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FUEL REDUCING REGROWTH FORESTS WITH A WIREGRASS FUEL TYPE: FIRE BEHAVIOUR GUIDE AND PRESCRIPTIONS

RESEARCH REPORT No. 40

Andrew J. Buckley

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Published by the Department of Conservation and Environment, 240 Victoria Parade, East Melbourne, Victoria, 3002, Australia, to whom all enquiries should be directed.

SUMMARY

Experimental burning was undertaken in stands of regrowth forest of age 16 to 34 years with a Wiregrass (*Tetrarrhena juncea*) or Bracken *(Pteridium esculentum)* fuel type at sites in the Bairnsdale and Orbost areas of East Gippsland, Victoria during the five year period from 1988 to 1992. This report covers results from the Wiregrass fuel type and presents prescriptions for fuel reducing these regrowth forests and a fire behaviour guide for predicting the behaviour of fires with a fireline intensity of less than about 1,000 kW/m.

The mean fine fuel load, which included an aerated, flammable, shrub fuel layer, was assessed at four sites which had remained unburnt for between 20 and 24 years to be between 16 and 22t/ha, with coarser stick debris contributing a mean of an additional 2 to 4t/ha and branch and old lóg material contributing a mean of 150 to 182 t/ha. The mean shrub height was 1.1 to 1.2m and the elevated dead fuel class was identified as adding significantly to the hazard of this fuel complex.

Fire behaviour data were collected from eighteen experimental fires, conducted mainly during autumn, but also during winter and spring, which were ignited from point sources in regrowth forest of age 23 to 34 years over a wide range of meteorological and fuel moisture conditions. Rates of spread of the head fires varied from very low or zero up to a maximum of 147m/h, corresponding to a fireline intensity of 970kW/m. However, the rates of spread of most head fires were less than 70m/h and the data collected covered the range of fire behaviour where fuel reduction burning objectives can be achieved without causing significant damage to regrowth forests. Indices of fuel moisture were identified which characterise a suitable burning window of opportunity and the fuel moisture content of the elevated dead fuel or the exposed surface litter and wind speed at canopy level were found to be the key variables affecting fire behaviour.

Models of fire behaviour were developed which related average scorch height to rate of spread and temperature, average scorch height to flame height, rate of spread at zero slope to the moisture content of elevated dead fuel and wind speed at canopy level, rate of spread at zero slope to the moisture content of exposed surface litter and wind speed at canopy level, average flame height to rate of spread and the moisture content of elevated dead fuel to the moisture content of exposed surface litter.

Levels and sources of stem damage were assessed and burning old log and fallen stag or stem and branch material were identified as the major sources of damage. Some 9% of stems greater than 10cm DBHOB in stands which had some upper crown scorch were damaged, whereas only 3% of stems in stands which did not have upper crown scorch were damaged. Crown scorch rather than stem damage was identified as the important damage factor to consider when prescribing burns.

A dominant stand height of 20m was identified as being the minimum level to which stands with the Wiregrass fuel type should have developed before burning should be prescribed. The 'Wiregrass Prescribed Burning Guide' specifies that for a stand of this height, the maximum rate of spread at 20°C which will meet the maximum scorch height prescribed of 13m (two-thirds of the dominant height) is 50m/h, which corresponds to a maximum fireline intensity of 335 kW/m (for a fine fuel load of 18t/ha). Similarly, for a stand of 30m dominant height, the maximum prescribed fireline intensity is 600kW/m.

INTRODUCTION

Protecting the regrowth forests[1] of East Gippsland, Victoria from wildfire is clearly identified as one of the primary objectives of the Fire Protection Plans of both Orbost and Bairnsdale Regions of the Department of Conservation and Natural Resources (CNR) (Barlett 1990, Long 1990). The growing timber resources of these forests are the basis of the future sustainable supply of sawlogs to the forest industry (Flinn and Mamers 1991) and are very important to the Regional economy (Timber Industry Strategy 1986). However, the task of protection is complex, given the large area of the resource (Radic 1990, Bartlett 1990), the hazardous nature of the elevated fuel types which typify these forests (Buckley 1992a, 1992b) and the long fire season which can occur each year.

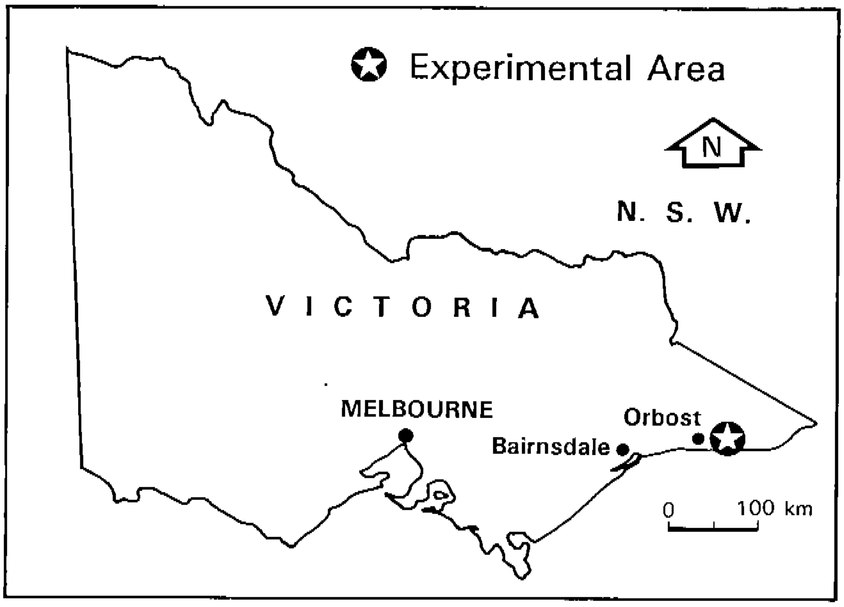
Fuel reduction burning is the primary tool for reducing fuel quantity and hence the impact of wildfire in a range of Victorian and Australian forests (Luke and McArthur 1978). This practice has been based on the fire behaviour guides of McArthur (1962), the McArthur forest fire danger meter (Luke and McArthur 1978) or the Forest Fire Behaviour Tables for Western Australia (Sneeuwjagt and Peet 1985). However, concerns about possible damage to young trees and difficulties of conducting fuel reduction burning of low intensity in the elevated fuel types of East Gippsland has restricted the use of this technique in regrowth forests.

In 1987, recognising the need for improved fuel management in these forests, the Fire Management Branch of CNR initiated a fire research project, with the aims of investigating the factors affecting low intensity fire behaviour and of developing prescriptions for fuel reducing these forests. Adopting an empirical approach, 28 experimental fires were ignited and studied in 16 to 34 year old regrowth forests with either of two broad fuel types typical of the coastal and foothill forests of East Gippsland, Wiregrass *(Tetrarrhena juncea)* or Austral Bracken *(Pteridium esculentum)*.

Experimental burning was undertaken over a five year period with the burning in the Wiregrass fuel type being located, as is shown on Figure 1, in the Orbost Region. Burning in the Bracken fuel type was conducted in the Bairnsdale Region, and the results will be the subject of a future report. The aims of this report are to present prescriptions for fuel reducing regrowth forests in East Gippsland with a Wiregrass fuel type and to present a fire behaviour guide for predicting the fire behaviour of fires with a fireline intensity of less than about 1000 kW/m.

[1] Defined as forests which are predominicantly even-aged and less than 40 years old (Radic 1990).

Figure 1. **General location of experimental burning in the Wiregrass fuel type, East Gippsland.**



METHODS

Location of experimental burning sites

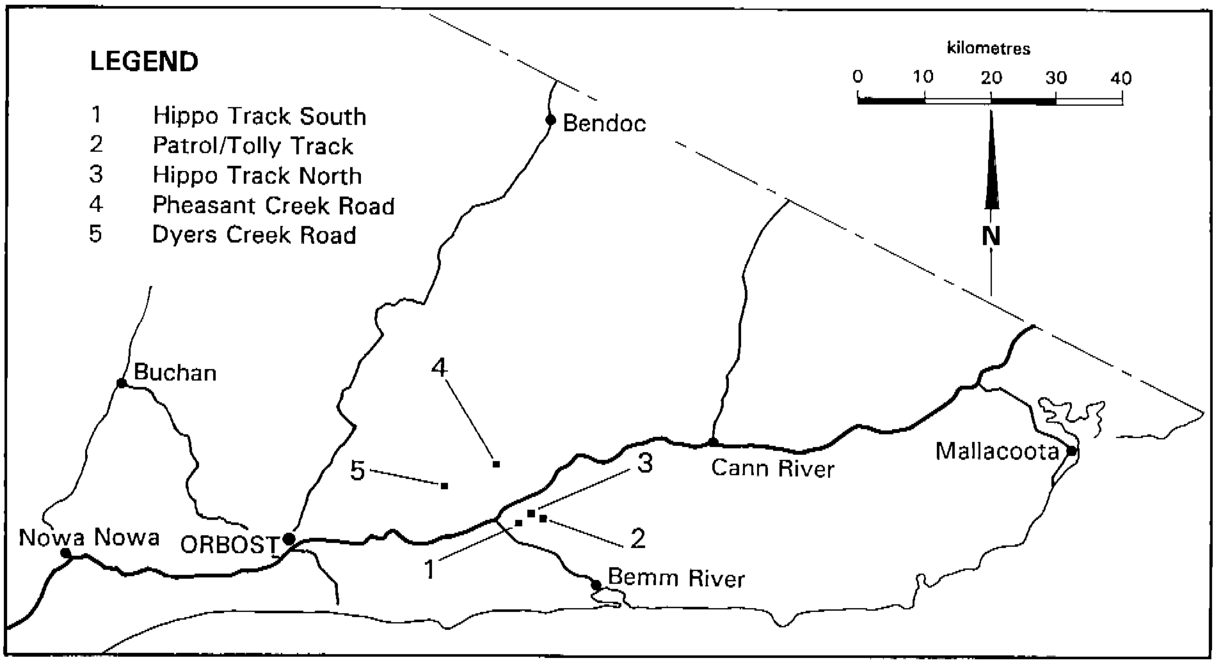
Sites for the experimental burning were selected to be representative of large areas of regrowth forest with long unburnt fuels and preferably to be near to a fuel reduced buffer. Detailed data were collected at three sites involving 14 experimental burns which were lit on blocks of area of between one and eight hectares. Most sites had slopes of 4^{o} or less and each block was surrounded by a mineral earth control line. Additional data were also collected from three experimental burns which were lit in thinning slash fuels but which also burnt in regrowth forest adjacent to the coupes (Buckley and Corkish 1991) and from one operational fuel reduction burn. The location and dates of the experimental burns in the Wiregrass fuel type are shown in Table 1 and on Figure 2.

Table 1. Location and dates of the experimental burns in the Wiregrass fuel type.

Burn identification	Location of burn	Date of burn
0/88/01/A	Patrol/Tolly Track	14 April 1988
0/88/02/A	Patrol/Tolly Track	15 April 1988
0/88/03/A	Patrol/Tolly Track	19 April 1988
0/88/04/W	Pheasant Creek Road	15 August 1988
0/88/05/S	Hippo Track South	13 October 1988
0/89/06/A	Hippo Track North	20 April 1989
0/89/07/A	Hippo Track North	26 April 1989
0/89/08/A	Hippo Track North	27 April 1989
0/90/09/A	Hippo Track North	19 March 1990
0/90/10/A	Hippo Track North	20 March 1990
0/90/11/A	Hippo Track North	21 March 1990
0/90/12/A	Dyers Creek Road	8 May 1990
0/90/13/A	Dyers Creek Road	9 May 1990
0/91/14/A	Hippo Track North	9 April 1991
0/92/15/A	Patrol Track	30 March 1992
0/92/16/A	Hippo Track South	31 March 1992
0/92/17/A	Hippo Track South	31 March 1992
0/92/18/A	Hippo Track South	13 April 1992

0 = Region prefix (O=Orbost), 88=year of burn (88=1988), 2 = burn number, A = season (A = autumn)

Figure 2. **Location of the sites where experimental burning was conducted in the Wiregrass fuel type.**



Stand and forest characteristics

The Wiregrass fuel type was dominated by *Tetrarrhena juncea* with other associated species including *Pteridium esculentum* (Austral Bracken), *Lepidosperma laterale* (Broad Sword Sedge), *Platylobium formosum* (Handsome Flat-pea), *Hakea sericea* (Silky Needlewood) and *Acacia terminalis* (Sunshine Wattle). The forest type where the experimental burns were conducted was classified as Silvertop Stringybark Open Forest III (Land Conservation Council 1974) and the stand age of the regrowth varied from 23 to 34 years. Older growth trees occurred at all sites.

The stand characteristics of basal area and dominant height of both regrowth and older growth at three sites, and diameter distribution and stocking at one site, were measured using a technique of variable probability sampling (Dilworth and Bell 1985). At each plot, a five factor (m^2/ha) basal area wedge was used to determine the number of 'in' tress and the height of the three largest diameter 'in' trees of dominant or co-dominant form was averaged to determine dominant height. Tree diameter (DBHOB) was measured over-bark at breast height (1.3m) and stems less than 5 cm DBHOB were not tallied.

Fuels

Fuel load and arrangement were assessed at each site prior to experimental burning. Fuel age of the long unburnt fuels varied from 20 to 24 years. The following classes of fine fuel (fuel less than 6 mm in thickness) were defined:

Litter bed fuel: Dead fine fuel, including surface fuel and fuel lower in the fuel profile. Those fuels such as eucalypt capsules and charcoal which do not ignite or burn readily were excluded.

Elevated dead fuel: Dead fine fuel forming part of, or being suspended in, the shrub layer. In this study, fuels in this class were concentrated at lower levels of the shrub complex and, although the boundary between the litter bed and the elevated dead fuel was often unclear, the boundary was usually assessed at about 10 cm above ground level.

Living shrub fuel: Living understorey fine fuel less than 2 m above ground level.

Stick debris (dead stick material of 6 to 25 mm thickness) and coarse fuel (of thickness greater than 25 mm) were also assessed at each site. The fine fuel and stick debris were assessed by destructively sampling square plots of area 0.37 m^2. These plots were systematically located within the burning sites and the sampling frame was subjectively placed at each sampling point to be representative of fuels at that point. The height of the living shrub complex on each plot, ignoring the strands of Wiregrass or shrub fuel located above the main shrub layer, was measured. Fuels were then partly sorted and taken to the laboratory for further sorting and weighing. Sub-samples of fuel from each fuel class from each plot were oven-dried to enable the weight of each fuel sample to be adjusted for moisture content.

Coarse fuels were assessed using a line intercept technique (van Wagner 1968, Brown 1974). Fuels were measured and then recorded into under-bark diameter classes (2.6 to 5.0 cm, 5.1 to 10.0 cm and in 10.0 cm classes for larger diameters) along transects of either 30 m or 50 m. The wood volume data calculated from the diameter distributions were converted to dry weight using a density of 0.75g/cm^3 for fuels with a diameter less than or equal to 30 cm and a density of 0.64g/cm^3 for fuels with a diameter of greater than 30 cm (Buckley and Corkish 1991).

Fuel moisture content

The moisture content of the fine fuel was determined by collecting fuel samples in jars before and during each burn, for subsequent oven drying. Samples were also collected on some days when a decision was made not to burn. Two or three samples of each fuel class were collected at each sampling time. Unless fuel moisture content was changing significantly during a burn, all samples for each fuel class were subsequently averaged to determine an average fuel moisture content. Fuel samples were collected from up to five classes of fuel and the type of sample that was allocated as being representative of each of these defined classes was:

Elevated dead fuel (EDFMC): Dead eucalypt leaves suspended in the shrub layer at about waist height.

Exposed surface litter (ESLMC):	Dead fine fuel (mainly leaves and petioles) found in the top 1.0cm of the litter bed and exposed to the weather elements of sun and wind in the gaps between clumps of Wiregrass.
Shaded surface litter (SSLMC):	Dead fine fuel (mainly leaves and petioles) found in the top 1.0cm of the litter bed and shaded from the weather elements below clumps of Wiregrass and shrub fuels.
Profile litter (AB) (PLMC (AB)):	Dead fine fuel situated *below* the surface litter in the litter bed. Fuel samples were generally collected from fuels shaded by clumps of Wiregrass and shrub fuels.
Profile litter (WA) (PLMC (WA)):	Dead fine fuel found in the *entire* litter bed above mineral soil and collected from the litter bed in the gaps between clumps of Wiregrass (derived from Sneeuwjagt and Peet 1985).

Collecting samples of profile litter in a standard manner was found to be easier if the entire profile was sampled. To enable profile litter moisture content (WA) to be estimated from profile litter moisture content (AB) for experimental burns where this sample had not been collected, an additional 31 pairs of samples were collected and a linear regression equation was developed between these two estimators of profile litter moisture content using Minitab[1] software (Ryan, *et al.* 1985).

Estimates of the available fuel factor, defined as being the proportion of the litter bed that was available to burn and calculated from a two-way table which relates surface and profile litter moisture contents (Sneeuwjagt and Peet 1985), were determined for each experimental burn and then related to three broad classes of fire behaviour (too high, acceptable, too low). The values of the fuel availability factor where burning was successful were then used to define a moisture content index which identified the broad fuel moisture conditions that are suitable for conducting burning in the Wiregrass fuel type.

Weather

Weather variables were measured on-site during each experimental burn. Dry bulb and wet bulb temperatures were measured using a Stevenson Screen that was located in the forest for the three experimental burns 0/88/1/A to 0/88/3/A, and using an Assman psychrometer for the other 15 burns. Wind speed at canopy level which was assumed to equal wind speed at 10m in the open was estimated using the Beaufort Scale (Bureau of Meteorology 1984, Rothermel and Rinehart 1983), rather than measured, because of the difficulties of measuring wind speed at canopy level or at 10m in the open when the fire was in fact burning near ground level within the forest. Wind speeds at 1.5m above ground level in the forest, which were low during the experimental burns, were unable to be accurately measured using a Dwyer hand held anemometer. Wind direction was measured using compass bearings. Cloud cover was assessed by estimating the number of eighths of the sky that were covered by cloud (Bureau of Meteorology 1984) and rainfall was measured by a rainguage located at each of the sites. The metric Byram Keetch Drought Index (Keetch and Byram 1968) and Soil Dryness Index (Mount 1972) were calculated from rainfall and temperature data that had been recorded at Orbost, about 35 km west of the burning sites, and these were graphed to indicate seasonal trends clearly. The McArthur drought factor, defined as a broad measure of fuel availability (Luke and McArthur 1978), was calculated for each burn using on-site rainfall and Orbost drought index data, and the equations developed by Noble et al. (1980) were used to calculate the McArthur forest fire danger index (Luke and McArthur 1978).

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[1]Minitab is the registered trademark of Minitab Inc.

Lighting technique

Each of the experimental burns where fire spread was measured was ignited by a point ignition which enabled a range of fire behaviour to be studied at each burn. A 0.5m diameter patch of fuel was partially wetted with a diesel/petrol mix from an unignited drip torch and then ignited with a fusee match. Point ignitions, spaced between 50m and 100m apart, were used to ignite experimental burns 0/90/11/A and 0/91/14/A which were conducted on larger blocks. The author was responsible for the decision to light each burn and a small suppression crew from the Orbost District of CNR supported the fire control function.

Fire behaviour

Conditions of fuel moisture and weather were selected mainly to be within the range where fire behaviour was likely to achieve fuel reduction objectives without damaging the growing trees. However, higher intensity fire behaviour which damaged tree crowns was also planned, so as to establish the limits of acceptable fire behaviour in the forests of different age.

Fire spread, flame height and other fire behaviour characteristics (such as spotting) of each experimental burn were observed in detail. Fires were allowed to spread until either they self extinguished or the head fire reached a control line. This time interval varied from 40 to 140 minutes, although flank and back fires were often measured for longer periods. The location of a given observation, such as fire perimeter at a given time, was determined by reference to wire "pig-tail" pins which had previously been placed at 10m intervals along lines radiating from the ignition point. Additional pins were placed to mark fire spread as required. The ground slope in the direction of each line of pins was also measured. The time when the fire perimeter reached each pin was noted, as was, at other convenient times, the location of the fire perimeter in between pins.

Flame height, defined as the vertical distance between the tip of the flame, excluding higher flame flashes, and ground level (Luke and McArthur 1978) and expressed as a mean height or as a range, were estimated by reference to 1m and 2m height marks on trees located adjacent to each pin. A number marked on each of these trees, corresponding to the distance of the pin from the point of ignition, helped to orientate the observer. These data were subsequently allocated to classes in 1m flame height intervals i.e. 0.0 to 0.9 up to 4.0 to 4.9m. If flame height had been recorded as a range outside these 1m intervals (e.g. 1.5 to 2.5m), then the mid point of that range (e.g. 2.0m) was used to place the observation in the appropriate flame height class (e.g. 2.0 to 2.9m).

To compare sensibly the rates of spread during and between each fire, a time interval of 20 minutes had previously been selected as a reasonable period over which to integrate the fuel and weather factors which determine fire spread. However, the fire spread data and hence the initial calculations of rate of spread, were based on fixed distance (isometric) rather than on fixed time interval (isochronic) data. Hence, these data were transformed by a simple arithmetic calculation to give rate of spread in 20 minute time intervals. Maps were then drawn showing the spread of the perimeter of each fire at time intervals of 20 minutes.

In developing a fire spread model, all of the rate of spread data was corrected to zero slope using the McArthur slope factors (McArthur 1962) and the initial 20 minutes of fire spread was considered to represent the 'acceleration phase' (Luke and McArthur 1978) under the prevailing conditions. Hence, the initial 20 minute rate of spread data were excluded from further analysis.

The fire perimeter was observed and described in terms of three zones; the head fire, flank fires and back fire (Burrows 1984). The actual rate of spread and fuel quantity data were used to calculate the quantitative expression of fire behaviour, fireline intensity[1]. Also, a measure of fire shape, the length (l) to breadth (b) ratio was calculated for each 20 minute time interval for each fire. The length of the fire was measured on the longest axis of fire spread from the back fire through the origin to the head fire and the breadth was measured perpendicular to this axis where the distance between the flanks was greatest. Fire behaviour observations were supported by 35mm slide photography.

Unburnt fine fuel

Fine fuels which remained unburnt were assessed by destructively sampling a small number of square plots of area 0.37 m^2. Unfortunately, not all burns were sampled and insufficient samples were taken following some burns to adequately sample unburnt fuels, particularly unburnt shrub fuels. Hence the data from the following burns where fire spread was sustained (0/88/1/A, 0/88/2/A, 0/88/5/S, 0/90/9/A, 0/90/10/A, 0/90/11/A and 0/92/16/A) were averaged (number of observations = 25) to determine a 'mean unburnt fine fuel load' for use in calculating fireline intensity. The unburnt fuel data from 0/89/8/A (number of observations = 3), was used to calculate fireline intensities for the three burns conducted during 1989 where fire spread was not sustained.

Crown scorch

Average scorch height was measured on trees burnt by different zones of each experimental fire at varying distances from the point of fire ignition. At each sample point, a ground radius of about 7m was selected from which to measure average scorch height.

For each burn, the location of each observation of average scorch height was overlayed onto the map of fire spread. Scorch height data could then be related to the rate of spread data and also to the observations of flame height (mid point of the flame height classes) made within a 5m radius of each scorch height sample point.

Stem damage

Stem damage was assessed at experimental burns 0/90/11/A and 0/91/14/A and at seven of the experimental burns conducted in the Bracken fuel type (burn details not reported), which included regrowth stands of the youngest ages burnt. Any death of the vascular cambium of regrowth stems was not apparent, unless the overlying bark was completely burnt, until subsequent tree growth caused the bark to split along the occluding edge of the scar. Consequently, the assessment of stem damage was delayed until at least nine months after the burn when all of this damage was evident.

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[1] Fireline intensity was devised by Byram (1959) as a measure of fire behaviour. It is the rate of energy release per unit length of fire front and is defined by the equation $I = Hwr$ where I denotes the fireline intensity (kW/m); H denotes the heat yield of fuel (kJ/kg), assumed to be 16,000 kJ/kg for forest fuels (Luke and McArthur 1978); w denotes the dry weight of fuel consumed (kg/m^2) (mean total less mean unburnt); and r denotes the forward rate of spread (m/s).

A detailed study of stem diameter, species, stem damage and fireline intensity was not attempted, as such a study was currently in progress in regrowth forest at Eden, New South Wales (Gill and Moore, 1992). Rather, the aim was to identify the sources of damage and the overall level of that damage which had resulted from the experimental burning. A diameter of 10cm DBHOB was selected to represent the minimum diameter of stems which may have final crop potential. All such trees on a 4m wide transect were examined for stem damage, and the distance from each fire-damaged tree to a possible major heat source (such as an old log from previous harvesting) was measured. Transects were located so as to sample the range of fireline intensity at each measured burn and the range of fireline intensity, including some higher intensity fire behaviour at junction zones, over the larger blocks where widely spaced points were ignited. The diameter was measured and the species recorded of each damaged tree. The stem damage data were grouped depending on whether or not upper crowns of trees at the burning site had been scorched and the significance of this grouping was tested at the 95% (0.05) level of confidence using the t-test (Freese 1967).

Data analysis

The fire behaviour data were analysed statistically using linear and multiple linear regression techniques with Minitab software (Ryan *et al.* 1985). These involved the use of one or more independent variable (e.g. wind speed, surface litter moisture content) to determine the model that minimised the variation in the dependent variable (e.g. rate of spread). Transformations of the independent variables including the square, square root, log 10, negative reciprocal and natural log were also tested where relationships may have been non-linear.

The statistical significance of the regression equations were examined using the Student t-test to test the significance of the intercept co-efficient and the co-efficients of the independent variables. The F-test was used to test the significance of the whole model and of the significance of improvement in goodness of fit of one model over a previous model. The residuals of the preferred models were plotted against the dependent and independent variables and were examined to ensure that the patterns showed no definite trends. Data from experimental burn 0/92/16/A were excluded from the data bases that were used to develop the fire behaviour models. Rather, these data were used as independent data in a chi-square test (Freese 1967) of the significance of each preferred model. Unless otherwise stated, these tests indicated a significant relationship. All tests of significance were conducted at the 95% (0.05) level of confidence.

The relationships tested were those between rate of spread at zero slope and the weather and fuel variables of wind speed, elevated dead fuel moisture content, exposed surface litter moisture content, profile litter moisture content (WA), fuel availability factor, fuel quantity, Byram Keetch Drought Index and McArthur's drought factor (number of observations = 41). Similarly, the relationships between the following variables were tested: scorch height versus rate of spread and temperature (number of observations = 47), scorch height versus flame height and temperature (number of observations = 64), flame height versus rate of spread (number of observations = 270) and elevated dead fuel moisture content versus exposed surface fuel moisture content (total number of observations = 44, number of observations excluding 1992 data = 27). The ratio of scorch height to flame height has been found to be higher in autumn than in spring in Jarrah *(Eucalyptus marginata)* forests (Wallace 1966) and in central Victorian mixed species forests (Tolhurst *et al.* 1992). Hence, the relevant data from the experimental burn conducted in spring (0/88/5/S) were excluded from the scorch height data bases.

RESULTS

Stand characteristics

The data on stand characteristics of the study sites are summarised in Table 2 and show that regrowth dominant height varied from 23.6 to 26.0 m, regrowth basal area varied from 30 to 33 m^2/ha and the age of the regrowth when burnt varied from 23 to 34 years. Radic (1990) provides considerable additional data (e.g. diameter distribution of stems for different age classes and stand densities) on the mensurational characteristics of the regrowth resource.

Table 2. Stand characteristics of the study sites.

Study site	Regrowth		Overwood		Age of regrowth when burnt (years)
	Basal area (m^2/ha)	Dominant height (m)	Basal area (m^2/ha)	Dominant height (m)	
Patrol/Tolly Track	33 (3)[1]	23.6 (2.6)	18 (6)	28.7(1.1)	23
Hippo Track South	30 (7)	24.9 (2.6)	10 (0)	29.5 (5.4)	30, 34
Hippo Track North	31 (14)	26.0 (1.5)	9 (2)	n.a.	32/26, 33/27, 34/28[2]

[1] mean and standard deviation
[2] stand contained regrowth of two ages

Fuels

The data on fine fuel load, which are summarised in Table 3, show a high total fine fuel load of mean 16 to 22 t/ha, comprising a mean of 11 to 16 t/ha of litter bed fuel and a mean of 6 to 8 t/ha of total shrub fuel. This shrub fuel included 2 to 3 t/ha of elevated dead fuel. Stick debris contributed a mean of 2 to 4 t/ha; and the coarse fuel data, which are summarised in Table 4, show a high fuel load of branch and old log material of mean 150 to 182 t/ha. Although the total fine fuel load varied between sites, the mean shrub height in these long unburnt fuels was a consistent 1.1 to 1.2 m.

Table 3. Fine fuel loads at the study sites.

Study Site	Shrub height (m)	Fine fuel load (0-6mm) (t/ha)					Stick debris (6-25mm) (t/ha)
		Elevated dead fuel	Living shrub fuel	Total shrub fuel	Litter bed fuel	Total fine fuel	
Patrol/Tolly Track	1.2 (0.2)[1]	3.1 (3.0)	5.2 (2.9)	8.3 (4.5)	10.9 (3.5)	19.3 (7.3)	2.1 (1.9)
Hippo Track South	1.2 (0.4)	2.1 (0.9)	4.7 (1.9)	6.9 (1.7)	15.5 (3.3)	22.4 (4.2)	3.7 (2.6)
Hippo Track South[2]	1.1 (0.2)	n.a.	n.a.	5.5 (2.9)	10.9 (2.0)	16.4 (2.8)	2.9 (1.5)
Hippo Track North	1.1 (0.3)	n.a.	n.a.	7.1 (4.4)	10.9 (3.4)	17.9 (3.4)	2.4 (1.3)

[1] mean and standard deviation
[2] fuel load data for 0/92/16/A, 0/92/17/A, 0/92/18/A: Source Fogarty (1993)

Table 4. Coarse fuel loads at the study sites.

Study site	Diameter class (cm) by dry weight (t/ha)			
	2.6 - 10.0	10.1 - 30.0	> 30.0	Total
Patrol/Tolly Track	6.4 (2.4)[1]	21.6 (5.1)	141.1 (108.9)	169.1 (102.9)
Hippo Track South	8.3 (2.4)	43.1 (26.0)	130.3 (80.6)	181.7 (88.1)
Hippo Track North	4.2 (1.6)	50.6 (13.8)	94.9 (90.8)	149.7 (84.8)

[1] mean and standard deviation

Fuel moisture content

The data that were collected on fine fuel moisture content during the experimental burning are summarised in Table 5. Mean moisture content values of elevated dead fuel varied from 11% to 18%, mean moisture content values of exposed surface litter varied from 13% to 30%, mean moisture content values of shaded surface litter varied from 25% to 55% and mean moisture content values of profile litter (WA) varied from 37% to 188%. The moisture content of replicate samples of the shaded surface litter class and the profile litter class varied considerably, as is shown by the high standard deviations. Fuel of higher moisture content from lower in the fuel profile, but collected as part of the sample of exposed surface litter, probably contributed to the variability between replicated samples of this class. The least variability between replicate samples was found in the elevated dead fuel class.

Table 5. Fine fuel moisture content data from the experimental burns.

Burn identification	Fine fuel moisture content (% ODW)				
	Elevated dead fuel	Exposed surface litter	Shaded surface litter	Profile litter (AB)	Profile litter (WA)
0/88/1/A	15 (1)[1]	15 (1)	28 (11)	119 (23)	119[2]
0/88/2/A	13 (1)	16 (1)	29 (10)	119 (23)	119[2]
0/88/3/A	14 (1)	20 (2)	26 (2)	119 (23)	119[2]
0/88/5/S	11 (1)	13 (2)	43 (22)	96 (85)	96[2]
0/89/6/A	17 (1)	30 (11)	55 (30)	188 (28)	188[2]
0/89/7/A	17 (2)	25 (3)	53 (19)	129 (50)	129[2]
0/89/8/A	18 (3)	27 (-)	32 (2)	75 (19)	70[2]
0/90/9/A	14 (1)	17 (3)	40 (17)	144 (77)	144[2]
0/90/10/A	15 (2)	19 (6)	25 (8)	75 (28)	71[2]
0/90/11/A	15 (1)	19 (4)	27 (8)	88 (63)	88[2]
0/91/14/A	13 (2)	15 (2)	34 (16)	44 (20)	31[2]
0/92/15/A	18 (1)	27 (4)	-	77 (16)	70 (13)
0/92/15/A	17 (0)	22 (2)	-	87 (19)	89 (15)
0/92/16/A	15 (1)	21 (5)	-	72 (23)	37 (6)
0/92/16/A	11 (1)	14 (1)	-	60 (17)	53 (17)
0/92/17/A	14 (2)	23 (1)	-	81 (25)	56 (15)
0/92/18/A	14 (1)	21 (4)	-	60 (21)	53 (13)

[1] mean and standard deviation

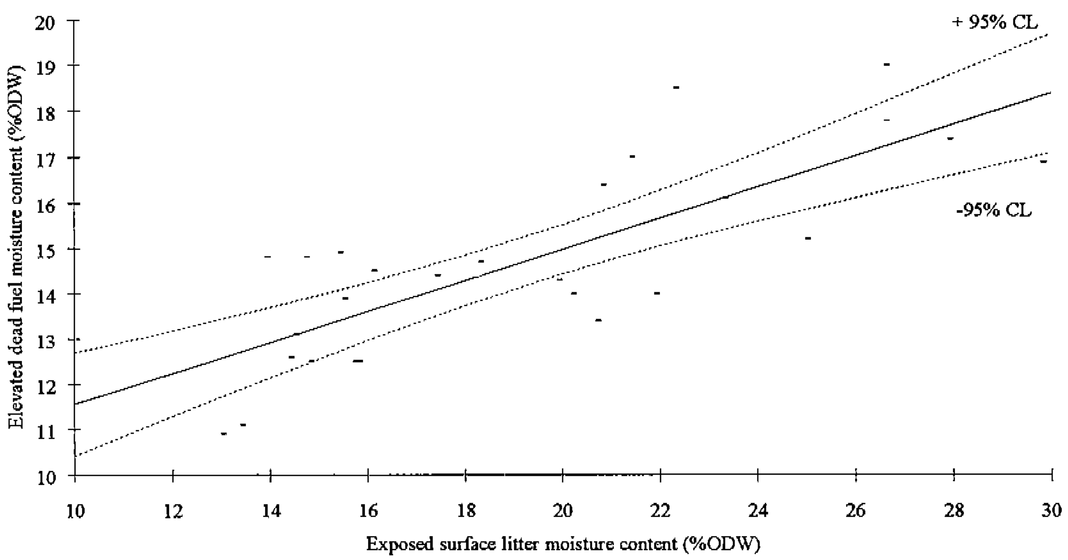
[2] If PLMC (AB) $\geq$ 90%, PLMC (WA) = PLMC (AB)
If PLMC (AB) $<$ 90%, PLMC (WA) = (PFMC(AB)-20.3)/0.775

Using the data from the smaller (n=27) fuel moisture data base, the moisture content of the elevated dead fuel (EDFMC) was found to be related to the moisture content of the exposed surface litter (ESLMC) by the following equation, with the standard errors shown in brackets below the coefficients:

$$\underset{}{EDFMC = \underset{(0.20)}{8.14} + \underset{(0.010)}{0.342}\, ESLMC} \qquad r^2(adj) = 60.8\%$$

This equation makes practical sense only where the value of moisture content of exposed surface litter is greater than or equal to the value of moisture content of elevated dead fuel i.e. at moisture contents of 12% or more. The equation, the 95% confidence limits (population mean) and the raw data are shown on Figure 3. When using data from the larger (n=44) fuel moisture content data base, a similar linear equation was derived but because the r^2 (adj) was lower (49.6%), the previous equation was adopted.

Figure 3. Raw data, regression equation and 95% confidence limits (population mean) of the relationship between elevated dead fuel moisture content and exposed surface litter moisture content.



The moisture content of the profile litter (AB) (PLMC(AB)) was found to be related to the moisture content of the profile litter (WA) (PLMC(WA) by the following equation, with the standard errors shown in brackets below the coefficients:

$$PLMC\,(AB) = \underset{(1.4)}{20.3} + \underset{(0.022)}{0.775}\, PLMC\,(WA) \qquad r^2(adj) = 57.3\%$$

This equation can be reversed to the form:

$$PLMC(WA) = (PLMC(AB) - 20.3)/0.775$$

However, these equations make practical sense only where the value of moisture content of profile litter (WA) is less than or equal to the value of moisture content of profile litter (AB). Hence, in applying this equation, the profile litter (WA) was assumed to equal profile litter (AB) for values of profile litter (AB) which were greater than 90%.

The available fuel factor of each of the experimental burns is highlighted on Figure 4. Fire spread was generally not sustained with an available fuel factor of 0.1 and fire behaviour was higher than acceptable with an available fuel factor of 0.5 or greater. Most of the successful burning was conducted under conditions of fuel moisture where the available fuel factor was 0.2 or 0.3.

Figure 4. Available fuel factors and broad fire behaviour of the experimental burns[1].

Exposed surface litter moisture content (%ODW)	Profile litter moisture content (%ODW)									
	10-14	15-19	20-24	25-30	31-40	41-60	61-80	81-120	121-160	161+
3-6	B	B	1.0	0.9	0.9					
7-9	B	B	1.0	0.8	0.7	0.6	0.5	0.4	0.3	0.3
10-12	B	A	1.0	0.8	0.6	0.5	0.4	0.3	0.3	0.3
13-15	B	A	1.0	0.7	0.5[a]	0.4[b]	0.3	0.3[bb]	0.2	0.2
16-18	A	A	1.0	0.6	0.4	0.3	0.3	0.2[b]	0.2[b]	0.1
19-21	A	1.0	0.9	0.5	0.4	0.3[bb]	0.2[b]	0.1[bb]	0.1	0.1
22-25	A	1.0	0.8	0.5	0.3	0.2[b]	0.1	0.1[c]	0.1[c]	0.1
26+			-	-	-	-	cc	-	-	c

[a] Behaviour of experimental burn was too high (as judged by high levels of scorch)
[b] Behaviour of experimental burn was acceptable (available fuel factors of 0.2 and 0.3 are highlighted)
[c] Behaviour of experimental burn was too low (as judged by low or zero rate of spread)

[1]Available fuel factor table reproduced and adapted from Sneeuwjagt and Peet(1985), with permission from the Department of Conservation and and Land Management, W.A. (Indices A and B represent dangerously dry fuels; prescribed burning is most successful in Western Australian fuels when the available fuel factor is between 0.3 and 0.7 inclusive).

Weather

The experimental burning was conducted under a wide range of seasonal and daily weather conditions, which are summarised in Table 6. Most burning was conducted during the autumn months of March and April, although successful burns were also conducted during winter and spring. Burns were conducted at temperatures of 16^{o} to 27^{o}C, relative humidities of 46% to 79% and at wind speeds almost entirely in the Beaufort Scale classes of 0-5 km/h and 6-11 km/h, with one data point being collected in the 12-19 km/h class. Drought factors were calculated to range from 4 to 9 but did not correspond with the similarly defined available fuel factor. Indices of the Byram Keetch Drought Index at which successful burning was conducted in the coastal forests ranged from 40 to 100. However, successful burning in late autumn on northern aspects of the foothill forests was also conducted at much lower indices. All burning was conducted at forest fire danger indices of five or less.

Table 6. Summary of weather variables, drought and forest fire danger indices measured at the experimental burns.

Burn identification	Temperature (^{o}C)	Relative humidity (%)	Wind speed at canopy (km/h)	Byram Keetch Drought Index (Orbost)	Drought factor	Forest fire danger index
0/88/1/A	20.0 to 21.0	73 to 86	0-5, 6-11	97	7	1 to 2
0/88/2/A	22.5 to 24.5	46 to 70	0-5, 6-11	98	7	2 to 5
0/88/3/A	19.0 to 20.5	67 to 68	0-5, 6-11	100	9	2 to 3
0/88/4/W	18.0 to 19.0	47 to 51	0-5, 6-11	39	7	3 to 4
0/88/5/5	17.0 to 18.5	40 to 53	0-5, 6-11	24	6	2 to 4
0/89/6/A	17.5	73	0-5	7	4	1
0/89/7/A	19.5 to 22.0	63 to 78	0-5	13	5	1 to 2
0/89/8/A	19.5 to 21.0	67 to 69	0-5, 6-11	15	5	1 to 2
0/90/9/A	17.2 to 19.5	59 to 65	0-5, 6-11	64	9	2 to 3
0/90/10/A	19.0 to 20.0	66 to 70	0-5, 6-11	65	9	2
0/90/11/A	21.0 to 21.5	72 to 75	0-5, 6-11	66	9	2
0/90/12/A	16.4 to 17.5	64 to 74	0.5, 6-11	11	6	1 to 2
0/90/13/A	17.0 to 18.5	52 to 66	0-5	12	6	1 to 2
0/91/14/A	20.8 to 21.0	66 to 69	0-5, 12-19	40	7	2 to 3
0/92/15/A	20.0 to 20.6	73 to 79	0-5	64	9	2
0/92/16/A	25.6 to 27.0	47 to 58	0-5	65	9	4 to 5
0/92/17/A	26.1 to 26.5	52 to 58	0-5, 6-11	65	9	5
0/92/18/A	23.3 to 24.7	54 to 74	0-5	79	9	2 to 4

Seasonal conditions, as represented by the Soil Dryness Index and the Byram Keetch Drought Index are shown in Appendix A for five years from 1987/88 to 1991/92 with the dates indicated when the burns were conducted. Both indices clearly show the same seasonal trends but actual values of the Byram Ketch Drought Index are consistently lower. The poor burning season of the wet autumn of 1989 can be compared with the seasons of autumn 1990, 1991 and 1992 where, following various combinations of summer rainfall, early autumn rains were followed by a period where conditions were characterised by a moderate but rising drought index and hence, subject to daily weather, generally good conditions for conducting fuel reduction burning.

Fire behaviour

The fire behaviour of the experimental burns varied widely, both between the separate zones of each burn and between each burn, as is shown in Table 7 and on Photos 1 to 4. Rates of spread of the head fires varied from very low or zero up to a maximum of 147m/h, corresponding to a fireline intensity of 970 kW/m. The maximum fireline intensity of 1005 kW/m was calculated for a lower rate of spread of 116 m/h but a higher quantity of fuel consumed. However the rates of spread of most head fires were less than 70 m/h.

Table 7. Rate of spread and fireline intensity data from the experimental burns.

Burn identification	Range in fire behaviour characteristics from t = 20 minutes after ignition					
	Back fire		Flank fire		Head fire	
	Rate of spread (m/h)	Fireline intensity (kW/m)	Rate of spread (m/h)	Fireline intensity (kW/m)	Rate of spread (m/h)	Fireline intensity (kW/m)
0/88/1/A	13 to 16	90 to 115	27 to 44	195 to 320	36 to 65	265 to 470
0/88/2/A	*	*	39 to 48	285 to 350	50 to 56	365 to 400
0/88/3/A	5 to 7	40 to 50	14 to 28	100 to 205	25 to 60	180 to 435
0/88/4/A	*	*	*	*	*	*
0/88/5/S	12	100	18 to 53	155 to 455	28 to 116	245 to 1005
0/89/6/A	0	0	0	0	0	0
0/89/7/A	0	0	7	30	5 to 18	20 to 85
0/89/8/A	0	0	13	60	24	110
0/90/9/A	9	60	9 to 26	60 to 175	15 to 31	100 to 205
0/90/10/A	5 to 15	35 to 100	13 to 38	85 to 255	10 to 50	65 to 335
0/90/11/A	5	35	15 to 41	100 to 275	120	795
0/90/12/A	*	*	*	*	*	*
0/90/13/A	*	*	*	*	*	*
0/91/14/A	11	70	58 to 70	385 to 465	54 to 147	360 to 970
0/92/15/A	*	*	*	*	*	*
0/92/16/A	13 to 24	80 to 145	25 to 42	150 to 250	30 to 51	175 to 305
0/92/17/A	*	*	*	*	49 to 89	290 to 530
0/92/18/A	*	*	13 to 24	75 to 145	46 to 57	275 to 340

* not measured

Photo 1. Circular fire development of experimental burn 0/88/2/A at 14 minutes after ignition.

Photo 2. Fire behaviour of the head fire of experimental burn 0/88/2/A at 29 minutes after ignition (20 minute rate of spread = 52m/h).

Photo 3. **Fire behaviour of the head fire of experimental burn 0/88/1/A at 51 minutes after ignition (20 minute rate of spread = 65m/h).**

Photo 4. **Fire behaviour of the rear flank and back fire of experimental burn 0/88/1/A at 46 minutes after ignition (20 minute rate of spread = 17m/h).**

The length to breadth ratios for each experimental burn, as is shown in Table 8, ranged from 0.9 to 1.8:1, with 28 of the 42 observations in the range of 0.9 to 1.2:1. The spread of the perimeters of each fire, which are shown in Appendix B, clearly show the directions of fire spread which were caused by both small and larger changes in wind direction, as well as the overall development of each point ignition.

Table 8. **Length to breadth ratios of the experimental burns.**

Burn identification	Length to breadth ratios at 20 minute time intervals						
	0 to 20	20 to 40	40 to 60	60 to 80	80 to 100	100 to 120	120 to 140
0/88/1/A	1.3 : 1	1.5 : 1	1.6 : 1	1.5 : 1			
0/88/2/A	1.1 : 1	1.0 : 1					
0/88/3/A	1.6 : 1	1.1 : 1	0.9 : 1	1.0 : 1			
0/88/4/A	*						
0/88/5/S	1.8 : 1	1.2 : 1	0.9 : 1	0.9 : 1			
0/89/6/A	*						
0/89/7/A	*						
0/89/8/A	*						
0/90/9/A	1.0 :1	0.9 : 1	0.9 : 1	1.0 : 1	1.1 : 1	1.2 : 1	1.2 : 1
0/90/10/A	1.4 : 1	1.4 : 1	1.3 : 1	1.6 : 1	1.6 : 1	1.6 : 1	
0/90/11/A	1.0 : 1	1.6 : 1					
0/90/12/A	*						
0/90/13/A	*						
0/91/14/A	0.9 : 1	0.8 : 1	0.9 : 1				
0/92/15/A	*						
0/92/16/A	1.2 : 1	1.1 : 1	1.1 : 1	1.1 : 1	1.2 : 1	1.2 : 1	
0/92/17/A	*						
0/92/18/A	1.1 : 1	1.4 : 1					

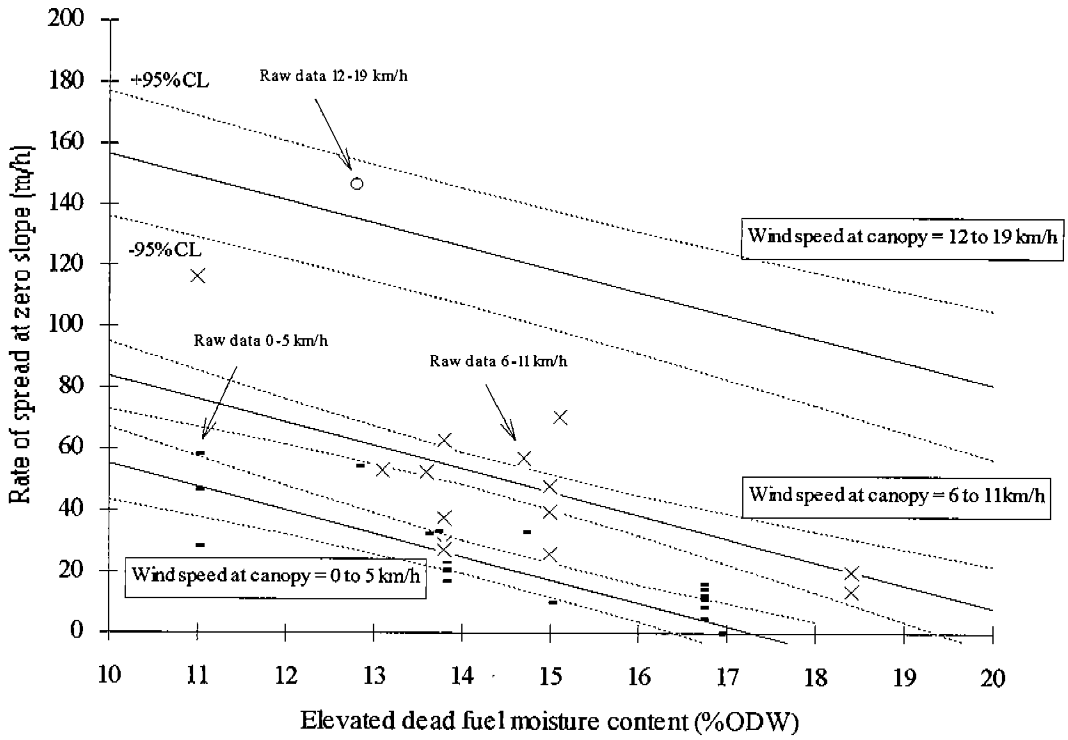
* not measured or fire spread not sustained

Elevated dead fuel moisture content (EDFMC) and wind speed squared ($WIND^2$) were found to be the strongest predictors of rate of spread at zero slope (ROS0) although, using the independent data, the chi-squared test just failed to indicate a significant relationship at the 0.05 level of probability. The variables were related by the following equation, with standard errors shown in brackets below the coefficients:

$$ROS0 = \underset{(2.6)}{128.0} - \underset{(0.18)}{7.58}\ EDFMC + \underset{(0.007)}{0.434}\ WIND^2 \qquad r^2(adj) = 79.1\%$$

The equation, the 95% confidence limits (population mean) and the raw data are shown on Figure 5. This relationship shows that fire spread in the Wiregrass fuel type is very responsive to an increase in wind speed and that when wind speed is a low 0 - 5 km/h, fire spread is not sustained when the elevated dead fuel moisture content is 16% or greater.

Figure 5. **Raw data, regression equation and 95% confidence limits (population mean) of the relationship between rate of spread at zero slope and elevated dead fuel moisture content and wind speed.**

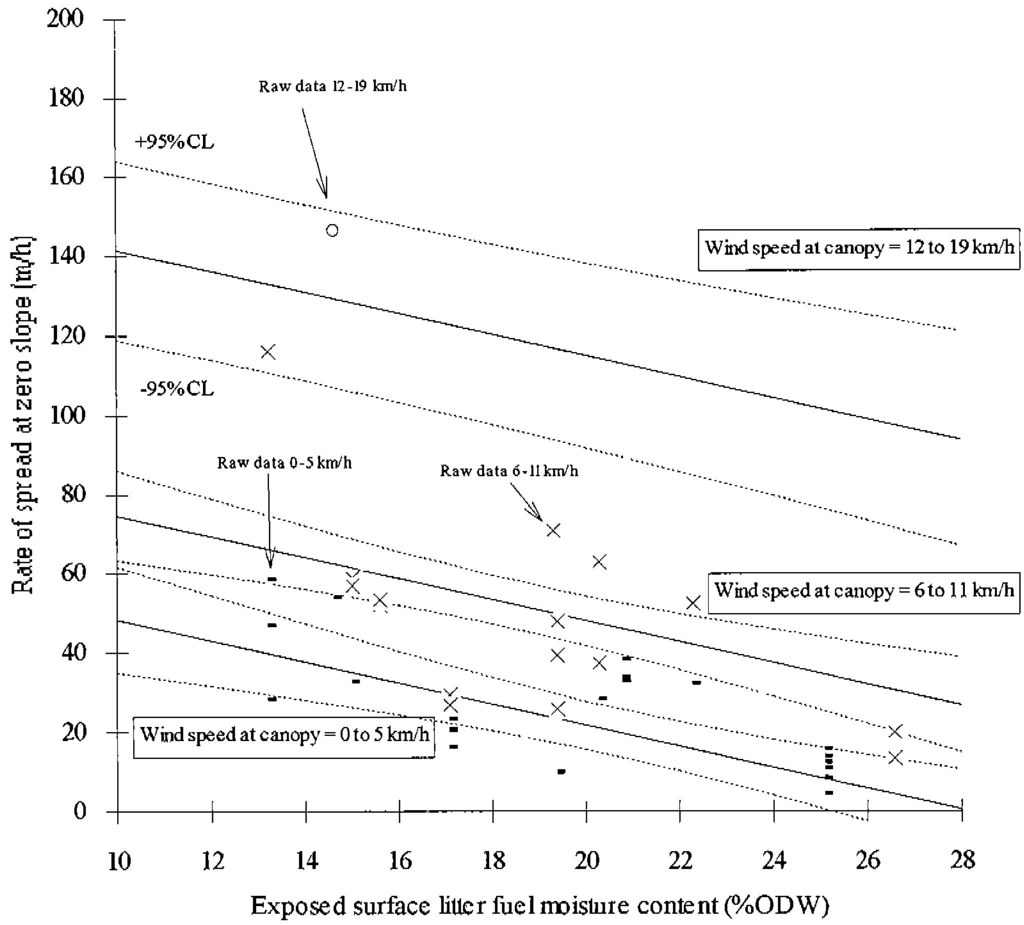


Exposed surface litter moisture content (ESLMC) and wind speed squared ($WIND^2$) were also found to predict strongly the rate of spread at zero slope (ROS0). They were related by the following equation, with standard errors shown in brackets below the coefficients:

$$ROS0 = \underset{(1.9)}{72.3} - \underset{(0.085)}{2.65}\ ESLMC + \underset{(0.009)}{0.398}\ WIND^2 \qquad r^2(adj) = 71.7\%$$

The equation, the 95% confidence limits (population mean) and the raw-data are shown on Figure 6. This relationship shows that when wind speed is a low 0 - 5 km/h, fire spread is not sustained when the exposed surface litter moisture content is 25% or greater. However, for burning operations to be practical, rates of spread must be greater than 20m/h and under these wind conditions this relationship shows that an exposed surface litter moisture content of 21% or less is required.

Figure 6. **Raw data, regression equation and 95% confidence limits (population mean) of the relationship between rate of spread at zero slope and exposed surface litter fuel moisture content and wind speed.**



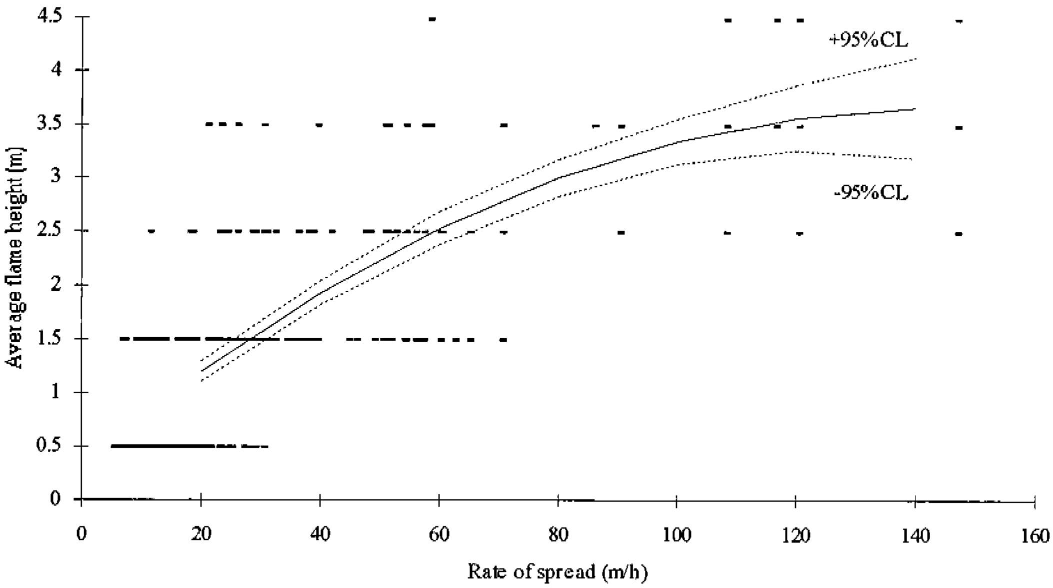
Adding the independent variables which represent further measures of fuel moisture content (i.e. profile litter moisture content (WA), fuel availability factor, Byram Keetch Drought Index or drought factor) did not improve the preferred relationship. Similarly, the independent variable of fuel quantity did not improve the model.

Rate of spread (ROS) was found to predict the average flame height (FHT) and was related by the following equation, with standard errors shown in brackets below the coefficients:

$$FHT = \underset{(0.01)}{0.35} + \underset{(0.0003)}{0.0458}\,ROS - \underset{(0.000002)}{0.000158}\,ROS^2 \qquad r^2(adj) = 56.2\%$$

The equation, the 95% confidence limits (population mean) and the raw data are shown on Figure 7. Using this model, when the rate of spread is 20m/h, the predicted average flame height is 1.2 m and when the rate of spread is 120m/h, the predicted average flame height is 3.6m.

Figure 7. **Raw data, regression equation and 95% confidence limits (population mean) of the relationship between average flame height and rate of spread.**



Unburnt fine fuel

The conditions of high moisture content of fuels lower in the fuel profile combined with the mild weather conditions under which most of the experimental burns were conducted resulted in a proportion of the fine fuels remaining unburnt. Fire spread was not sustained in a practical sense under the conditions of very high fuel moisture content measured during the three experimental burns conducted during autumn 1989. Hence, where these fuels did burn, the mean fine fuel load remaining unburnt was a high 7.4 t/ha (sd 1.0) which comprised of 6.4 t/ha (sd 1.9) of litter bed fuel and 1.0 t/ha (sd 1.7) of shrub fuel. At the experimental sites where burning was sustained, the mean fine fuel load remaining unburnt was 3.0 t/ha (sd 2.1) which comprised of 2.3t/ha (sd 1.5) of litter bed fuel and 0.7 t/ha (sd 1.3) of shrub fuel. Based on the measured fine fuel loads before burning and a mean of 3.0 t/ha of fine fuel which remained unburnt, 82 to 87% of fine fuel was removed by burning.

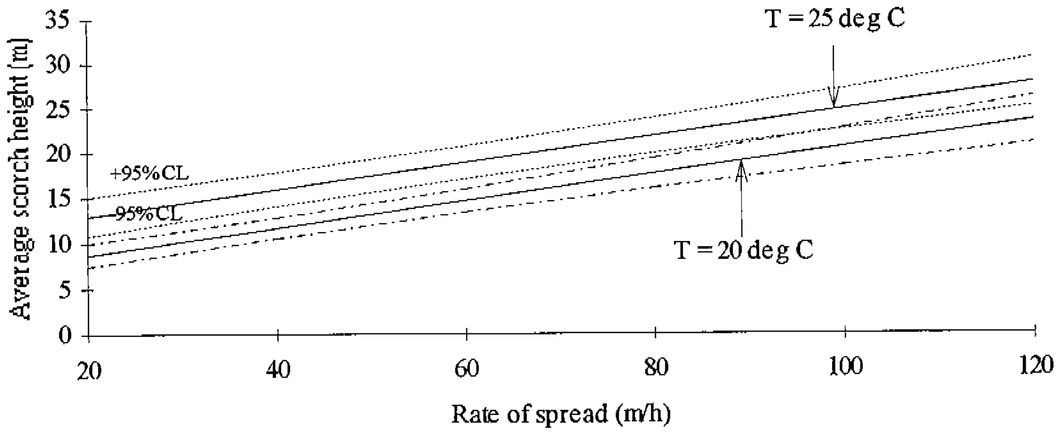
Crown scorch

Rate of spread (ROS) was found to be a strong predictor of average scorch height (SC) and temperature (T) was found to improve the relationship. They were related by the following equation, with standard errors shown in brackets below the coefficients:

$$SC = \underset{(0.7)}{-11.1} + \underset{(0.002)}{0.148}\,ROS + \underset{(0.033)}{0.844}\,T \qquad r^2(adj) = 74.1\%$$

The equation and the 95% confidence limits (population mean) for temperatures of 20°C and 25°C are shown on Figure 8. Hence, for a rate of spread of 60 m/h, the predicted average scorch height at 18°C is 13m, at 22°C is 16 m and at 26° is 20m.

Figure 8. **Regression equation and 95% confidence limits (population mean) of the relationship between average scorch height and rate of spread at temperatures of 20°C and 25°C.**

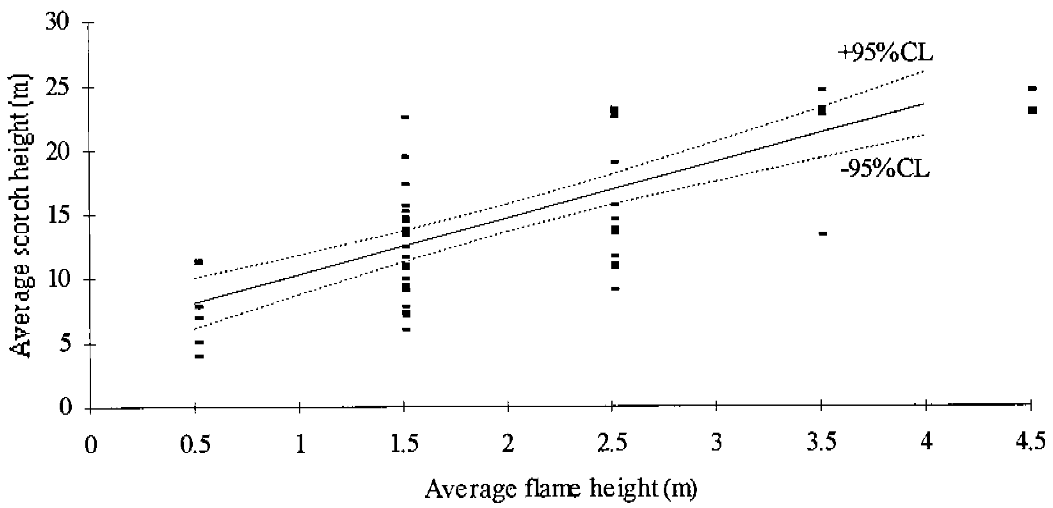


Average flame height (FHT) was also found to be a predictor of average scorch height (SC). They were related by the following equation with standard errors shown in brackets below the coefficients:

$$SC = 5.89 + 4.40\ FHT \qquad r^2(adj) = 50.3\%$$
$$(0.15)\ (0.07)$$

Adding temperature as a second independent variable did not improve the model, nor did any of the transformations. The equation, the 95% confidence limits (population mean) and the raw data are shown on Figure 9. Using this model, when the average flame height is 1.2m, the predicted average scorch height is 11m and when the flame height is 3.6m, the predicted average scorch height is 22m.

Figure 9. **Raw data, regression equation and 95% confidence limits (population mean) of the relationship between average scorch height and average flame height.**



Stem damage

Stem damage occurred to a mean of 6.2% of the total of 838 stems that were assessed. The major sources of damage were old log material (from harvesting) (42%), fallen stag[1] or stem and branch material (39%), followed by stumps (9%) and an unknown source, which was probably the intensity of the flame front (10%). The damaged stems were located a mean of 0.3m (sd = 0.4) from the three known damage sources. Stem damage increased at the experimental burns, as is shown in Tables 9 and 10, where fire intensity from active fire fronts or junctions zones was high enough to cause upper crown scorch and epicormic crown development. A mean of 9.2% (sd = 3.4) of stems were damaged compared to a mean of a very low 2.6% (sd = 1.2) where upper crowns had not been scorched and, as shown by the t-test at the 0.05 level of probability, these two means were significantly different. However, at this 9.2% level of stem damage, crown damage from scorch was potentially of much greater significance to the growth of the stand.

Table 9. Stem damage data from experimental burns where some of the upper crowns <u>had</u> been scorched.

Burn identification	Age of regrowth when burnt (years)	Percentage of burnt area assessed (%)	Number of regrowth stems assessed	Percentage of regrowth stems damaged (%)	Mean DBHOB of damaged stems (cm)
0/90/11/A	27, 33	3.3	45	8.9	19.7 (5.1)[3]
9/91/14/A[1]	28, 34	1.9	120	4.2	15.3 (5.6)
B/90/4/A	16	1.5	150	8.7	15.0 (3.9)
B/91/6/A	18	n.a.	152	10.5	16.9 (4.7)
B/91/8/A[2]	26	1.3	161	13.7	14.2 (3.6)
Mean (sd)				9.2 (3.4)	

[1] 25.0% of stems had epicormic crowns
[2] 28.6% of stems had epicormic crowns
[3] mean and standard deviation

[1] Dead old growth trees (known as stags) which had resulted from Tordon poisoning operations were a major damage source at B/91/8A. These stags had fallen prior to the burn and ignited during the burn or burnt, fell over and then continued to burn.

Table 10. Stem damage data from experimental burns where upper crowns had not been scorched.

Burn identification	Age of regrowth when burnt (years)	Percentage of burnt area assessed (%)	Number of regrowth stems assessed	Percentage of regrowth stems damaged (%)	Mean DBHOB of damaged stems (cm)
B/89/2/S	16	3.6	42	2.4	11.2 (0.0)[1]
B/91/7/A	26	2.2	73	4.1	11.6 (2.3)
B/91/9/A	26	6.6	81	2.5	12.8 (0.0)
B/91/10/A	26	1.7	81	1.2	10.5 (0.0)
Mean (sd)				2.6(1.2)	

[1] mean and standard deviation

DISCUSSION

The empirical approach to developing fire behaviour guides for forest fuels has been used successfully in Australia (e.g. McArthur 1962, 1967, 1973, FCV 1970, Peet 1972, Sneeuwjagt and Peet 1985 and Cheney *et al.* 1992) and in Canada (e.g. Van Wagner 1990, Alexander *et al.* 1991). This approach has widespread support among Australian fire managers (Burrows and Sneeuwjagt 1988), despite the difficulties of adequately replicating the fuel, site, seasonal and weather conditions within the short burning seasons and limited project time lines. The data collected in this study cover the range of fire behaviour where fuel reduction objectives can be achieved without causing significant damage to regrowth forests. Hence, these data provide a high degree of confidence in the fire behaviour models developed, provided that they are applied within the Wiregrass fuel type and under similar conditions of fuel moisture and weather.

The apparent lack of a significant relationship between fuel load and rate of spread in these data can be attributed to the long unburnt status of the fuels that were studied and to the limited variation in total fuel load between most sites. Alternatively, this result may support other recent research which indicates that fuel load alone may not be a strong predictor of fire behaviour (Cheney 1990a). However, an important factor is fuel structure, particularly where shrub fuels dominate the fuel complex, as shown by the significant relationship between shrub height (near-surface fuel height) and rate of spread in the shrub dominated, but relatively uniform, fuels of the regrowth forests of south eastern New South Wales (Cheney *et al.* 1992). In East Gippsland, Wiregrass fuel development does vary between sites and with time since fire (Fogarty 1993) and the relationship between shrub height and rate of spread that was developed by Cheney *et al.* (1992) may be appropriate to use to modify the predicted rate of spread in Wiregrass fuel complexes that are more or less developed then at the sites of the present study. However, until this is verified by field measurement, a reasonable rule of thumb is that the expected effect in Wiregrass fuels of shrub height greater than 1.2m is fire behaviour that is greater than predicted and conversely, where shrub height is less than 1.2m, fire behaviour that is less than predicted.

The apparent lack of effect of the moisture content of profile fuels on rate of spread may be attributed to the lack of any data where the moisture content of profile fuels was low. The moisture content of profile fuels was greater than 50% ODW for nearly all burns and free moisture was almost always present. Moist profile fuels were identified over 30 years ago by McArthur (1962) as being an important factor in low intensity fire behaviour and subsequently published prescribed burning guides have similarly stressed or quantified this factor (Peet 1972, Woodman and Rawson 1982, Sneeuwjagt and Peet 1985, McCaw 1986, Burrows *et al.* 1988 and Buckley and Corkish 1991). Wet fuels generate considerably less heat radiation than dry fuels (Vines 1981) and cause a proportion of the fine fuel to remain unburnt and hence, for a given rate of spread, to generate lower fireline intensities. The practical experience with these fire behaviour experiments indicated that, to achieve low intensity fire behaviour in the highly flammable Wiregrass fuels, the moisture content of profile fuels must be high.

Adopting the available fuel factors of Sneeuwjagt and Peet (1985) to indicate a 'moisture content window' for conducting burning in Wiregrass fuels clearly showed that the suitable window was narrower than for the Western Australian fuel type. The definition of available fuel factor implies that a percentage of fuel is available to burn and in fact does burn. However, burning under conditions of available fuel factors of 0.2, 0.3 and 0.4 resulted in a much higher proportion of the fine fuel being removed than implied by these factors. Hence, rather than conducting many more burns to derive a new table of fuel availability factors for Wiregrass fuels, a suitable 'moisture content window' for burning can be identified by using the existing factors and, to avoid possible confusion, re-naming them as moisture content indices.

The apparent lack of significance of the McArthur drought factor as an additional independent variable in predicting rate of spread was not surprising as the fuel drying curves used to derive these factors were developed for the litter only fuel type (Luke and McArthur 1978) which, it is reasonable to assume, exhibits quite different drying characteristics. Direct measures of elevated dead or exposed surface and profile litter moisture contents to define a 'moisture content window' suitable for burning offers the advantages of accuracy, site specificity and a potential to model[1] predictively compared to the analogue approach of the McArthur forest fire danger meter.

The high levels of humidity of up to 79% at which fire spread was sustained were surprising. Relative humidity is a key variable affecting fuel moisture content (Luke and McArthur, 1978) and, as shown by comparing the present results to the Controlled Burning Meter Mk2 (FCV 1970), rates of spread in Wiregrass fuels are sustained at much higher surface fuel moisture contents than in litter only fuels. Observations during the experimental burning indicated that when the relative humidity was greater than 60% early in the afternoon and was not decreasing, the moisture content of elevated dead and exposed surface fuels had, as a consequence, probably reached a minimum for the day. Such a situation facilitates increased confidence in predicting fire behaviour during the following few hours. Similarly, a high relative humidity in the late afternoon indicated suitable conditions, provided that any sea breeze was of a low strength, for successful burning in regrowth stands. The preferred range of relative humidity for conducting burning in Wiregrass fuels is greater than 60% and burning should not be conducted when relative humidity is less than 50%.

The importance of the elevated dead fuel class within the Wiregrass fuel complex was shown, not by its relatively low fuel load, but by the strong relationship with rate of spread and by the sustained spread of experimental fires when the moisture content of exposed surface litter was greater than 20% ODW. Under prescribed burning conditions most eucalypt fuels are self extinguishing at a fuel moisture of around 20% ODW (Cheney 1981) but in Wiregrass fuels, the elevated dead fuel, which was of lower moisture content than the damp surface fuel and which was located within the flammable shrub layer, appeared to ensure that fire spread was sustained. Clearly, this fuel class adds significantly to the hazard of the fuel complex.

The moisture content of either elevated dead or exposed surface litter combined with wind speed at canopy level can be used to predict, within reasonable confidence limits, the rate of spread on level ground of fire in Wiregrass fuels. The fire spread models for prescribed burning in various Australian fuel types summarised by Cheney (1981) all use the moisture content of surface fuels (or an analogue which predicts moisture content) and wind speed as key variables predicting fire spread, although the form of each model varies. Cheney *et al.* (1992) identified the moisture content of elevated dead fuel (near-surface dead fuel) as a significant variable in the elevated fuel type studied, although the moisture content of surface fuel was not shown to be significant. Variables must be carefully defined so that they can be directly measured in the field by a method which provides consistent results. The elevated dead fuel variable in this study, because of the ease of identification and collection, the lower errors involved in sampling and the greater statistical significance of the fire spread model, is preferred.

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[1] Comprehensive fuel moisture content and weather data have been collected for the Wiregrass fuel type in East Gippsland during the 1991/92 spring, summer and autumn period by Fogarty (pers. comm.). These data should enable the drying patterns and fuel moisture regimes to be modelled and hence, to allow managers to predict fuel moisture content for fire control purposes and also to predict when sites on different aspects will be broadly suitable for fuel reduction burning (Liam Fogarty, Fire Research Officer, C/- Fire Management Branch, CNR, Melbourne).

Using the Beaufort Scale to estimate, rather than an instrument to measure, wind speed had the important advantage that this scale can be readily used by operational staff conducting operational burns, but had the disadvantage that, as the data were not electronically measured, the options for analysis were reduced. Representative siting of sensitive cup anemometers at canopy level or at 10m in the open is difficult when the fire is in fact burning near ground level within the forest. Similar difficulties are faced when siting instruments to measure the wind speed actually experienced at the flame front, difficulties which are compounded if equipment and technical assistance is limited. The wind ratios defined by McArthur (1962) between wind speed at 10m in the open and wind speed at 1.5m within a fully stocked stand, 21m to 30m tall, were considered to represent the ratios at the experimental sites and hence to indicate a 1.5m wind speed for operational purposes. However, the low in-forest wind speeds which are suitable for conducting fuel reduction burning in Wiregrass fuels and which correspond to Beaufort Scale numbers 1 and 2 are very difficult to measure by hand held anemometers, unless the instrument is very sensitive. The clear definitions of the Beaufort Scale classes, particularly when the specifications of tree movement used by Rothermel and Rinehart (1983) are included, provide a practical method of estimating wind speed in the field.

Excluding the variable of slope in the experimental design did not cause any difficulty in developing a fire spread model. The slope factors of McArthur (1962) are accepted and adopted for all Australian tables of fire behaviour (Cheney 1981) and the most recent studies of Cheney *et al.* (1992) confirmed the suitability of these factors for use in forests with a shrub fuel type. The possibility of any additional interaction between shrub fuel and slope on rate of spread seems unlikely. Based on these factors, which indicate that a 10° slope will double rate of spread, but depending on the predicted rate of spread on level ground, the lighting of fires to burn uphill in regrowth forests on slopes greater than about 10° should be avoided.

The finding that scorch height was related to flame height was consistent with McArthur (1962) although, for a given flame height, predicted scorch height was more than one-and-a-half times higher in the current study. Similarly, the finding that scorch height was related to rate of spread and/or temperature was consistent with other Australian studies. Specifically, temperature was shown to be a variable affecting crown scorch on the Control Burning Meter Mk2 (FCV 1970), by Tolhurst *et al.* (1992) and by Cheney *et al.* (1992). Cheney *et al.* (1992) also identified that wind speed affected crown scorch and recommended against burning under zero wind conditions because of increased convective transfer of heat energy and hence higher scorch height. The scorch height predicted for a given rate of spread and temperature is significantly greater for this study than that predicted by the Prescribed Burning Guide for Young Regrowth Forests of Silvertip Ash (Cheney *et al.* 1992). This can be at least partly explained by higher shrub height and also higher fuel loads and hence higher fireline intensities for a given rate of spread at the experimental sites in East Gippsland. The importance of temperature to scorch height can be clearly seen and burning should be conducted when temperatures do not exceed $25^{\circ}C$ and preferably, when temperatures do not exceed $22^{\circ}C$.

A clear limit to the conditions under which prescribed burning may be conducted in regrowth forests is scorch height. Fire behaviour which causes widespread crown scorch has a high visual impact and results in a rapid return of available fuel to the site (Luke and McArthur 1978) and a significantly reduced rate of basal area growth (Incoll 1981). Epicormic shoots replace the scorched crown and, with increasing fire severity, the leading shoot may be killed resulting in a dry spike remaining and a new leading shoot developing from lower on the stem. Hence, a stem kink will result and the entry of wood decay fungi and wood destroying insects will be facilitated. When prescribing fire behaviour, a scorch height limit of two thirds of the dominant height of the stand gives limited scope for actual fire behaviour to be greater than planned without causing excessive damage. Having defined this scorch height limit, the scorch height model can then be used to define the matrix of rate of spread and temperature that meets this limit.

Based on the scorch height predictions of the model and the practicalities of conducting burning in Wiregrass fuels, burning should only be conducted in regrowth stands with this fuel type which have reached a minimum dominant height of 20m. Unpublished growth data of Geary[1] and Incoll[2] for Silvertop shows that height growth of this species varies widely in Gippsland between sites of different site index, level of overwood and stand density. Hence, stands may reach this minimum prescribed height by 15 years of age, or more likely, not until 20 years of age or even longer.

The finding that stem damage from prescribed burning in regrowth stands was low should allay the concerns of forest managers. High levels of stem damage had previously been measured in some coupes of thinned regrowth forest following fuel reduction burning of thinning slash (Cheney *et al.* 1990b, Buckley and Corkish 1991) hence, enhancing the entry of wood decay fungi and wood destroying insects in the damaged stems. Results from this study indicate that in unthinned stands, low levels of stem damage can be expected when upper crowns have not been scorched and that higher, but still acceptable, levels of about 9% of stems greater than 10cm DBHOB will be damaged when upper crown scorch occurs. Although Gill and Moore (1992) did not find any significant difference in level of stem damage to Silvertop regrowth stems based on fireline intensity, they did find that a similar level of about 10% of all trees greater than 9 cm DBHOB will be butt damaged by fires of intensity of up to 1700kW/m and that the proportion of trees with stem damage increases rapidly as DBHOB decreases below 9 cm. Both studies identified burning old log material to be an important source of damage. Once ignited, this source may burn with a long residence time, hence explaining why damage to trees of larger diameter with thicker bark can be expected. Based on the low levels of stem damage to stems greater than 10cm DBHOB measured in both this study and by Gill and Moore (1992), the important damage factor to consider when prescribing fire in regrowth forest is the height of crown scorch.

Prescriptions for conducting fuel reduction burning and a guide to fire behaviour in regrowth forests with a Wiregrass fuel type is presented in Appendix C as the 'Wiregrass Prescribed Burning Guide for Regrowth Forests in East Gippsland'. By using this guide, and considering a stand with a dominant height of 20m and a prescribed average scorch height of 13m, fires should be ignited from a point source under conditions which result in a maximum rate of spread at 20°C of 50m/h and, if the total fine fuel lead is 18t/ha, result in a maximum fireline intensity of 335kW/m. Similarly, for a stand with a dominant height of 30m, the maximum fireline intensity should be 600kW/m.

Conducting successful fuel reduction burning in regrowth forests requires that planning and operations be closely integrated (Buckley 1992a), based on a clear understanding of the objectives of burning, the area to be burnt, the weather, fuel and topographic factors which contribute to fire behaviour, appropriate techniques of ignition and effective methods of control. Tree crowns, in particular, can be damaged with only a small change in a fire behaviour variable such as wind speed and hence, a high standard of professional practice is required. The Wiregrass Prescribed Burning Guide should enable officers to plan and conduct burning operations with an improved understanding and confidence and hence, achieve high standard outcomes and, providing adequate resources are available, to improve the fuel management of the regrowth forest resource in East Gippsland.

[1] Peter Geary, Research Scientist, CNR, Orbost.
[2] Bill Incoll, Scientist, Timber Assessment, CNR, Kew.

CONCLUSIONS

Fire behaviour in regrowth forests with a well developed and hazardous Wiregrass fuel type can be predicted over the range of fireline intensities suitable for conducting fuel reduction burning. Fuel moisture content and wind speed are the key variables affecting fire behaviour. The moisture content of elevated dead fuel or exposed surface litter and the moisture content of profile fuels can be related and moisture content indices identified which are a suitable burning window of opportunity. Burning must be conducted only when the moisture content of profile fuels is high and wind speed is low.

Models of fire behaviour, summarised in the Wiregrass Prescribed Burning Guide, enable predictions within reasonable limits of confidence to be made of average scorch height from rate of spread and temperature, rate of spread at zero slope for fires ignited from a point source from the moisture content of elevated dead fuel and wind speed at canopy level or the moisture content of exposed surface litter and wind speed at canopy level and flame height from rate of spread. The McArthur slope factors must be used to correct the predicted rate of spread at zero slope for actual slope conditions and, provided fuel load is known or estimated, fireline intensity can be calculated.

Prescriptions detailed in the Wiregrass Prescribed Burning Guide, which include maximum or minimum and the preferred range of fuel moisture or weather variables can be used to prescribe fuel reduction burning in regrowth forests with this fuel type and of dominant height 20m or greater. Fires should not be ignited to burn uphill on slopes greater than about 10^{o} in regrowth forests and burning units should be ignited with a planned, widely spaced grid of spot fires.

Damage to stems is not a limiting factor when prescribing fuel reduction burning in unthinned regrowth forests. Rather, the critical factor is crown scorch and hence, considering a stand with a dominant height of 20m and a prescribed average scorch height of 13m, the maximum rate of spread at $20^{o}C$ should be 50m/h, and if the total fine fuel load is 18 t/ha, the maximum fireline intensity should be 335kW/m. Similarly, for a stand with a dominant height of 30m, the maximum fireline intensity should be 600 kW/m.

The Wiregrass Prescribed Burning Guide should enable officers to plan and conduct burning operations with an improved understanding and confidence and hence, achieve high standard outcomes and, providing adequate resources are available, to improve the fuel management of the regrowth forest resource in East Gippsland.

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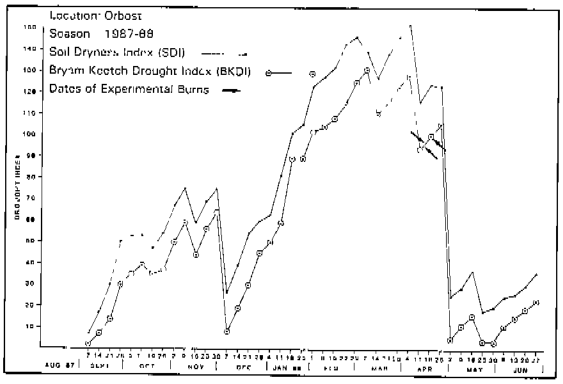
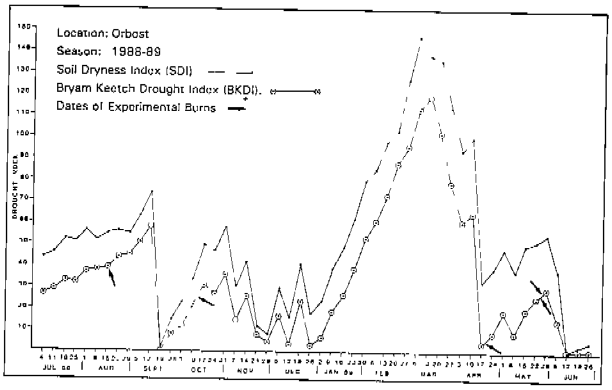
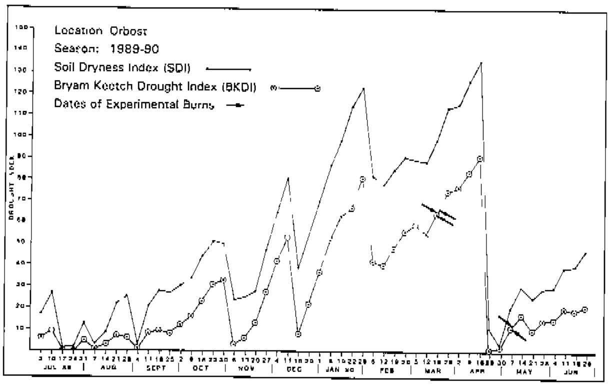
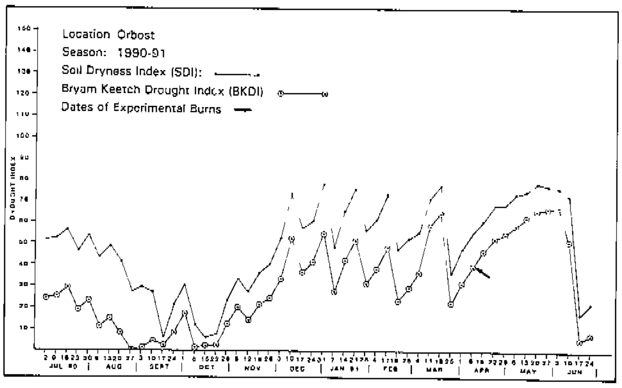
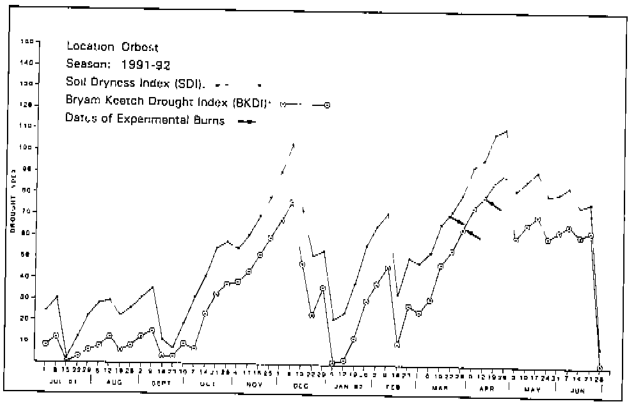
APPENDIX A. Graphs of Soil Dryness Index and Byram Keetch Drought Index, with dates of the experimental burns indicated, for 1987 - 88 to 1991 - 92 for Orbost.





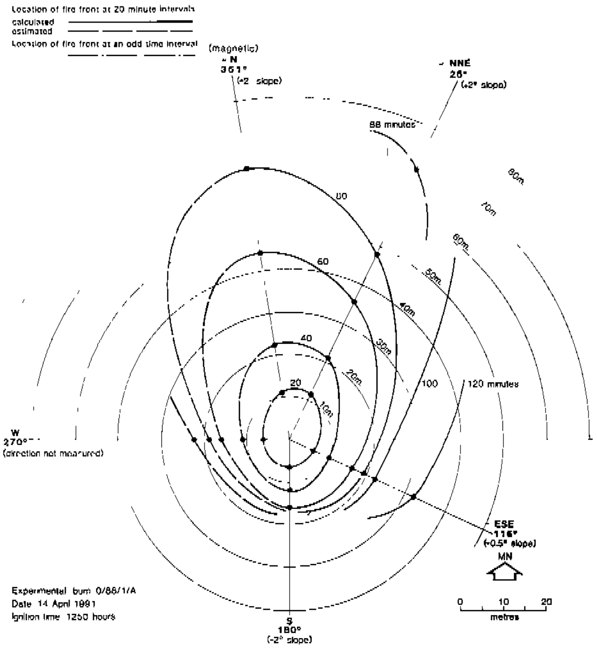




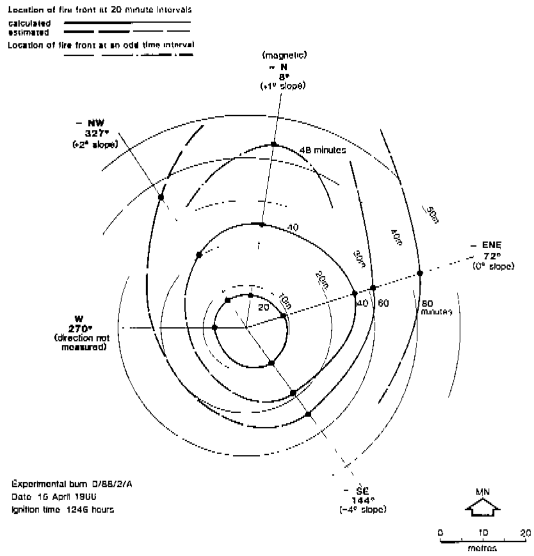


APPENDIX B. Maps of fire spread of the experimental burns at 20 minute time intervals from ignition.

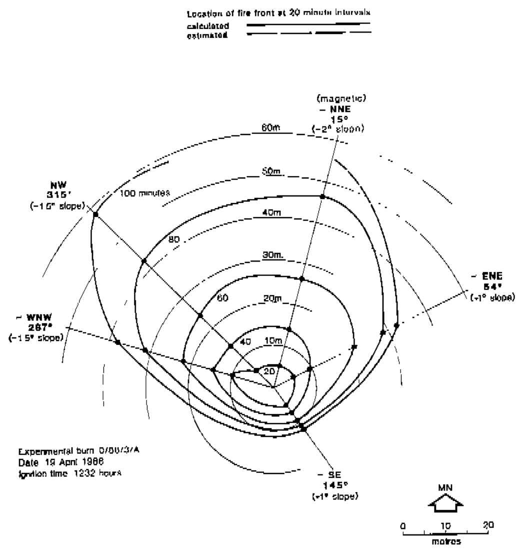
Appendix B1. Experimental burn 0/88/1/A.



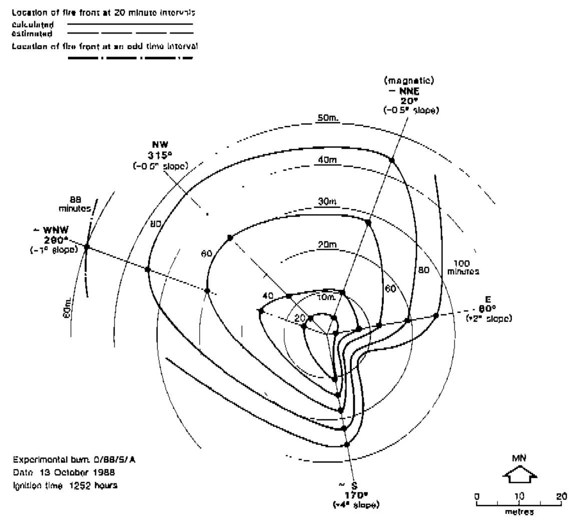
Appendix B2. Experimental burn 0/88/2/A.



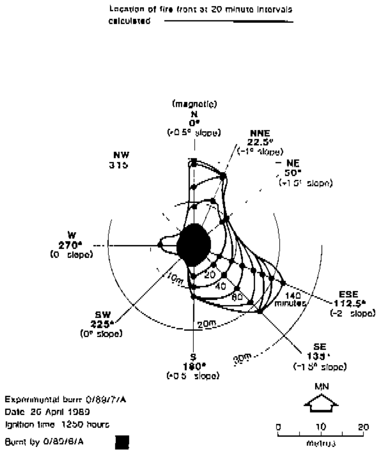
Appendix B3. Experimental burn 0/88/3/A.



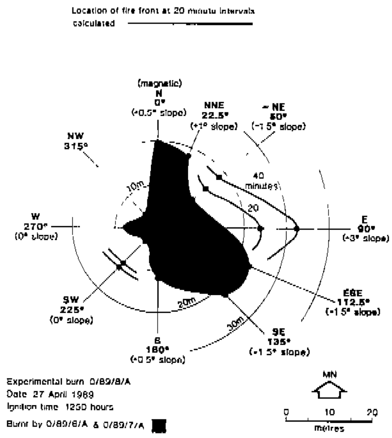
Appendix B4. Experimental burn 0/88/5/A.



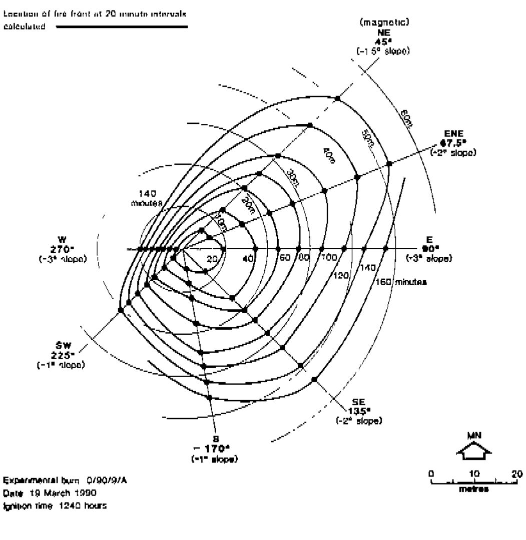
Appendix B5. Experimental burn 0/89/7/A.



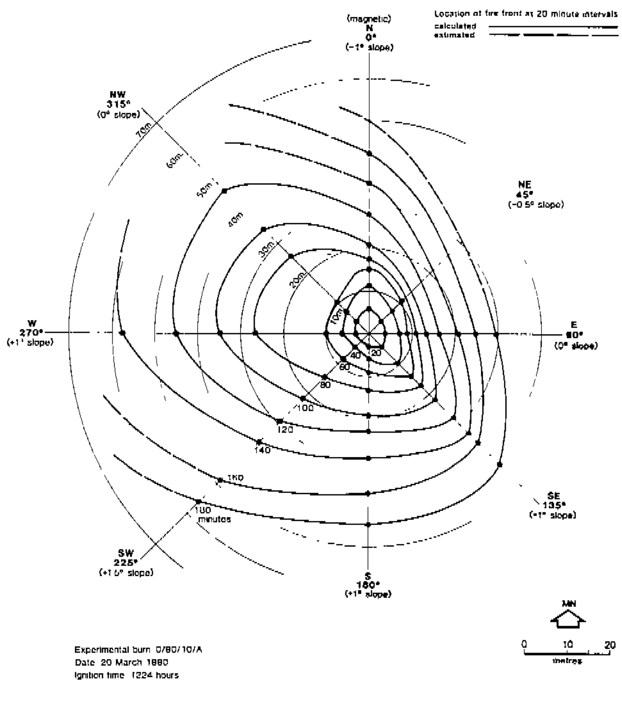
Appendix B6. Experimental burn 0/89/8/A.



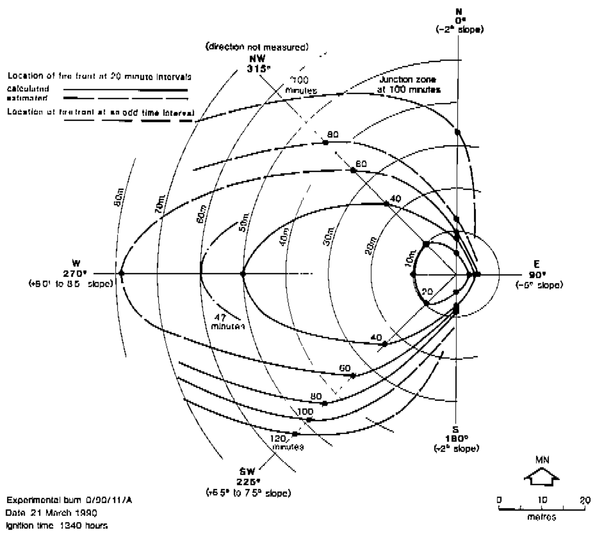
Appendix B7. Experimental burn 0/90/9/A.



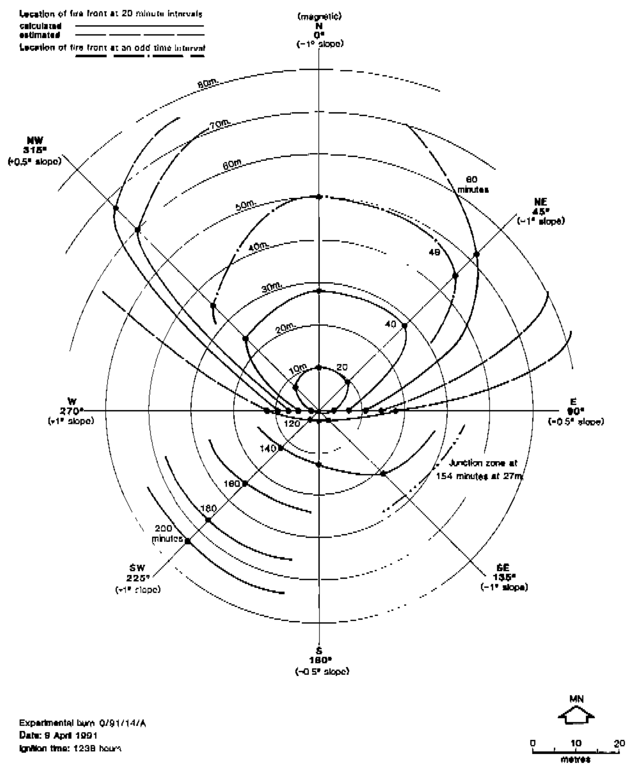
Appendix B8. Experimental burn 0/90/10/A.



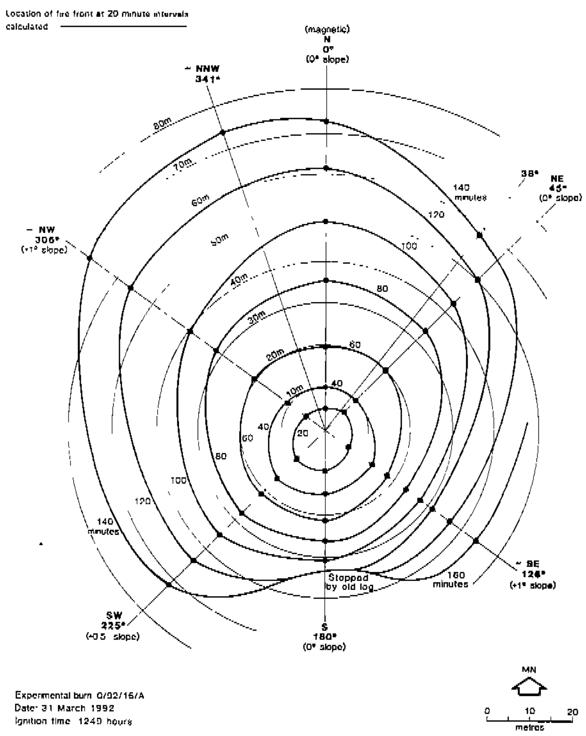
Appendix B9. Experimental burn 0/90/11/A.



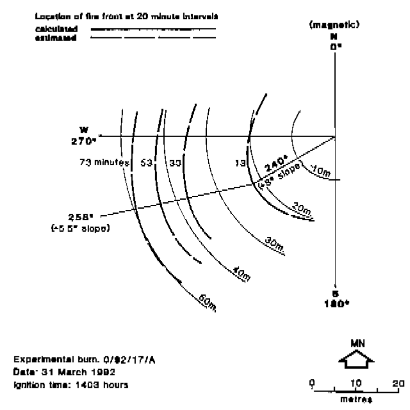
Appendix B10. Experimental burn 0/91/14/A.



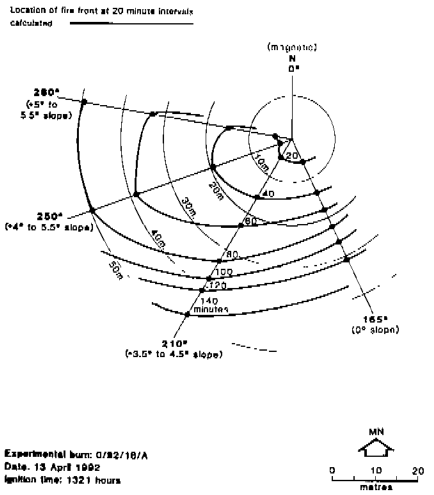
Appendix B11. Experimental burn 0/92/16/A.



Appendix B12. Experimental burn 0/92/17/A.



Appendix B13. Experimental burn 0/92/18/A.



APPENDIX C: WIREGRASS PRESCRIBED BURNING GUIDE FOR REGROWTH FORESTS IN EAST GIPPSLAND (VERSION 1)

Andrew J Buckley
September 1993

A Scope of this guide

B Definitions and measurement techniques

C Procedures for using this guide

Figure 1. Pro-forma tables for use by officers conducting burns

D Prescribed conditions

1. Stand height
2. Fire behaviour
3. Weather
4. Fine fuel moisture content
5. Fire ignition

E Fire behaviour tables for Wiregrass fuels

Table 2. Defined moisture content indices for prescribed burning in Wiregrass fuels

Table 3. Average scorch height (m) as predicted by rate of spread (m/h) and temperature (°C)

Table 4. Rate of spread at zero slope (m/h) as predicted by elevated dead fuel moisture content (% ODW) and wind speed at canopy (km/h)

Table 5. Rate of spread at zero slope (m/h) as predicted by exposed surface fuel moisture content (% ODW) and wind speed at canopy (km/h)

Table 6. Rate of spread correction factors for varying slopes

Table 7. Average flame height (m) as predicted by rate of spread (m/h)

Table 8. Fireline intensity (kW/m) as calculated from rate of spread (m/h) and total fine fuel load (t/ha)

F Additional tables

Table 9. Estimating and measuring wind speed in regrowth forest

Table 10. Recommended spacing between spot fires

A Scope of this guide

This guide is for operational use by CNR staff who conduct fuel reduction burns in regrowth eucalypt forests with a Wiregrass fuel type in East Gippsland. The guide contains prescriptions of stand height, fire behaviour, weather, fuel moisture content and fire ignition. Tables are also presented which enable fire behaviour characteristics such as rate of spread, flame height and scorch height to be estimated from readily measured variables.

B Definitions and measurement techniques

Term	Definition	Measurement technique
Fuel:		
Fine Fuel	Fuel less than 6mm in thickness	
Litter bed fuel (t/ha)	Dead fine fuel, including surface fuel and fuel lower in the fuel profile	Measure litter depth with a depth guage and predict fuel load (see Fogarty 1993)
Living shrub fuel (t/ha)	Living understorey fine fuel less than 2m above ground level	Measure shrub height with a height pole, estimate percentage cover and predict fuel load (see Fogarty 1993)
Elevated dead fuel (t/ha)	Dead fine fuel forming part of, or being suspended in, the shrub layer	As for living shrub fuel
Total fine fuel (t/ha)	Total of the litter bed, elevated dead and living shrub fuel loads	
Shrub height (m)	Height of the living shrub complex, ignoring the strands of Wiregrass or shrub fuel that are present above the main shrub layer	Measure shrub height with a height pole (see Fogarty 1993)
Stand:		
Dominant height	The average of the height of the three largest diameter 'in' trees selected on a plot by a technique of variable probability sampling	Measure the height of the selected trees with a clinometer on a small number of plots
Fuel moisture:		
Moisture content index	Indices relating the moisture content of elevated dead fuel, exposed surface litter and profile litter which identify the broad fuel moisture conditions that are suitable for burning	Table 2
Elevated dead fuel moisture content (EDFMC) (%ODW)	The moisture content of dead eucalypt leaves suspended in the shrub layer at waist height	Directly measure the moisture content of at least three samples with a moisture meter and average the readings
Exposed surface litter moisture content (ESLMC) (%ODW)	The moisture content of dead fine fuel (mainly leaves and petroles) found in the top 1.0 cm of the litter bed and exposed to the weather elements of sun and wind between clumps of Wiregrass	Directly measure the moisture content of at least three samples with a moisture meter and average the readings

Profile litter moisture content (PLMC) (%ODW)	Dead fine fuel found in the entire litter bed above mineral soil and collected from the litter bed in the gaps between clumps of Wiregrass	Directly measure the moisture content of at least three samples with a moisture meter and average the readings or monitor drying trends following rain by oven drying samples
Byram Keetch Drought Index (BKDI)	A numerical value reflecting the dryness of soils, deep forest litter, logs and living vegetation and expressed as a scale from 0 to 200	Measure daily rainfall and maximum temperature and update the index daily using the standard procedure at specified locations
Weather:		
Temperature (^{O}C)	Air temperature	Measure with a sling psychrometer
Relative humidity (%)	The ratio of the actual vapour pressure of the atmosphere to its saturation atmosphere	Measure with a sling psychrometer
Wind speed at 10m in the open (km/h)	The average of the mean value of the gusts and the mean value of the lulls over a period of time	Estimate using Beaufort Scale classes (Table 9)
Wind speed at canopy level (km/h)	Assumed to be the equivalent of wind speed at 10m in the open	Estimate using Beaufort Scale classes, modified with specifications of tree movement (Table 9)
Wind speed at 1.5m (km/h)	The average of the mean value of the gusts and the mean value of the lulls over a five minute period	Directly measure the wind speed at 1.5m over a five minute period with a sensitive anemometer
Fire behaviour:		
Rate of spread (m/h)	The forward progress per unit time of the headfire or of another specified part of the fire perimeter	Measure or estimate the distance of fire spread over a known time interval and convert to an equivalent distance burnt per hour
Rate of spread at zero slope (m/h)	The predicted rate of spread after at least a 20 minute acceleration period of a headfire ignited from a point source and burning at zero slope	Tables 4 and 5
Flame height (m)	The vertical distance between the tip of the flame and ground level, excluding higher flame flashes	Table 7
Scorch height (m)	The height above ground level up to which foliage has been browned by fire	Table 3
Fireline intensity (kW/m)	The rate of energy release per unit length of fire front, defined by the equation I=Hwr I = fireline intensity (kW/m) H = heat yield of fuel (kJ/kg) (16,000 kJ/kg) W = dry weight of fuel consumed (kg/m^2) (mean total less mean unburnt) r = forward rate of spread (m/s)	Table 8
Test fire	A controlled fire ignited to evaluate fire behaviour	Ignite a spot fire and allow it to burn for at least 20 minutes (acceleration phase) then measure the distance of fire spread over the next 20 minutes and multiply the distance of fire spread (m) x 3 to convert to m/h
Spread factor (slope)	A factor to correct for the effect of slope on actual or predicted rate of spread	Table 9

C Procedure for using this guide

The following instructions identify some tasks to be performed during a pre-burn assessment and other tasks to be performed on the day of the burn. Pro-forma tables to assist with this task are included as Figure 1 and actual examples, which are shown in italics in the text, are also shown in these tables.

This guide should be used in conjunction with relevant Departmental instructions. Further information on the planning and operational factors that should or must be considered when implementing prescriptions is discussed in Research Report No. 33 'Fuel Reducing a Stand of Eucalypt Regrowth in East Gippsland - A Case Study'.

Pre-burn assessment

1. Identify the boundaries of the burning unit.
2. Sub-divide the burning unit into broad areas of similar slope, fuel and stand type.
3. Identify the critical area or areas to be sampled (e.g. area of regrowth of minimum height).
4. Measure the fuel load of the shrub fuel and the litter bed fuel using indirect techniques (see Fogarty 1993) (e.g. *18t/ha*).
5. Measure the height of the shrub fuel (e.g. *1.2m*).
6. Measure the dominant height of the stand (e.g. *20m*).
7. Prescribe a scorch height limit (e.g. *13m*).
8. Prescribe a maximum rate of spread at a temperature of (say) 20°C (Table 3) which meets this scorch height limit (e.g. *50m/h*).
9. Prescribe a maximum fireline intensity (Table 8) using the maximum rate of spread and the total fine fuel load (e.g. *50m/h, 18t/ha, 335kW/m*).
10. Measure the slope (e.g. *+ 6°*).
11. Identify the slope factor (Table 6) to correct the prescribed maximum rate of spread (actual slope) to the equivalent rate of spread at zero slope (e.g. *1.5, 50m/h ÷ 1.5 = 33m/h*).
12. Decide on the method of lighting (hand or aerial) and on any pre-burn works that are required (e.g. walking track construction, boundary widening, boundary stag removal).

Day of the burn - Fire behaviour

1. Measure temperature (e.g. *22°C*), relative humidity (e.g. *60%*) and the moisture content of elevated dead fuel (e.g. *13% ODW*), estimate wind speed at canopy level (e.g. *0 - 5km/h*) and measure or estimate the moisture content of profile litter (e.g. *70% ODW*).
2. Identify the moisture content index (Table 2) (e.g. *0.3*).
3. Predict the rate of spread at zero slope from the moisture content of elevated dead fuel and wind speed at canopy (Table 4) (e.g. *30m/h*).
4. Measure the slope (i.e. *+ 6°*).
5. Identify the slope factor (Table 6) to correct the predicted rate of spread at zero slope to the rate of spread predicted for the actual slope (e.g. *1.5, 30m/h x 1.5 = 45m/h*).
6. Predict the scorch height (Table 3) at the prevailing temperature and the predicted rate of spread (e.g. *22°C, 45m/h, 14m*).
7. Check if the actual weather and fuel moisture conditions and the predicted fire behaviour variables are within prescription.
8. Light a test burn in an area of typical fuel and slope.
9. Calculate the rate of spread of the test burn and then decide whether or not to proceed with igniting the burning unit.
10. Where conditions within the burning unit of fuel moisture content, wind speed or slope are significantly different from the test burn site, appropriate correction must be made to the predicted fire behaviour.

Day of the burn - Ignition spacing

1. Use the actual rate of spread of the test burn and the number of burning hours available to determine the spacing between ignitions (Table 10) (e.g. *40m/h, 3 hours, 120m*). Remember to allow for the effect on fire behaviour of different slopes within the burning unit.
2. Mark the planned location of ignition points on a map of the burning unit.
3. Monitor the weather conditions, particularly wind speed and relative humidity, and the behaviour of the burning fires, following ignition.
4. As the burn progresses, be prepared to decrease the distance between ignition points if fire behaviour is less than expected and increase the distance between ignition points if fire behaviour is greater than expected.
5. Ensure that boundaries are secured and patrol the burn as required.

Figure 1. Pro-forma tables for use by officers conducting burns.

Predicting and Prescribing Fire Behaviour in Wiregrass Fuels

Burn OIC: ______________ Burn number: ______________ Date: ______________

A Pre-burn assessment

Total fine fuel load (t/ha)	Average shrub height (m)	Dominant height (m)	Prescribed scorch height (m)	Prescribed maximum rate of spread at 20°C (m/h)	Prescribed maximum fireline intensity (kW/h)	Slope (degrees)	Slope factor	Prescribed maximum rate of spread at zero slope (m/h)
18	*1.2*	*20*	*13*	*50*	*335*	*+6*	*1.5*	*33*

B Day of the Burn - Fire behaviour

Time (hours)	Temper-ature (°c)	Relative humidity (%)	Wind-speed at canopy (km/h)	Elevated dead fuel moisture content (% ODW)	Profile litter moisture content (% ODW)	Moisture content index	Predicted rate of spread at zero slope (m/h)	Predicted rate of spread at actual slope (m/h)	Predicted scorch height (m)
1500	*22*	*60*	*0-5*	*13*	*70*	*0.3*	*30*	*45*	*14*

C Day of the Burn - Ignition spacing

Time (hours)	Test burn rate of spread (m/h)	Slope at test burn (degrees)	Number of hours of burning time	Spacing of ignitions (m)
1500 - 1520	*40*	*+6°*	*3*	*120*

D Prescribed Conditions

1. Stand height

(a) Regrowth stands with a Wiregrass fuel type should have a dominant height of at least **20m** before burning is prescribed.

2. Fire behaviour

(a) The fire behaviour tables should be used to prescribe and predict fire behaviour.
(b) The fire behaviour tables apply to long unburnt Wiregrass fuels of total fine fuel load between 16 and 22 t/ha and of average shrub height **1.2m**
  * Fire behaviour **greater** than predicted can be expected in fuel complexes with a higher shrub height
  * Fire behaviour **less** than predicted can be expected in fuel complexes with a lower shrub height.

(c) A scorch height limit of **two-thirds** of the dominant height should be used for planning the prescribed fire behaviour.
(d) For a stand with a dominant height of **20m** and a prescribed average scorch height of **13m**, the maximum rate of spread at **20°C** should be **50m/h**. If the total fine fuel load is **18t/ha**, the maximum *fireline intensity* should be **335kW/m**.
(e) For a stand with a dominant height of **30m** and a prescribed average scorch height of **20m**, the maximum rate of spread at **20°C** should be **90m/h**. If the total fine fuel load is 18t/ha, the maximum *fireline intensity* should be **600kW/m**.

3. Weather

(a) The maximum Byram Keetch Drought Index for **autumn** = 100, the preferred range is ≤ **80**.
(b) The maximum Byram Keetch Drought Index for **spring** = 30.
(c) The maximum temperature = **25°C**, the preferred range is ≤ **22°C**.
(d) The minimum relative humidity = **50%**, the preferred range is ≥ **60%**.
(e) The maximum wind speed at canopy = **6-11 km/h**, the preferred range is **0-5 km/h**.
(f) Burning during mid to late afternoon under conditions of low wind speed is preferred.
(g) Given that the conditions of weather and fuel moisture content are within prescription, the maximum forest fire danger index (FDI) = **5**.

4. Fine fuel moisture content

(a) The moisture content index should be **0.2** or **0.3**. It may be **0.4** where the dominant height is **≥ 30m**.
(b) The minimum moisture content of profile litter (% ODW) = **41 to 60%**; the preferred range is **> 60%**.
(c) The minimum moisture content of elevated dead fuel (% ODW) = **11%** (where wind speed = 0-5 km/h); the preferred range is ≥ **13%**.
(d) The minimum moisture content of exposed surface litter (% ODW) = **12%**. (where wind speed = 0-5 km/h); the preferred range is ≥ **16%**.

5. Fire ignition

(a) Prepared walking tracks are required to enable crews to ignite burning units by hand.

(b) Fires should not be ignited to burn uphill on slopes greater than **10^{o}**. The actual rate of spread on level ground may require that this limit be further decreased.

(c) Prior to igniting a burning unit, a **test fire** should be lit to test the accuracy of the fire behaviour predictions.

(d) Widely spaced **spot fires** should be used to ignite the burning unit, and the planned location of the ignition points should be marked on a map.

(e) Scorch at junction zones can be minimised by ensuring that spot fires meet in the late afternoon or early evening.

(f) Officers-in-charge should manipulate rate of spread (i.e. burning conditions), number of hours of burning time and the spacing of ignition spots to achieve the objectives of the burn.

E Fire behaviour tables for Wiregrass fuels

Table 2. Defined moisture content indices[a] for prescribed burning in Wiregrass fuels.

Elevated dead fuel moisture content[b] (%ODW)	Exposed surface litter moisture content[c] (%ODW)	Profile litter moisture content[d] (%ODW)							
		20-24	25-30	31-40	41-60	61-80	81-120	121-160	161+
-	7-10	1.0	0.8	0.7	0.6	0.5	-	-	-
11-12	11-12	1.0	0.8	0.6	0.5	0.4	0.3	0.3	0.3
13	13-15	1.0	0.7	0.5	0.4	0.3	0.3	0.2	0.2
14	16-18	1.0	0.6	0.4	0.3	0.3	0.2	0.2	0.1
15	19-21	0.9	0.5	0.4	0.3	0.2	0.2	0.1	0.1
16	22-25	0.8	0.5	0.4	0.2	0.1	0.1	0.1	0.1
17+	26+	-	-	-	-	-	-	-	-

In Wiregrass fuels in East Gippsland:

1. Fuel reduction burning in regrowth forests should be conducted only when the moisture content index is 0.2 or 0.3
2. Fuel reduction burning may also be conducted in forests with a dominant height of greater than 30m when the moisture content index is 0.4

[a] This table of moisture content indices is modified from the table of available fuel factors of Sneeuwjagt and Peet (1985)

[b]Elevated dead fuel moisture content (%ODW): Moisture content of dead eucalypt leaves suspended in the shrub layer at waist height and calculated by averaging measurements of at least three samples.

[c]Exposed surface litter moisture content (%ODW): Moisture content of dead fine fuel (mainly leaves and petioles) found in the top 1.0 cm of the litter bed and exposed to the weather elements of sun and wind in the gaps between clumps of Wiregrass (this class is included for interest, so sampling is not normally required).

[d]Profile litter moisture content (%ODW): Moisture content of dead fine fuel found in the entire litter bed above mineral soil and collected from the litter bed in the gaps between clumps of Wiregrass and calculated by averaging the measurements of at least three samples.

Table 3. **Average scorch height (m) as predicted by rate of spread (m/h) and temperature (°C).**

Rate of spread (m/h)	Average scorch height[a] (m)				
	Temp.=18 °C	Temp.=20°C	Temp.=22°C	Temp.=24°C	Temp.=26°C
20	7	9	10	12	14
30	9	10	12	14	15
40	10	12	13	15	17
50	12	13	15	17	18
60	13	15	16	18	20
70	15	16	18	20	21
80	16	18	19	21	23
90	17	19	21	23	24
100	19	21	22	24	26
110	20	22	24	25	27
120	22	24	25	27	29

[a] For burning conducted during autumn

Table 4. Rate of spread at zero slope (m/h) as predicted by elevated dead fuel moisture content (%ODW) and wind speed at canopy (km/h). *(preferred model for predicting rate of spread).*

Elevated dead fuel moisture content[a] (%ODW)	Wind speed at canopy[b] (km/h)		
	0-5	6-11	12-19
10	50	85	d
11	45	75	150
12	40	70	140
13	30	60	135
14	25	55	125
15	15	45	120
16	10	40	110
17	-	30	d
18	-	25	d
19	-	15	d
20	-	10	d

[a] Elevated dead fuel moisture content (%ODW): Moisture content of dead eucalypt leaves suspended in the shrub layer at waist height and calculated by averaging measurements of at least three samples

[b] Wind speed at canopy (km/h): Defined by Beaufort Scale classes and equal to the wind speed at 10m in the open (see Table 9)

[c] Rate of spread (m/h): Predicted rate of spread after at least a 20 minute acceleration period of a head fire burning at zero slope and ignited from a point source

[d] The model is unreliable in this range

Table 5. Rate of spread at zero slope (m/h) as predicted by exposed surface litter moisture content (% ODW) and wind speed at canopy (km/h).

Exposed surface litter moisture content[a] (% ODW)	Wind speed at canopy[b] (km/h)		
	0 - 5	6 - 11	12 - 19
10	50	75	d
11	45	70	140
12	45	70	135
13	40	65	135
14	40	65	130
15	35	60	130
16	30	60	125
17	30	55	125
18	25	55	120
19	25	50	120
20	20	50	d
21	20	45	d
22	15	45	d
23	15	40	d
24	10	35	d
25	-	35	d

[a]Exposed surface litter moisture content (%ODW): Moisture content of dead fine fuel (mainly leaves and petioles) found in the top 1.0cm of the litter bed and exposed to the weather elements of sun and wind in the gaps between clumps of Wiregrass and calculated by averaging measurements of at least three samples

[b]Wind speed at canopy (km/h): Defined by Beaufort Scale classes and equal to the wind speed at 10m in the open (see Table 9)

[c]Rate of spread (m/h): Predicted rate of spread after at least a 20 minute acceleration period of a head fire burning at zero slope and ignited from a point source

[d]The model is unreliable in this range.

Table 6. Rate of spread correction factors for varying slopes[a].

Slope (degrees)	Spread factor
-10	0.6
-5	0.8
level	1.0
+2	1.1
+4	1.3
+6	1.5
+8	1.7
+10	2.0
+12	2.3
+14	2.6
+16	3.0
+18	3.5
+20	4.0

[a]McArthur (1962)

Table 7. Average flame height (m) as predicted by rate of spread (m/h).

Rate of spread (m/h)	Average flame height[a] (m)
20	1.2
40	1.9
60	2.5
80	3.0
100	3.4
120	3.6

[a]Average flame height (m): The vertical distance between the tip of the flame and ground level, excluding higher flame flashes.

Table 8. Fireline intensity[a] (kW/m) as calculated from rate of spread (m/h) and total fine fuel load (t/ha).

Rate of spread (m/h)	Total fine fuel load (t/ha)				
	14	16	18	20	22
20	100	115	135	150	170
30	145	175	200	225	255
40	195	230	265	300	340
50	245	290	335	380	420
60	295	345	400	455	505
70	340	405	465	530	590
80	390	460	535	605	675
90	440	520	600	680	760
100	490	580	665	755	845
110	540	635	735	830	930
120	585	.695	800	905	1,015

[a]Defined by the equation I = Hwr where:

- I denotes the fireline intensity (kW/m)
- H denotes the heat yield of fuel (kJ/kg) and assumed to be 16,000 kJ/kg
- W denotes the dry weight of fuel consumed (kg/m^2); the unburnt fine fuel load is assumed to be the equivalent of 3t/ha
- r denotes the forward rate of spread (m/s)

E Additional tables

Table 9. Estimating and measuring[a] wind speed in regrowth forests.

Beaufort Scale	Description	Wind speed at 10m above ground in the open (km/h)	Wind speed at 1.5m in the forest[b] (km/h)	Specifications for estimating speed over land[c]
0	calm	< 1	< 1	Calm; smoke rises vertically.
1	light air	1 to 5	1.3 to 2.0	Direction of wind shown by smoke drift but not by wind vanes; slender branchlets and twigs of trees move gently.
2	light breeze	6 to 11	2.2 to 3.0	Wind felt on face, leaves rustle; ordinary vanes moved by wind; trees of pole size in the open sway gently; tops of trees in dense stands intermittently sway gently.
3	gentle breeze	12 to 19	3.2 to 4.4	Leaves and small twigs in constant motion; wind extends light flag; trees of pole size in the open sway very noticeably; tops of trees in dense stands sway.

[a]To measure wind speed at 1.5m in the forest with a hand held anemometer, hold the anemometer at eye level and observe over a period of five minutes the fluctuation of the pointer and visually estimate the mean value of the lulls and mean value of the gusts; calculate mean wind speed by averaging these two values.

[b]McArthur (1962). Wind speed at 1.5m in the forest for a well stocked stand, 21m to 30m tall.

[c]Bureau of Meteorology (1984) and Rothermel and Rinehart (1983).

Table 10. Recommended spacing between spot fires

Forward rate of spread (m/h)	Number of hours of burning time				
	1	2	3	4	5
20	20	40	60	80	100
30	30	60	90	120	150
40	40	80	120	160	200
50	50	100	150	200	250
60	60	120	180	240	300
70	70	140	210	280	
80	80	160	240		
90	90	180	270		
100	100	200	300		
110	110	220			
120	120	240			

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