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Fire from a flora, fauna and soil perspective: sensible heat measurement

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ABSTRACT

The two main areas of interest in landscape fires are the protection of human life and property, and the ecological effects of fire regimes. The protection of human life and property involves the provision of adequate fire prevention and suppression strategies and requires an understanding of aspects of fire behaviour such as rate of spread, flame height and fire intensity. However, an understanding of the ecological effects of fire is as complex as the different ecological systems themselves. In this paper I address the issue of characterizing fires in a way that will help forest managers to predict the likely effects of a fire on a forest community under different environmental conditions.

Three methods of measuring the sensible heat output from different fires, the billy calorimeter, the heat sensitive plate and scorch height are presented. Sensible heat is defined as the integration of heat in the forms of radiation, convection and conduction resulting from a fire and the environmental conditions at the time of the fire. The fire behaviour and environmental factors affecting the sensible heat flux measured are explored. Measures of sensible heat are used to correlate the effects of fire on tree boles, soil chemistry and soil invertebrates. The usefulness of these measures as measures of the ecological effects of fire are discussed.

It is concluded that sensible heat output from a fire is a key criterion for determining the effect of individual fires on flora, fauna and soils.

INTRODUCTION

The need to control and use fire in natural and cultivated landscapes has led to an interest in describing fires and the conditions under which they occur. However, as Van Wagner (1965) pointed out, the subjective nature of fire descriptions made it nearly impossible to compare different fires in different places and at different times described by different people. Byram (1959) significantly advanced fire research by proposing a measure of fire intensity which combined the heat of combustion of the fuel burnt, the amount of fuel burnt and the rate of spread of the fire front. At last here was an objective measure of fire behaviour which described the rate of energy output along a given length of the fire front. Over the past 30 years Byram's fireline intensity has been used as an essential descriptor of any fire being studied for research purposes, but is less commonly used by fire managers or fire fighters. However, by itself, Byram's fireline intensity does not give a complete picture of fire behaviour from a fire controllers point of view nor a fire ecologists point of view (Tangren 1976).

Fire controllers are interested in aspects of fire behaviour such as its intensity, its rate of spread, spotting distance and flame height, and while fire ecologists are also interested in fire intensity, they are also interested in the total amount of heat output, the duration of the heating, the moisture conditions of the soil and vegetation (alive and dead) and the general fire regime. McArthur and Cheney (1966) suggested that fire intensity, duration of heating, and the proportion of fuel available at the time of the fire were important fire characteristics needed to adequately describe a fire for ecological studies. While this may be true, nearly 30 years later, our ability to relate the effects of fire on flora, fauna and soils is coarse and crude. This is firstly due to the complexity of the interactions between the physiological state of plants and animals at the time of a fire, with the fire, and secondly the variability of fire, soil, plants and animals within even a small area of a bushfire. For this reason this paper will focus on some measures of sensible heat output from bushfires which integrate many of the variables involved in the ecological effects of fire.

The idea of a sensible heat measuring device in the flaming zone of the fire was first reported by Martin (1963). Martin used roasting dishes set at one foot (0.3 m) and four feet (1.2 m) above ground level to measure the heat load of a forest fire. No results from these calorimeters were recorded. Later Beaufait

(1966) used one gallon (4.5 L) paint tins filled with 3 L of water, painted black on the outside and fitted with a lid with a 1 cm hole in the middle, to measure the amount of heat transferred to the calorimeter by measuring the amount of water lost through evaporation and the rise in temperature of the water remaining in the calorimeter. Beaufait reported that there was a wide variation in response to different fires, but did not report on how the output was being used. Knight (1981) described a development of another calorimeter, the billy calorimeter, which used a sensing device to record the duration and rate of heating (heat flux) as well as the total heat load. However, Knight found that the main factor affecting trees and vegetation were related to the increase in temperature of the billy rather than the rate of increase. As with Beaufait's billy, Knight found that the billy temperature was related to the amount of fuel burnt (and hence the total heat output) rather than the fire intensity.

Heat-sensitive materials have been used to measure the sensible heat below the flaming zone. These materials undergo recognizable and irreversible changes and offer a cheaper and more convenient alternative to the use of thermocouples (e.g. Raison *et al.* 1986) or other electrical sensing devices (e.g. Hodgkinson *et al.* 1982). In addition, heat sensitive materials are more easily placed in many locations within the one fire and can give a good spatial measure of temperature variability (Hobbs *et al.* 1984).

Some of the first quantitative work on the impacts of fire was done by Beadle in 1940. Beadle used organic compounds with different melting points in glass tubes to determine the maximum temperature reached by the soil subjected to a surface fire. He measured the temperature profile in the soil by placing these tubes at various depths. From the results of this work and a knowledge of the heating effect on lignotubers and seeds, he was able to predict the effects of different fires on the regeneration process.

Fire ecologists are usually interested in the time/ temperature profile of the soil during and after a fire. A number of well known changes take place depending on the temperature reached by the soil and these are summarized in Walker *et al.* (1986). Temperatures between ambient and 125°C usually affect biological activity in the soil, between 200°C and 600°C affect the soil chemistry and temperatures greater than 600°C affect the physical nature of the soil. Usually, a moving fire only affects the top 1 to 3 cm of the soil (e.g. Tomkins *et al.* 1991; Raison *et al.* 1986), but a stationary fire such as a burning log pile can have an affect more than 30 cm deep (e.g. Tunstall *et al.* 1976; Cromer and Vines 1966).

Three methods of measuring sensible heat are discussed in this paper: the billy calorimeter, the heat sensitive plate and scorch height. Results are presented of measurements made in 35 low intensity fires (< 500 kW.m^{-1}) in mixed eucalypt forest in the foothills of north-central Victoria. Each of the three methods is discussed in turn.

METHODS

This work was conducted as part of the Fire Effects Research Program in the Wombat State Forest, Victoria. A detailed description of this study and its component projects can be found in Tolhurst and Flinn (1992).

Site Description

There are five study areas located on the Great Dividing Range within the Wombat State Forest which is 80 km north-west of Melbourne, Victoria (latitude 37°25', longitude 144°15'). The elevation of the study areas ranges between 550 m and 730 m. The average annual rainfall is 890 mm with at least 30 mm falling in each month of the year and about 70 per cent falling in winter and spring. Air temperatures in the region are cool, with average monthly temperatures being less than 6°C for three months of the year (June, July and August) and about 15°C in summer, although maximum temperatures may exceed 37°C in summer. The study areas are in forest comprising Messmate (*Eucalyptus obliqua* L'Herit), Candlebark (*Eucalyptus rubida* Deane & Maiden), and Narrow-leaf Peppermint (*Eucalyptus radiata* Sieber ex DC) in the approximate ratio 5:3:2 respectively. The soils are yellow podzols derived from Ordovician sedimentary rocks.

Instrument Description

The Billy Calorimeter used in this study was based on the design of Knight (1981). The billy was a 3 L 'Milo' tin, painted with matt black paint on the outside and with a temperature sensing device inserted through the base of the billy. A lid was placed on the billy and water in the billy was kept stirred with a toy boat motor and propeller assembly powered by a single AA sized battery. The temperature sensing device in the billy was an analogue device (AD590) connected in series with a 10 k resistor and a 9 V transistor battery which gave a 10 mV change in output for each 1°C change in temperature. A cable was run underground from the billy to a safe area outside the plot where the changes in voltage (temperature) were manually recorded by reading the voltage across the resistor with a multimeter. The necessity of burying the cable limited the distance from the fire edge to the recorder to about 30 m. Later, after much trouble, an electronic circuit was designed to convert the voltage output from the billy to a frequency which was then sent via a frequency modulated (FM) transmitter to a radio receiver with another circuit which converted the frequency signal back to a voltage which was measured up to 150 m away from the fire's edge.

The heat sensitive plates were made from 0.3 mm thick aluminium flashing. The flashing was roughened with sandpaper on one side and a series of Thermochrom crayons (Faber Castell) were marked on the plate. The plate was then folded in two and hammered flat to ensure no blackening of the marked surface could occur in the fire. The performance of the crayons was tested in a muffle furnace and an interpretation chart was designed for estimating the temperature and duration of heating to which the plates were exposed (Appendix 1). The final plate measured approximately 5 cm x 12 cm. Earlier laboratory studies by the author had shown that the use of ceramic tiles as a carrier for the crayons significantly increased the time necessary for the a crayon to change colour, and when the tile was wrapped in aluminium foil as would be necessary for use in a fire situation, this time was increased further. Aluminium flashing has a lower heat capacity and better conducting properties than a ceramic tile and was found to satisfy our needs.

Treatments and Measurements

The results presented here are from experimental fires on 20 plots (4 at each of the 5 study areas) covering an area 35 m x 35 m. Each plot was within a larger fire area ranging in size from 3 ha to 35 ha (15 ha average). A 40 m line of fire was ignited downwind and/or downslope of the plots to achieve a headfire through the plot. Table 1 summarizes the fire behaviour and weather conditions. Some plots were burnt three times over a six-year period.

Fifteen fine fuel samples (< 6 mm) were collected before and after burning from 0.1 m^2 quadrats on each plot, oven dried at 105°C, and weighed to determine the fuel load and the amount of fuel burnt. Fire behaviour observations were made at 15 or more predetermined locations within each plot marked with a 1 m high post. Rate of spread was measured between each reference point, flame height was visually estimated and flame angle was measured from photographs taken as the fire front passed each point. Rate of spread, flame height, and flame angle were recorded at each of these points and then averaged for the plot. Fine fuel moisture contents were measured about every 30 minutes for the duration of the fire using a Marconi Moisture Meter (electrical resistance type meter). Weather conditions were measured and recorded at a permanent automatic weather station in the open and within 2 km of the fire and supplementary readings were taken in the forest during the course of the fire.

Two billy calorimeters were setup within the plot to be burnt. The billies were placed in a representative fuel-bed about 10 m inside the plot boundary. The billies were placed on the soil surface and a cable from the temperature sensing device was buried to about 2 cm below ground level in a slot made with a spade, perpendicular to the anticipated direction of the fire. The cable was buried until it reached outside the plot area to a safe site for an observer. Changes in the temperature of the billies were recorded manually. Care was taken to cause minimal disturbance to the fuel-bed when the billies were set up.

TABLE 1
Fire behaviour and weather conditions during the course of this experiment (n=35).

FIRE BEHAVIOUR VARIABLES	MEAN	MAXIMUM	MINIMUM
Forward rate of spread (m.h^{-1})	35	150	5
Fine fuel load before fire (t.ha^{-1})	14.7	20.9	9.5
Fine fuel load after fire (t.ha^{-1})	7.5	12.3	4.2
Intensity (kJ.m^{-1})[a]	169	556	25
Heat output (MJ.m^{-2})[b]	15.2	31.1	3.7
Flame height (m)	0.38	0.86	0.11
Scorch height (m)	5.6	12.5	1.6
Fuel moisture content (% oven dry weight)	12.7	17.0	9.0
Proportion of fuel burnt (%)	51	73	14
WEATHER VARIABLES			
Air temperature (°C)	18	24	11
Relative humidity (%)	52	75	28
Wind speed at 10 m in open (km.h^{-1})	11.9	25.8	0.6
Drought factor[c]	7.3	10.0	3.8
Soil dryness index[d] (mm equiv.)	48	136	8
Keetch Byram drought index[e] (mm equiv.)	17	102	3

[a] Fire-line intensity (Byram 1959)

[b] Heat output = available fuel energy (Byram 1959)

[c] Proportion of fine fuel available (McArthur 1973)

[d] Mount (1972)

[e] Keetch and Byram (1968)

Twelve heat sensitive plates were inserted between the fuel bed and the soil surface at uniformly spaced locations across the plot on the day of the fire. These plates were collected for analysis after the burnt area had cooled.

The upper limit of the visible scorch was measured on every scorched tree within a plot a few days after the fire. A fibreglass tape and Suunto clinometer were used to measure scorch heights. The average scorch height on a plot was used in this analysis.

The diameter of all regrowth trees and their bark thickness were measured near ground level on the burnt plots at least three to nine months after the fire. The trees were recorded as alive or fire-killed. Diameters were measured with a diameter tape and bark thickness was measured at four places around the circumference using a Gill-type bark probe (Gill *et al.* 1982). This was only done after the first rotation fires because there were insufficient trees killed by the second and third rotation fires.

Analysis

Tree diameter was plotted against bark thickness of all trees measured noting those that had died. An example of such a graph is shown in Figure 1. The threshold level of diameter and bark thickness was read off these graphs and used for the correlation and regression analysis with the billy parameters, fire behaviour variables and weather variables.

The temperature time curve of each billy calorimeter was plotted. Five parameters were determined from these curves, two of them (T_{max}, T_t) were related to the increase in temperature of the billy above the initial temperature, one (t) was the time duration of a rise in temperature at a rate greater than 1.2°C.min^{-1} and the other two (r_1 , r_2) were related to the rate of temperature increase as defined in equations (1) and (2). Most temperature time curves followed the form of equation (1) but some followed equation (2). The parameters for equation (1) were determined for each billy measurement using a line of best fit approach and the parameters for equation (2) were determined where this was the best model. These six parameters were tested for linear correlation (Pearson's) with the diameter and bark thickness of the trees killed by the fires, and for correlation with the other fire and weather variables measured. A stepwise multi-regression was used to test the correlation of the diameter and bark thickness of the killed trees with the billy parameters, fire behaviour variables and weather variables.

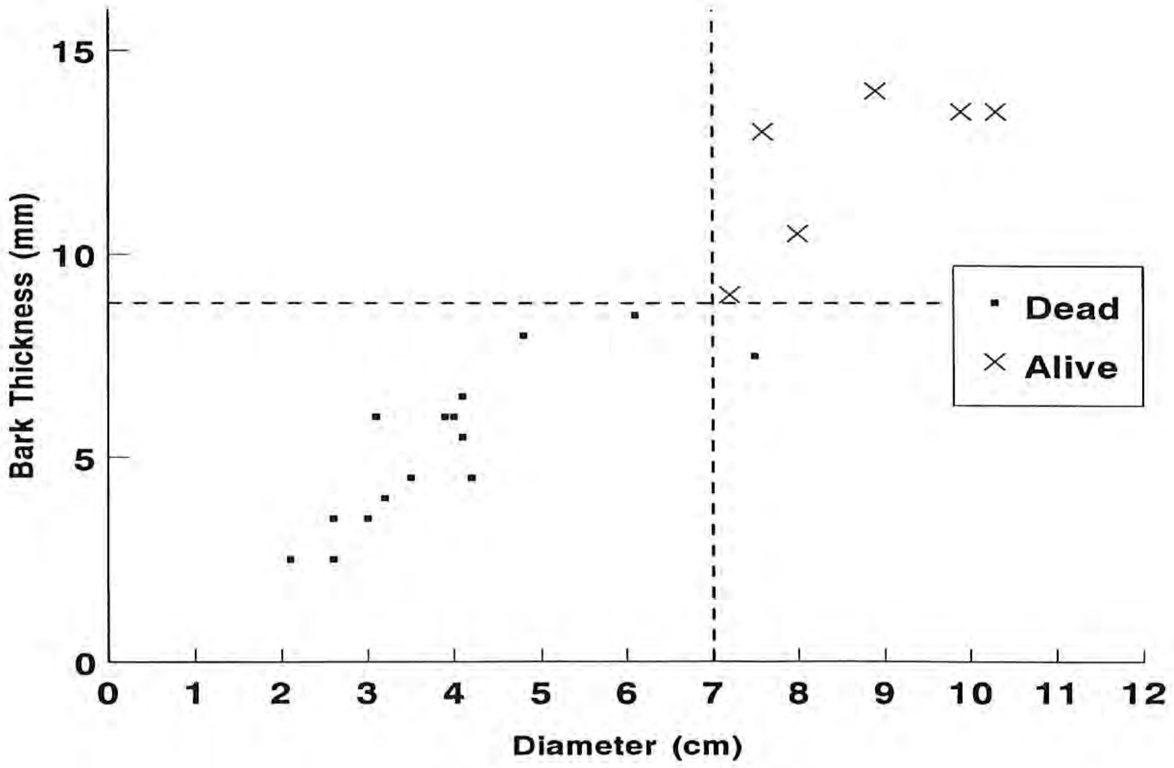


Figure 1. An example of bark thickness plotted against diameter of all trees measured on a burnt plot (35 m x 35 m) showing the delineation between the dead and alive trees and the threshold bark thickness and diameters for that particular fire. The majority of these trees were Narrow-leaf Peppermint (E. radiata).

$$T_t = \frac{T_{max}}{1 + \left(\frac{T_{max}-0.5}{0.5}\right) e^{-r_1 t}} \quad \text{.........} \ (1)$$

$$T_t = T_{max}\,(1 - r_2^{-t}) \quad \text{..........} \ (2)$$

where: T_t = temperature a time t (°C)
T_{max} = maximum increase in temperature above ambient (°C)
t = time (minutes)
r_1,r_2 = rate of increase in temperature (°C.min^{-1})

The maximum temperature reached by each heat sensitive plate was determined and recorded. A graph of the proportion of plates reaching various temperatures was drawn. The mean, maximum and minimum temperature reached by a plate within each plot was recorded. The mean temperature of the plates was tested for correlation with the effects of the fire on the legume seedlings, invertebrates and soils.

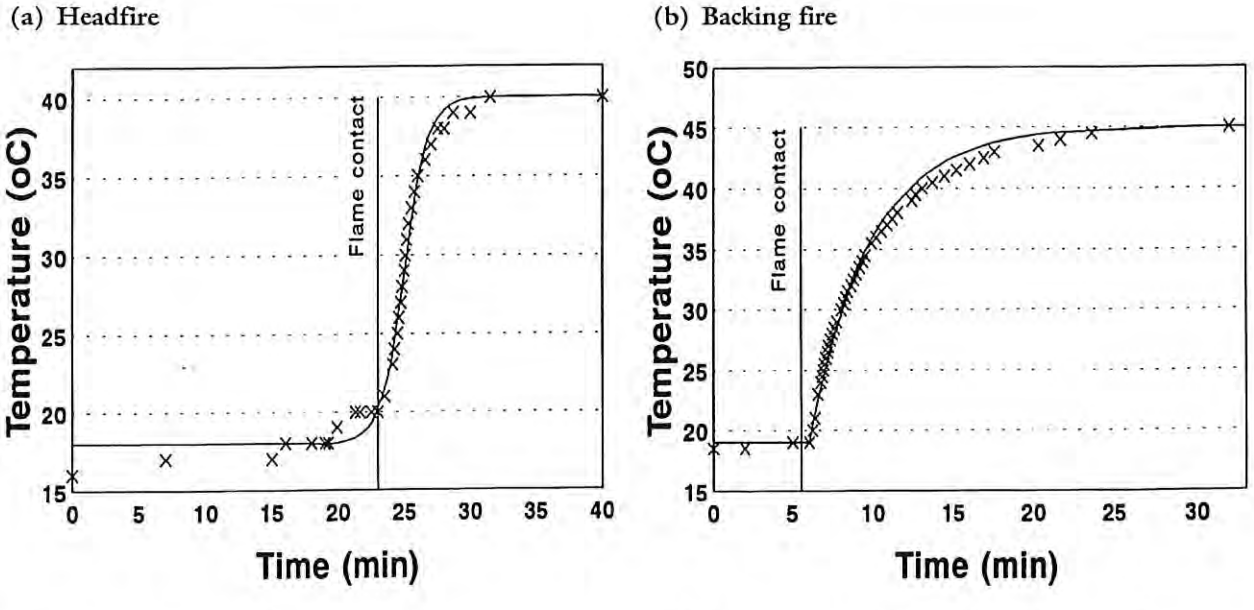
RESULTS

Billy Calorimeter

The temperature time curves of the billy calorimeter followed two distinctive patterns. The first was described by the logistic equation (equation (1)), where the fire affecting the billy was predominantly a headfire with forward leaning flames (flame angle < 90°) and the second pattern was described by an asymptotic inverse log relationship described by equation (2) where the fire affecting the billy was predominantly a backfire with flames leaning away for the billy (flame angle > 90°). Examples of each of these are shown in Figures 2a and 2b respectively. In the logistic model, the temperature of the billy started to rise 2-3 minutes before the flames came in contact will the billy and rose steeply soon after the flames surrounded it. In the asymptotic inverse log model the temperature increase did not start until nearly half a minute after the flaming front had come in contact with the billy after which the rate of temperature increase was rapid and then decreased gradually.

The duration of temperature increase at a rate at least 1.2°C.min^{-1}, averaged 6.1 minutes (se=0.44, n=59), but lasted for up to 14 minutes, which was long after the flaming front had passed. This duration of heating tended to be shorter for headfires ($\bar{x}$=5.7 min., se=0.53, n=43) and longer for the backfires ($\bar{x}$=7.0 min., se=0.65, n=16), but this difference was not statistically significant.

The linear correlations between the diameter and bark thickness of the trees killed by each fire are given in Table 2. The only correlation that is significant is that between tree diameter and the increase in temperature above ambient (T_{max} in equations (1) and (2)). T_{max} was most strongly correlated with the total heat output from the fire (Pearson's correlation coefficient = 0.44, Pr = 0.0004) which is directly related to the amount of fuel burnt. The heat output of the fire was more strongly correlated to the diameter of the trees killed than the temperature increase in the billy, T_{max}, (Pearson's correlation coefficient of 0.73, Pr = 0.0001).


(a) Headfire

(b) Backing fire

Figure 2. An example of the temperature time response curve for a billy calorimeter (a) in front of a headfire, and (b) in front of a back fire. The observed points are marked individually (x) and the predicted models are shown as a solid line (—) (a) is equation (1) and (b) is equation (2).

TABLE 2

Pearson's linear correlation coefficient between the threshold tree diameter and bark thickness of trees killed by fire. The probability of the correlation being greater than zero is given in brackets and n=33 for all correlations.

	TEMPERATURE INCREASE ABOVE AMBIENT (T_{max})	DURATION OF HEATING AT 1.2°C.min^{-1} OR FASTER	RATE OF HEATING (r_1 IN EQUATION (1))
Diameter	0.36	0.28	0.04
	(0.038)	(0.113)	(0.819)
Bark Thickness	0.07	0.05	0.03
	(0.711)	(0.793)	(0.856)

When all fire behaviour, weather and billy calorimeter variables were included in a stepwise multiple linear regression analysis, none of the billy variables were included in the final regression. The threshold diameter and bark thickness of killed trees was best predicted by the relationships:

Threshold Diameter = 0.21 Heat Output - 0.52 Fuel Moisture - 0.29 Scorch Ht + 0.37 KBDI + 9.25

(r^2=0.80, n=33, Pr = 0.0001)

Data range: Threshold Diameter, 4.5 to 10.5 cm
Heat Output, 3.7 to 31.1 MJ m^{-2}
Fuel Moisture, 9.0 to 17.0 per cent oven dry weight
Scorch Height, 1.6 to 12.5 m
KBDI, 3.1 to 101.8 (mm equivalents)

Threshold Bark Thickness = 3.72 Flame Height + 0.048 Heat Output + 5.67

(r^2=0.46, n=33, Pr = 0.0001)

Data range: Threshold Bark Thickness, 4.0 to 9.7 mm
Flame Height, 0.1 to 0.9 m
Heat Output, 3.7 to 31.1 MJ m^{-2}

The above regressions and Table 2 show that it was easier to predict the threshold diameter of the trees killed by the fire, under the experimental conditions experienced, than the threshold bark thickness. This may be due to less variability in the diameter measurements and reflect better the bark thickness of the trees before the fire and it may be due in part to a greater ability of larger trees to dissipate heat.

Using the measured fire behaviour and environmental variables, the maximum temperature rise and the rate of this rise in the billy calorimeter were best described by the following regressions:

T_{max} = 1.06 Heat Output - 0.19 KBDI - 16.03 Flame Height + 17.94

(r^2=0.30, n=33, Pr = 0.0006)

Data range: T_{max}, 6 to 60°C
Heat Output, 3.7 to 31.1 MJ m^{-2}
KBDI, 3.1 to 101.8 (mm equivalents)
Flame Height, 0.1 to 0.9 m

r_1 = -0.082 Fuel Moisture + 1.66

(r^2=0.19, n=33, Pr = 0.0005)

Data range: r_1, 0.15 to 2.00°C.min^{-1}
Fuel Moisture, 9.0 to 17.0 per cent oven dry weight

The temperature rise in the billy can be used to calculate the amount of heat absorbed. The billies described here have a water capacity of 2800 g, a basal area of 177 cm^2 and a height of 17 cm. Since the heat capacity of water is 4.1868 J.deg^{-1}.g^{-1}, then a 1°C rise in temperature of the billy is equivalent to 662 kJ.m^{-2}. If the water in the billy was to rise by 40°C, the the heat absorbed would be equivalent to 26.5 MJ.m^{-2}, about 177 per cent of the expected heat yield from a low intensity fire of 15 MJ.m^{-2}. This indicates that the heat catchment of the billy can be at least twice the area occupied by the billy.

Heat Sensitive Plates

The heat sensitive plates gave a spatial measure of the temperature variability between the litter and the mineral soil surface. The average, maximum and minimum temperatures for each fire are summarized in Table 3. Surface soil temperatures were much lower in the first rotation (1R) spring fires compared with the second (2R) and third rotation (3R) fires and the autumn fires. The 2R and 3R spring fires applied just as much or more heat to the soil surface as the autumn fires, but the 2R autumn fires heated the surface soil less than the 1R autumn fires.

TABLE 3

Summary statistics of surface soil temperature for two different seasons and three different rotations (1R, 2R, 3R). Temperatures are in °C and the standard errors of the means are shown in parentheses. All values are based on the average of 12 observations per fire. Fire rotations were 2-4 years apart.

	SPRING 1R	SPRING 2R	SPRING 3R	AUTUMN 1R	AUTUMN 2R
Mean	161	403	427	367	292
	(30)	*(14)*	*(55)*	*(39)*	*(40)*
Maximum	340	453	577	530	396
Minimum	83	370	239	185	149

The spatial variability of the surface soil heating can be better seen in Figures 3 a, b, c, d and e using the method of presentation suggested by Hobbs *et al.* (1984). Figure 3a shows that the variability in surface soil temperature in the 1R spring fires was relatively low, with few areas being heated above 300°C, but most the area was heated to about 100°C. This was in contrast to the 2R spring fires shown in Figure 3b where most of the soils were heated to 350°C, but few higher than 500°C. The 3R spring fires (Fig. 3c) were quite variable and there was a fairly even distribution of temperatures across the burnt area, indicating a patchier burn. Figure 3d shows that the 1R autumn fires, like the 1R spring fires, were not especially variable either, however, the temperatures reached at the soil surface were generally above 400°C. As with the 3R spring fires, the 2R autumn fires (Fig. 3e) were patchy and showed a wide range in temperatures.

The surface soil temperature can be combined with the moisture content of the soil at the time of burning with the diffusivity of the soil (diffusivity = conductivity/capacity) to provide an indication of the depth and amount of soil heating. A model such as that proposed by Aston and Gill (1976) or Campbell *et al.* (1990) can be used to predict soil temperature profiles in time. The moisture content of the soil can be estimated using a modified form of Mount's soil dryness index (Mount 1972). The modification of this index is to invert it to become a 'soil moisture index' and to express this as a proportion of 50 mm rather than the usual 200 mm. This last modification more closely reflects the average moisture content of the top 10 cm of soil. Figure 4 shows how this soil moisture index relates to gravimetrically determined soil moistures.

Combining data from the vegetation project and the fire behaviour project described in Tolhurst and Flinn (1992), a clear association is apparent between the increase in legume density following fire and the surface soil temperature. A summary of the results is shown in Table 4. This shows that even though the fire intensity and the total heat output from the fires in spring and autumn were similar, the average surface soil temperatures were very different and the increase in legume density was most pronounced with the higher indicated surface soil temperatures. This observation concurs with the conclusion of Christensen and Kimber (1975) that the percentage of fuel consumed and hence the degree of exposure of mineral soil is the more important than the fire intensity *per se* or the amount of heat output from the fires.

The heat sensitive plates also give a measure of heat transfer to the soil. The heat capacity of aluminium is 0.90 J.deg^{-1}.g^{-1}, each plate weighs approximately 12 g and covers an area of about 60 cm^{2}, therefore the amount of heat absorbed by a single plate is 1.8 kJ.deg^{-1}.m^{-2} and the heat input into the soil is therefore a product of 1.8 times the maximum temperature of the plate. If the total heat output from the fire is about 15 MJ.m^{-2}, then the proportion of heat being transferred from the fire to the soil is directly related to the maximum temperature of the plate. Table 5 indicates the amount and proportion of heat transferred to the soil as measured by a heat sensitive plate described here.

TABLE 4

Average fire intensity, total heat output, surface soil temperature and increase in legume density associated with spring and autumn fires in the Blakeville Fire Effects Study Area, Wombat State Forest, Victoria.

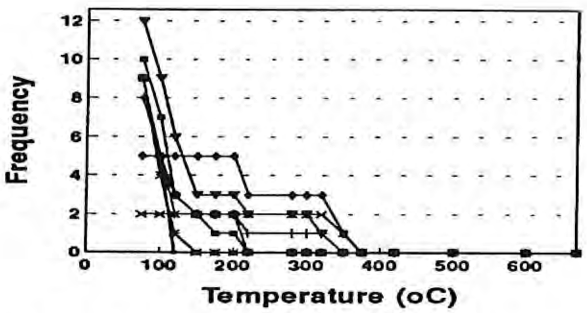
SEASON	FIRE INTENSITY (kW.m^{-1})	HEAT OUTPUT MJ.m^{-2})	SURFACE SOIL TEMPERATURE (°C)	FACTOR OF LEGUME DENSITY INCREASE (POST-FIRE/PRE-FIRE)
Spring	205	16.9	78	6.0
Autumn	156	15.4	315	12.3

TABLE 5

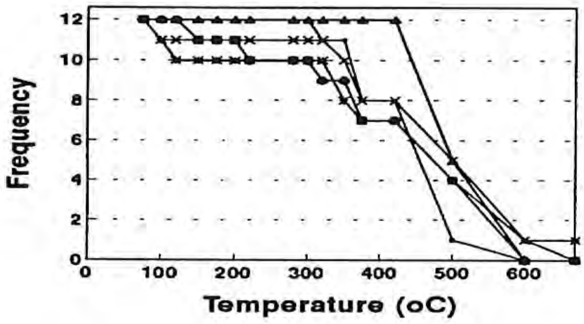
Relationship between maximum temperature of a heat sensitive plate and the amount of heat absorbed and the proportion of the total heat released by a 15 MJ.m^{-2} fire.

Maximum Temperature (°C)	100	200	300	400	500	600
Heat Input to Soil (kJ.m^{-2})	180	360	540	720	900	1080
Percentage of Total Fire Heat	1.2	2.4	3.6	4.8	6.0	7.2

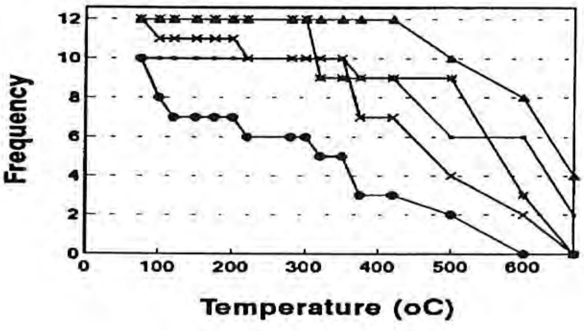
(a) 1 R Spring



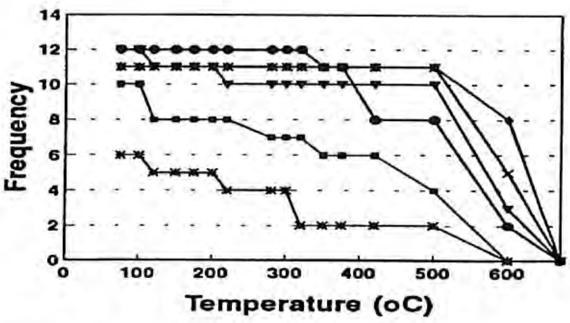
(b) 2 R Spring



(c) 3 R Spring



(d) 1 R Autumn



(e) 2 R Autumn

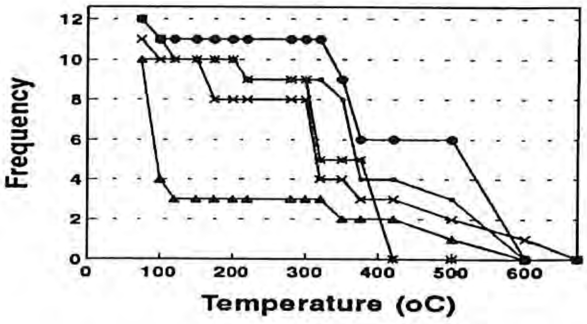


Figure 3. Frequency distribution of temperatures reached at the soil's surface during spring and autumn burning with up to three successive fires. Temperatures were measured with heat sensitive plates. Each line represents one fire replicate. (a) is the 1R spring fires, (b) is the 2R spring fires, (c) is the 3R spring fires, (d) is the 1R autumn fires and (e) is the 2R autumn fires.

Scorch Height

The third measure of sensitive heat is indicated by the trees on the site. Scorching of the leaves results from the interaction of the temperature of the air in the vicinity of the leaves, the amount of heat being released from the fire and the cooling rate of transpiration.

The scorch height of the fires in spring was found to be about 4 to 6 m, the scorch height in autumn was 7 to 12 m even though the average fire intensities in spring and autumn were similar (150 kJ.m^{-1}, Tolhurst and Flinn 1992). Average scorch height was best predicted by the amount of fine fuel burnt in combination with the air temperature within the forest and the Keetch Byram drought index (KBDI). The relationship between these variables was described by the function:

$$\text{Scorch Ht.} = 0.631\ \text{Fine Fuel Burnt} + 0.375\ \text{Air Temperature} + 0.052\ \text{KBDI} - 6.977$$

$$(r^2=0.64,\ n=25,\ Pr = 0.0001)$$

where: Scorch Ht = average scorch height (m) (data range, 1.6 to 12.5 m)
Fine Fuel Burnt = (t ha^{-1}) (data range, 2.0 to 14.7 t ha^{-1})
Air Temperature = (°C) (data range, 12.0 to 24.0°C)
KBDI = Keetch Byram drought index (mm equivalents) (data range, 3.0 to 57.0)

DISCUSSION

Billy Calorimeter - a Flaming Zone Pyranometer

The billy calorimeter used here proved successful in providing information which differentiated between fires. The total amount of heat absorbed by the billy reflected the amount of heat released from the fuel, as was found by Beaufait (1966) and Knight (1981), but it was also related to the Keetch Byram Drought Index and average flame height. However, because the fuel had been sampled from 15 points within the plot and the billy only sampled one point, it could be expected that the amount of fuel burnt would give a better average heat output for the plot and hence be better correlated with the threshold diameters and bark

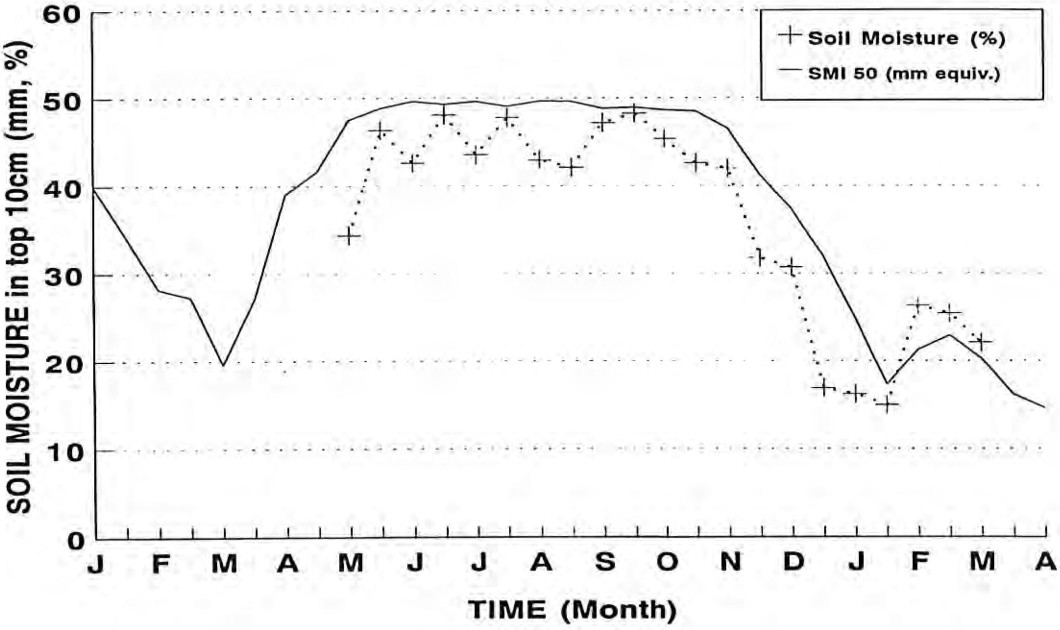


Figure 4. Seasonal variation in gravimetrically determined soil moisture content of the top 10 cm of soil and the soil moisture index calculated using meteorological data.

thickness of fire killed trees. More billies may improve their correlation. The rate at which the heat was absorbed by the billies during the fire varied between fires, but this could not be related to the mortality of the trees within the plot. The rate of heat absorbed by the billy was significantly, but weakly negatively correlated with fine fuel moisture content, which is probably due to a greater rate of combustion when the fuels are drier (Cheney 1981).

The response curve obtained from the billy was similar in shape to that reported by Vines (1968) for the temperature of a jarrah (*Eucalyptus marginata* Sm.) tree bole at the cambium layer when exposed to a 'fierce' fire, it was also similar to those reported by Gill and Ashton (1968) when exposing bark to a radiant heater in the laboratory, and those obtained by Fahnestock and Hare (1964) in forest fires, indicating that the billy calorimeter is a reasonable analogue of a tree. The main difference between the billy and a tree is that there is no cooling mechanism in the billy and therefore the temperature falls much slower than it does in a tree. Trees are able to conduct heat away from the base of the tree through sap movement associated with transpiration at longitudinal movement rates of up to 15 cm.min^{-1} (Doley and Grieve 1966). Another difference between the billy and a tree bole is the height of the billy. Hare (1965) observed that under windy conditions, a convection column on the lee of the tree increases the heat load on the bole. There was little opportunity for this phenomenon to develop with a billy. However, for the limited set of fire and weather conditions experienced in this experiment, the total heat output from the fire, the fine fuel moisture content, average scorch height and the Keetch Byram Drought Index were most closely correlated with the size of the trees killed by the fire.

The experimental fires in which the billy calorimeter has been used to date have been in natural fuel beds. In this situation the amount of sensible heat has been strongly correlated to the amount of fuel burnt. Generally, the more fuel burnt the longer the period of heating and so no additional information is provided by knowing the duration or rate of heating. These conditions may change if wind or slope are more dominant in the fire behaviour, as a greater proportion of the heat may move along close to the ground surface before rising and therefore generate a greater amount of sensible heat in the flaming zone. Because the moisture content of the fuel may affect the rate of combustion, it may be expected to affect the amount of heat released, but usually the conditions under which fuel moisture are higher will coincide with conditions when a smaller percentage of the total fuel will be burnt.

Although there was a strong linear relationship between the bark thickness of the trees and diameter, the threshold diameter for tree mortality was more easily predicted than the threshold bark thickness. In functional terms bark thickness is a better variable to measure because Gill and Ashton (1968), Vines (1968), and Hare (1965) have shown that bark thickness is the primary factor in determining whether or not the cambium is exposed to lethal temperatures for a given fire intensity or heat exposure, but this could be used to advantage. In this study, we found that the thickness of bark killed on large trees was similar to the threshold bark thickness of fire killed trees. Gill *et al.* (1986) also found that the amount of bark killed on gums was related to the period of flaming. Where gum barked trees occur, the thickness of the bark killed by the fire could be used as a direct measure of sensible heat output from the fire, solar radiation, wind effects and ambient air temperature, but this could not be measured until a number of months after a fire when decortication occurs.

Heat Sensitive Materials - Below Flaming Zone Pyranometers

The heat sensitive plates show a variation in the fires not apparent in the fire intensity or heat output of the fires. The patchiness of the 2R autumn fires and the 3R spring fires are evident from the frequency graphs and this can be translated into patchiness in the effects the fire will have on the soils, plants and invertebrates. The contrast in the 1R spring and 1R autumn fires is not apparent when viewing fire intensity data, but the surface soil temperature differences are marked. This has had a significant affect on the legume seedling regeneration which will later be reflected in a difference in the structure of the understorey. The heat sensitive plates have therefore been useful in identifying differences in fires at an ecological level.

The temperature profile of the soil is related to the surface temperature of the soil, its heat capacity, and its thermal conductivity properties, these in turn are affected by the density and moisture content of the soil. Scotter (1970) and Raison *et al.* (1986) found a strong relationship between the surface soil temperature and the temperature profile induced by forest fires. The surface soil temperature as measured by the heat sensitive plates could therefore be used in conjunction with estimates of soil moisture and thermal conductivity to estimate the temperature profile induced by a fire.

Data from the heat sensitive plates can be used directly to correlate with the ecological effects of fire. Noble (1984) found a strong linear relationship between the proportion of eucalypt lignotubers surviving a fire and the surface soil temperature measured with this technique. Collett *et al.* (1993) found a strong correlation between the surface soil temperature measured during a fire and the subsequent abundance of annelids (earth-worms) for successive fires on the same site even though the intensity of the two fires were similar. Bentley and Fenner (1958) used heat sensitive plates to measure the soil temperature profiles in grass and shrub fuel and found it an objective way to classify seedbeds. I would also expect that the surface soil temperatures could be used to predict the patterns of post fire germination of legumes as reported by Auld

(1986) and Auld and O'Connell (1991) in the same way as the data presented here shows.

The amount of heat absorbed by the plate also indicates the proportion of heat being directed to the soil. Because the heat capacity and weight of the material being used for the plate is known, the indicated temperature can be used to calculate the amount of heat absorbed so, for example, if a fire yields 15 000 kJ.m^{-2} of energy, and the plate reaches 400°C, then the proportion of heat absorbed is about 4.8 per cent which agrees with previous published results. Raison *et al.* (1986) found that between 4.5 per cent and 6.9 per cent of the heat released from the surface fuel in a low intensity forest fire was transferred to the soil, Packham (1970) calculated that about 5 per cent of the energy released is transferred to the soil and DeBano *et al.* (1977) suggested that only about 8 per cent of the heat was transferred into the soil. The amount of heat transferred to the soil will be a function of the amount of heat released by the fire, and the proportion of the surface fuel burnt and hence the amount left behind to insulate the soil. Heat sensitive plates integrate all these factors well. The advantage of heat sensitive plates is that it gives a good indication of the variability of the fire which is difficult to get with measurements of fire intensity.

Hobbs and Gimingham (1984) used a combination of thermocouples and heat sensitive plates in their study of heath fires. They found that the maximum temperature reached in any fire showed a similar pattern in relation to the fuel structure as did the duration of heating over 400°C. This indicated that very little information was lost by using the maximum temperature alone. Fire intensity was also measured in these fires and it was found that the relationship between fuel structure and intensity was different to that of temperature and fuel structure. The authors expressed the view that 'direct temperature measurements may provide more meaningful information' than fire intensity values.

Scorch Height - Above Flaming Zone Pyranometers

The measurement of scorch height is an end in itself. The canopy of the overstorey is important to arboreal birds, mammals and invertebrates who rely on the canopy for food. Reduction in the canopy can also lead to reduced timber production or perhaps timber degrade (Kellas *et al.* 1984).

Scorch height has been found to be related to the ambient air temperature, wind speed and flame height (Van Wagner 1973; Cheney *et al.* 1992; Buckley 1993). Scorching of the canopy occurs when leaf tissues can no longer cope with the heat load of the fire. Therefore, scorching is dependent on the characteristics of the fire, the air environment of the forest and the structural and physiological status of the trees.

In this study, scorch height was found to be significantly related to the heat output of the fire, the ambient air temperature and the seasonal dryness as indicated by the Keetch Byram Drought index. Because the tree canopy is above the surface fire, it has to cope with the convective heat produced by the burning litter. In higher intensity fires and fires with a shrubby understorey, radiation may become more important. The ambient air temperature is important because it determines what increase in temperature is needed for lethal temperatures to be reached. Ambient air temperature may also affect the rate of combustion and affect the relative humidity of the air. The KBDI affects the ability of the canopy to cope with the heat load. When the KBDI is high, there will be greater moisture stress on the trees and therefore they will be less able to dissipate heat as rapidly through transpiration. Scorch height is therefore a useful measure of sensible heat output above the flaming zone, integrating fire and seasonal conditions.

A useful result from this work is the finding that KBDI is an important predicting variable. The observations by Wallace (1966) that scorch height in jarrah (*Eucalyptus marginata* Sm.) forest was seven times flame height in spring and 14 times flame height in autumn can be reflected in the Keetch Byram Drought Index. Scorch height can therefore be predicted with more precision than that provided by the Forest Fire Danger Meter (McArthur 1973).

CONCLUSIONS

The billy calorimeter was used to measure the amount and rate of sensible heat transfer in the flaming zone of a surface forest fires. Two distinct temperature profiles were described for the rate of temperature increase in the billy calorimeter. The first followed a logistic function which described the temperature profile when the billy was exposed to a headfire, and the second was an asymptotic inverse logarithmic function which applied when the billy was exposed to a backfire. The maximum increase in the billy temperature (T_{max}), was related to the total heat output of the fire, the seasonal dryness as measured by the Keetch Byram drought index and flame height. The rate of temperature increase was weakly related to the ambient air temperature.

The most useful information derived from the billy calorimeter was the total temperature rise above ambient. While this was statistically related to the threshold diameter of the trees killed by the fires measured, the amount of fuel burnt was the primary factor affecting tree death. The rate of temperature increase of the billy was not significantly related to tree death in this study. Further investigations are needed to determine if these same conclusions are true under high intensity fires and when wind or slope are more dominant factors. Where gum barked trees exist, the thickness of the bark killed by a fire is a useful measure of sensible heat output, but this cannot be measured until several months after the fire.

Heat sensitive plates were used to measure the amount of sensible heat transferred to the soil below the flaming zone of a surface forest fire. Maximum surface soil temperatures could be used in conjunction with estimates of soil moisture content and soil conductivity to estimate soil temperature profiles resulting from fires. The maximum surface soil temperatures in themselves were correlated with the survival of earthworms, establishment of legume seedlings, and death of lignotubers. Heat sensitive plates were useful for indicating the amount of variability in a fire which is not evident from measures of fire behaviour such as fire intensity.

Tree scorch height was used as a measure of the amount of sensible heat transferred above the flaming zone of a surface forest fire. This measure was reliant on there being an uneven-aged forest so that scorch height could be measured when it was less than canopy levels. Scorch height was easy to determine and was directly related to the ecological impacts of fire on tree growth, and arboreal animal food supply.

Measures of sensible heat integrate fire, weather, topographic and seasonal conditions as well as heat transfer processes. They therefore offer an efficient way of quantifying fires in an ecologically meaningful way.

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APPENDIX 1

		TIME IN MINUTES									
°C	CRAYON	0	1	2	3	4	5	7	10	15	20
670	670	GREEN	DARKER	DARKER	GREY/GREEN	LT/GREY		MELT DOWN OF FOIL →			
	600	BLUE	AQUA	WHT/AQUA	WHITE	WHITE					
	500	LT/BROWN	DK/BROWN	PINK	SAME	•••					
	420	WHITE	YELLOW	GREY							
	350	BROWN	RED/BROWN	SAME							
600	670	GREEN	N.C.	N.C.	DARKER	SAME	SAME	WHT/GREY	GREY	SAME	SAME
	600	BLUE	N.C.	N.C.	LIGHTER	LIGHTER	WHT/AQUA	WHITE	SAME	SAME	SAME
	500	LT/BROWN	DARKER	DARKER	DK/BROWN	SAME	RED/GREY	SAME	SAME	PINK	
	420	WHITE	YELLOW	YELL/BROWN	YEL/GREY	SAME	SAME	SAME	YELLOW	SAME	WHITE
	350	BROWN	RED/BROWN	DARKER	DARKER	SAME	BLACK				
500	600	BLUE	N.C.	N.C.	N.C.	LIGHTER	SAME	LIGHTER	SAME	WHITE	SAME
	500	LT/BROWN	N.C.	DARKER	DARKER	N.C.	DARKER	DK/BROWN	DK/BROWN	SAME	SAME
	420	WHITE	WHT/YELLOW	YELLOW	YEL/BROWN	YEL/BROWN	SAME	SAME	SAME		
	350	BROWN	DARKER	RED/BROWN	SAME	SAME	•••				
	320	GREEN	LT/BLUE	SAME	FAWN	SAME	•••				
420	500	LT/BROWN	N.C.	DARKER	DARKER	DARKER	SAME	SAME	DK/BROWN	DK/BROWN	SAME
	420	WHITE	N.C.	SAME	CREAM	SAME	WHT/YELLOW	YELLOW	DARKER	YEL/BROWN	YEL/BROWN
	350	BROWN	DARKER	DK/BROWN	RED/BROWN	SAME	SAME	DK/BROWN	SAME	SAME	SAME
	320	GREEN	LIGHTER	LT/BLUE	LIGHTER	SAME	SAME	GREY/BLUE	SAME	FAWN	FN/GREEN
	300	PL/GREEN	OLV/GREEN	DARKER	•••	SAME	SAME	SAME	SAME	SAME	
350	420	WHITE	N.C.	N.C.	DARKER	SAME	SAME	SAME	SAME	WHT/YELLOW	YELL/BROWN
	350	BROWN	N.C.	LIGHTER	SAME	LIGHTER	SAME	SAME	SAME	RED/BROWN	SAME
	320	GREEN	N.C.	DK/GREEN	LT/BLUE	GREY/BLUE	GREY	SAME	SAME	SAME	DK/GREEN
	300	PL/GREEN	DARKER	BRN/GREEN	DARKER	SAME	SAME				
	280	LT/GREEN	OLV/GREEN	BLACK	BLACK	SAME	SAME				
300	320	GREEN	N.C.	N.C.	N.C	N.C.	LIGHTER	LT/BLUE	SAME	GREY/BLUE	SAME
	300	PL/GREEN	DARKER	DARKER	SAME	DARKER	DARKER	BRN/GREEN	SAME	OLV/GREEN	SAME
	280	LT/GREEN	DARKER	SAME	SAME	SAME	GREEN/GREY	GREY	SAME	SAME	•••
	220	WHITE	DARKER	SAME	SAME	DARKER	YEL/BROWN	YEL/BROWN	LT/BROWN	DARKER	•••
	200	DK/BLUE	DK/GREEN	BLACK	SAME	•••					
200	220	WHITE	N.C.	N.C	N.C.	N.C.	N.C.	DARKER	DARKER	LT/YELLOW	LT/YELLOW
	200	DK/BLUE	DARKER	DARKER	DARKER	DARKER	DARKER	DARKER	DARKER	BLACK	
	150	FN/GREEN	DARKER	FAWN	PURPLE	DARKER	SAME	•••			
	120	CREAM	FAWN	DARKER	FN/GREEN	SAME	SAME	•••			
	100	FAWN	PINK	BLUE	SAME	SAME	•••				
150	150	FN/GREEN	N.C.	N.C.	N.C.	N.C.	GREENER	GREENER	FAWN	FAWN	PURPLE
	120	CREAM	N.C.	N.C.	N.C.	DARKER	FN/GREEN	VIOLET	SAME	•••	
	100	FAWN	N.C.	DARKER	BLUE	SAME	•••				
	75	CRM/GREEN	GREENER	DARKER	DARKER	AQUA	SAME	•••			
	65	FN/GREEN	FAWN	OLV/GREEN	BLUE/GREEN	SAME	•••				
100	150	FN/GREEN	N.C.	•••							
	120	CREAM	N.C.	N.C.	N.C.	N.C.	N.C.	N.C.	N.C.	FN/GREEN	VIOLET
	100	FAWN	N.C.	N.C.	N.C.	N.C.	N.C.	N.C.	DARKER	BLUE	SAME
	75	CRM/GREEN	N.C.	DARKER	DARKER	AQUA	SAME	•••			
	65	FN/GREEN	N.C.	OLV/GREEN	OLV/GREEN	BLUE/GREEN	SAME	•••			
75	150	FN/GREEN	N.C.	•••							
	120	CREAM	N.C.	•••							
	100	FAWN	N.C.	•••							
	75	CRM/GREEN	N.C.	N.C.	DARKER	DARKER	AQUA	SAME	•••		
	65	FN/GREEN	N.C.	N.C.	OLV/GREEN	BLUE/GREEN	SAME	•••			