of Australian Plants.* University of Western Australia: Nedlands, Western Australia. pp. 65-87.

Gill, A.M. and Knight, I.K. (1991). Fire measurement. In: Cheney, N.P. and Gill, A.M. (Eds). *Conference on Bushfire Modelling and Fire Danger Rating Systems. Proceedings 11-13 July 1988, Canberra. CSIRO, Melbourne.* pp. 137-146.

Gill, A.M., Cheney, N.P., Walker, J. and Tunstall, B.R. (1986). Bark losses from two eucalypt species following fires of different intensities. *Australian Forest Research* **16**, 1-7.

Jacoby, P.W., Ansley, R.J. and Trevino, B.A. (1992). Technical note: an improved method for measuring temperatures during range fires. *Journal of Range Management* **45**, 216-220.

Luke, R.H. and McArthur, A.G. (1978). *Bushfires in Australia.* Australian Government Publishing Service, Canberra.

Mercer, G.N., Gill, A.M. and Weber, R.O. (1994). A time dependent model of fire impact on seeds in woody fruits. *Australian Journal of Botany* **42**, 71-81.

Rothermel. R.C. (1972). A mathematical model for predicting fire spread in wildland fuels. *USDA Forest Service Research Paper* INT-115, 40p.

Rothermel, R.C. and Deeming, J.E. (1980). Measuring and interpreting fire behavior for correlation with fire effects. *United States Department of Agriculture Forest Service General Technical Report* INT-93, 4p.

Simard, A.J., Eenigenburg, J.E., Adams, K.B., Nisse, R.L. and Deacon, A.G. (1984). A general procedure for sampling and analysing wildland fire spread. *Forest Science* **30**, 51-64.

Van Wagner, C.E. (1973). Height of crown scorch in forest fires. *Canadian Journal of Forestry* **3**, 373-378.

Weber, R.O., Gill, A.M., Lyons, P.R.A., Moore, P.H.R. and Bradstock, R.A. (1993). Modelling wildland fire temperatures. (Preprint)

Yih, C.S. (1952). Free convection due to a point source of heat. *Proceedings of 1st U.S.National Congress of Applied Mechanics.* pp. 941-947.