Department of
Sustainability and
Environment

Surface fine fuel hazard rating - forest fuels

in East Gippsland

Research report no. 44

Victoria
The Place To Be

Surface fine fuel hazard rating - forest fuels in East Gippsland

Research Report No. 44

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Summary

The method of assessing surface fine fuel, based on measurements of surface fine fuel load, was examined to investigate whether this could be replaced by measurements of structural fuel. A faster and more cost-efficient method of estimating surface fine fuel hazard was sought.

Surface fine fuel load, litter-bed height, stand height and near-surface fuel abundance were assessed on 12, one-hectare study plots dispersed through the foothill and coastal sclerophyll forests of East Gippsland, Victoria. Average litter-bed heights ranged from 20 to 48 mm, surface fine fuel loads from 6 to 20 t/ha and stand heights from 20 to 38 m.

Relationships were investigated between surface fine fuel load and stand height, litter-bed height and stand height, and surface fine fuel load and litter-bed height. Surface fine fuel load and litter-bed height were both found to be correlated with stand height, and it is suggested that measurements of stand height over broad areas may be useful for predicting surface fine fuel hazard levels. Further research is required to confirm this, however. Surface fine fuel load was found to correlate with litter-bed height, the correlation improving when the plots with litter-only fuels (i.e. little or no near-surface fuels) were included in the analysis.

Nine of the study plots, located in current fuel reduction burning areas, were subjected to experimental burning. Forest Fire Danger Indices (FDIs) at the time of the experimental fires ranged from FDI 2 to FDI 6, forward rates of spread ranged from 29 to 100 m/hr and flame heights ranged from 0.4 to 1.3 m. Models of fire behaviour were developed which related forward rate of spread to surface fine fuel load, forward rate of spread to litter-bed height, flame height to surface fine fuel load and flame height to litter-bed height. Better correlations were found between the two fire-behaviour variables and litter-bed height than between these two variables and surface fine fuel load, indicating that, at low FDIs, fire behaviour was better related to litter-bed height than it was to surface fine fuel load.

It is therefore proposed that measurement of litter-bed height could be used to replace measurement of surface fine fuel load for assessments of surface fine fuel hazard. Five classes of litter-bed height were suggested to correspond with the five categories of surface fine fuel hazard—Low, Moderate, High, Very High and Extreme—described by Wilson (1993) but which, in that report, were based on measurement or estimation of surface fine fuel load. This proposed method of assessing surface fine fuel hazard could then be combined with assessments of bark hazard and elevated fuel hazard to derive an Overall Fuel Hazard rating for a site. A series of reference photographs of the various categories of surface fine fuel hazard are presented to assist quick visual assessments.

Increases in forward rates of spread and flame height were observed to be associated with certain levels of near-surface fuels. It was proposed that the occurrence of near-surface fuels that interact with surface fine fuels should be incorporated into the assessment procedure. It is suggested that the surface fine fuel hazard rating should be increased when the cover of near-surface fuels exceeds 40%. This needs to be confirmed by further fire behaviour studies.

Introduction

Prior to the 1990s, assessment of fine fuel hazard in Australian forests was often thought of in terms of measuring the weight per unit area of the litter and other fine fuels present on the forest floor. This concept followed directly from the work of McArthur (1962, 1967, 1973) who used surface fine fuel load as a principal predictor of fire behaviour in forests where litter was the predominant fuel. Although McArthur (1962) contended that knowledge of surface fine fuel quantity was a primary prerequisite for prediction of fire behaviour, he proposed that field officers might use measurement of litter-bed height and an assessment of post-fire age to quickly estimate surface fine fuel quantity.

The inadequacy of simple quantitative measurements to assess fine fuel hazard where elevated and bark fuel complexes occurred in the forests became recognised in Victoria in the late 1980s (Tolhurst et al. 1992). In addition, reduction in operational resources militated against quantitative assessments. It also became recognised that the period of reduced fire severity following either wildfire or fuel-reduction burning was attributable to a reduction in the overall fuel hazard levels rather than just the reduction of surface fine fuel loads (Tolhurst et al. 1992; Buckley 1993).

In fulfilment of its legislative obligations to protect life, property and assets from wildfire, the Department of Sustainability and Environment (DSE) is required to strategically manage fuel hazard levels across broad areas of public land in the State. DSE therefore sought alternative systems for assessing both surface fine fuel and overall fuel hazard. Such systems needed to be simple and cost effective and to assist the development and implementation of achievable strategic Fire Protection Plans.

Following McArthur's work, a number of researchers looked at ways of accounting for the influence of elevated fuels in fire behaviour predictive models. They also looked at easier and better methods of assessing surface fine fuel hazard, as it was found that the structure of surface fine fuel was often more important than simple surface fine fuel load in determining fire behaviour outcomes, particularly in terms of rates of spread and flame heights. Peet (1972), in discussing litter quantity—in relation to experimental fires conducted in Jarrah (*Eucalyptus marginata)* forests in Western Australia—observed:

> Litter weight, by itself, was not satisfactory for describing changes in forward rate of spread. It was surprising to find that the inaccurate visual observations of depth and cover were better correlated with spread rate than were measurements of weight.

Sneeuwjagt and Peet (1985), following further developmental work in measuring litter-bed height, included litter-bed height as an input variable to their 'Forest Fire Behaviour Tables' for Western Australia. This measurement of litter-bed height was used, in conjunction with other forest structure and weather variables, to give predictions of fire behaviour across a range of forest types and ages. Tolhurst et al. (1992) found that a variable derived from both litter-bed height and surface fine fuel weight—the 'packing ratio'—was the best for explaining variations in rates of spread and flame heights in experimental fires in the Wombat State Forest in central Victoria.

Cheney et al. (1992) introduced the concept of 'near-surface fuel' to describe elevated fuels, such as tussocks, bracken and small shrubs, found in the first 50 cm above the soil surface. Cheney et al. (1992) found that the fuel moisture content of the dead fuel suspended in these near-surface fuels (which consisted of both live and dead material) was an important variable in explaining differences in rates of spread in their experimental fires in coastal regrowth forests in southern New South Wales, while the height and cover values of these near-surface fuels were important in explaining the variations in flame height. This conforms closely with Buckley (1993) who found that elevated dead fuel moisture content was useful in constructing a predictive model for rates of spread of prescribed fires in the wiregrass-dominated coastal forests of East Gippsland, Victoria. In this same forest type, Fogarty (1993) found that litter-bed height, combined with an estimation of elevated fuel height and cover (wiregrass and shrubs), gave a useful way to estimate overall fuel loads and hazard levels.

From these studies it appeared that the factors important to assessment of surface fine fuel hazard are principally those of fine fuel structure, that is:

- litter-bed height

  and

- height, cover and the *suspending* or *micro-elevating* capacity of near-surface fuels.

The procedure for measuring surface fine fuel loads in forests is outlined in CNR (1992). This suggests using a 0.1 m^2 fine-fuel sampling frame to sample in transects at a minimum intensity of 15 plots across a (nominal) 200-ha fuel reduction burn area. In practice, there was rarely the time or resources to conduct this type of fuel sampling prior to the prescribed burning season, and fire managers would be much better served by a system that enables rapid estimation of fuel hazard (of both surface, elevated and bark fuels).

The Elevated Fuel Guide (Wilson 1993) and the Bark Hazard Guide (Wilson 1992) used visual assessment procedures based on a series of reference photographs and accompanying descriptions to arrive at an assessment of elevated fuel and bark hazard levels respectively. Five hazard levels were recognised, ranging from Low to Extreme. In practice, except for a brief period immediately following a wildfire or prescribed burn, Low hazard levels are not found in forests or other native vegetation.

In the Elevated Fuel Guide, Wilson (1993) also proposed combining the three components of bark, elevated and surface fine fuels in assessment of the Overall Fuel Hazard[1] rating for a site. He further proposed assessing the probability of success or failure of a 'Reference First Attack' suppression effort in terms of the Overall Fuel Hazard rating of the site for a given range of Forest Fire Danger Indices (McArthur 1973). The principal reasons for wanting to derive an Overall Fuel Hazard were proposed by Wilson (1992a) to be:

- to assess the potential difficulty of suppressing a fire on a particular site at a given Forest Fire Danger Index

  and

- to arrive at threshold (or *trigger*) levels for fuel-reduction burning in different Fuel Management Zones as fuel hazard levels increase.

Wilson's (1993) proposals, however, still used surface fine fuel quantity as the principal method of assessing surface fine fuel hazard and this required the time-consuming assessment of surface fine fuel quantities. This study therefore proposed to investigate simplifying and improving the assessment of surface fine fuel hazard. This was done by investigating structural measurements and visual assessments of classes of surface fine fuel hazard to see whether they were sufficiently related to fire behaviour to enable replacement of measurements of surface fine fuel load in the Overall Fuel Hazard assessment process.

[1] Overall Fuel Hazard is a term used by Wilson (1993) to define the sum of the influences of the three components of fine fuel hazard – surface fine fuel, elevated fuel and bark attached to tree boles.

For litter-bed height measurement, it was proposed to:

- define a method of easily, and reasonably accurately, measuring litter-bed height in the field using a simple depth gauge
- investigate how well litter-bed height is related to fire behaviour
- if a relationship between litter-bed height and fire behaviour is found, divide the litter-bed height range into five classes of surface fine fuel hazard—Low, Moderate, High, Very High, Extreme.

For visual assessment, it was proposed to produce a series of reference photographs (with brief accompanying descriptions) similar to the Bark Hazard and Elevated Fuel Guides (Wilson 1992 and 1993 respectively) which would allow visual assessment of five—Low, Moderate, High, Very High, Extreme—classes of surface fine fuel hazard. This visual assessment would also attempt to incorporate how near-surface fuels (up to 50 cm above the ground) influenced surface fine fuel hazard.

Method

Fuel hazard study plots

A range of surface fine fuel hazard types were assessed by measuring a series of 12 study plots located across a range of near-coastal to high foothill sites in East Gippsland, Victoria. These extended from 30 km north-west of Nowa Nowa, through the Colquhoun Forest and east to Orbost (Figure 1.1).

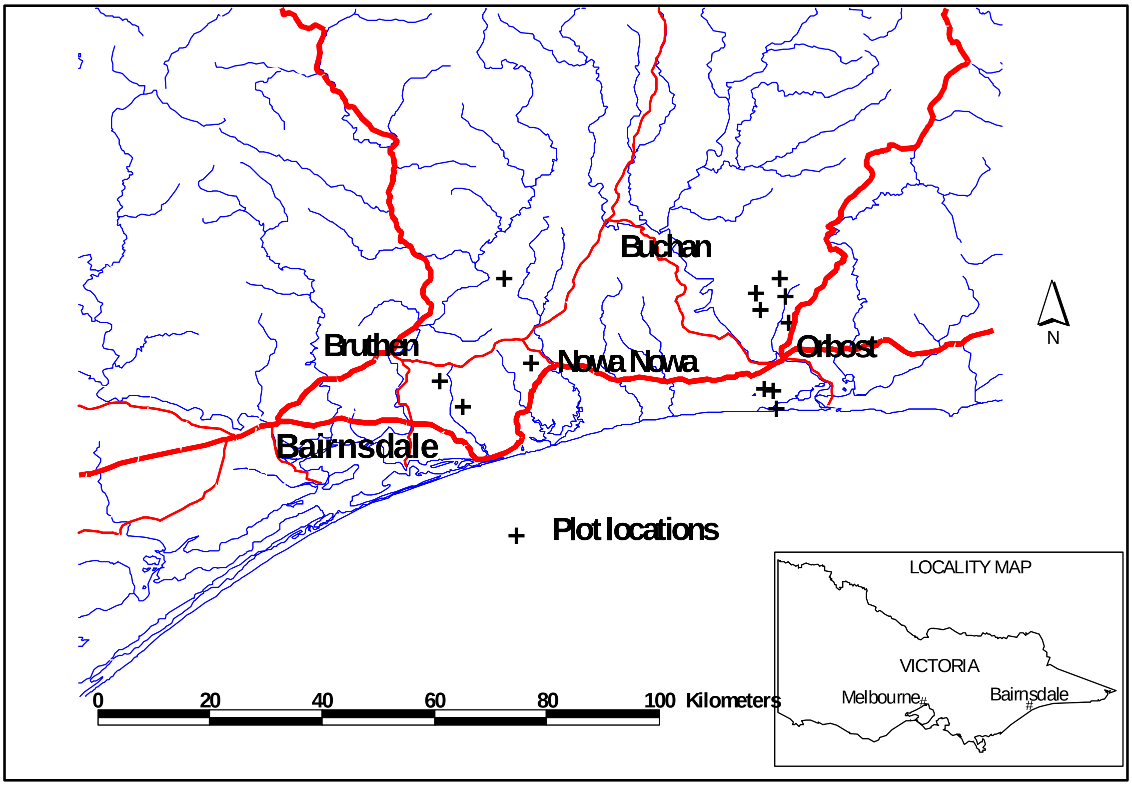

Figure 1.1 Location of plots assessed in this study

Each study plot was 100 m by 100 m in size and located so as to cover a range of sites of differing biomass productivity. Table 1 provides site descriptions for each of the 12 plots.

Table 1 Site description for the 12 plots studied

Plot name	Elevation AMSL* (metres)	Longitude	Latitude	Rainfall (approx.) (mm)	Time since last fire (years)
Cherry Tree 1	200	148°24'00"	37°36'35"	800	2
Cherry Tree 2	190	148°23'15"	37°37'25"	800	2
Waygara 1	50	148°22'50"	37°45'30"	800	8
Waygara 2	55	148°23'10"	37°45'10"	800	8
Waygara 3	40	148°23'30"	37°46'35"	800	15
Colquhuon 1	160	148°02'30"	37°42'30"	850	15
Colquhuon 2	90	148°00'25"	37°46'40"	850	15
Colquhuon 3	90	147°58'50"	37°45'15"	850	15
Mt Beaver	410	148°00'40"	37°34'40"	900	12
Silvertop 1	180	148°21'00"	37°37'20"	800	20
Silvertop 2	230	148°24'45"	37°36'10"	900	20
Old Bonang Hwy	100	148°28'30"	37°39'45"	800	8

*AMSL – above mean sea level

Except for the Mt Beaver plot, which was in mature Foothill Dry Sclerophyll Forest (Woodgate et al. 1994), all study plots were located in mature Lowland Sclerophyll Forest (ibid). The most common overstorey species was Silvertop (*Eucalyptus sieberi*) with lesser occurrences of White Stringybark (*E. globoidea*) and Yellow Stringybark (*E. muellerana*). Structurally, all plots consisted of mature trees with a very sparse shrub understorey, while ground cover comprised mainly surface litter and some grass.

The study plots were located at sites where the main fuels consisted of litter. An attempt was made to deliberately exclude sites with a lot of near-surface and elevated fuels to minimise their influences on the experimental burns, although Waygara 2 contained a significant amount of tussock grass (being a near-surface live fine fuel) in addition to litter fuels.

Some of the long unburnt sites (e.g. Silvertop 2; Mt Beaver) showed development of a range of low ground vegetation that interacted with the litter. These live near-surface fuels consisted of ground twiners, tussocks—of fine-leaved *Poa* spp. and coarse-leaved Mat-rushes (*Lomandra* spp.) and Sword-sedges (*Lepidosperma* spp.)—some live and dead Austral Bracken (*Pteridium esculentum*) and a range of small herbs and forbs. Parts of the Colquhuon 2 and Old Bonang Highway plots contained significant amounts of both live and dead bracken and it appeared that, where bracken was present, the amount of litter-bed was reduced. Nevertheless, the total amount of dead fuel on each of the 15 sampling points with significant amounts of bracken was often close to the total on those sampling points without bracken, as the dead bracken tended to make up the balance of the dead biomass.

Coastal East Gippsland's climate is generally mild with warm to hot summers and cool, wet winters. The coastal influence means that summers are often moister than for the rest of Victoria and, lying as it does to the lee of the Great Dividing Range, warmer and drier airstreams mean that its winters can be milder than the rest of eastern Victoria. These climatic effects influenced the conditions under which the study plots were burned and relative humidities were generally higher than may be experienced elsewhere in Victoria during the same period.

The specific measurements taken at each study plot were:

stand height
litter-bed height
surface fine fuel load
height and cover of elevated and near-surface fuels

Stand height

Stand height is used as an indicator of site productivity. Heights were measured using a 30-m measuring tape and a Suunto clinometer. The heights of the tallest three mature trees on each study plot were measured and averaged to provide an estimate of stand height.

Litter-bed height

The litter-bed was measured for height and photographed. Litter-bed height was defined as the vertical height, above the mineral soil surface, of the accumulation of leaves, bark and twigs and other debris less than about 6 mm thick. It was measured with a simple depth gauge consisting of a slotted plywood disc of about 20-cm diameter mounted on a plastic ruler (Figure 1.2).

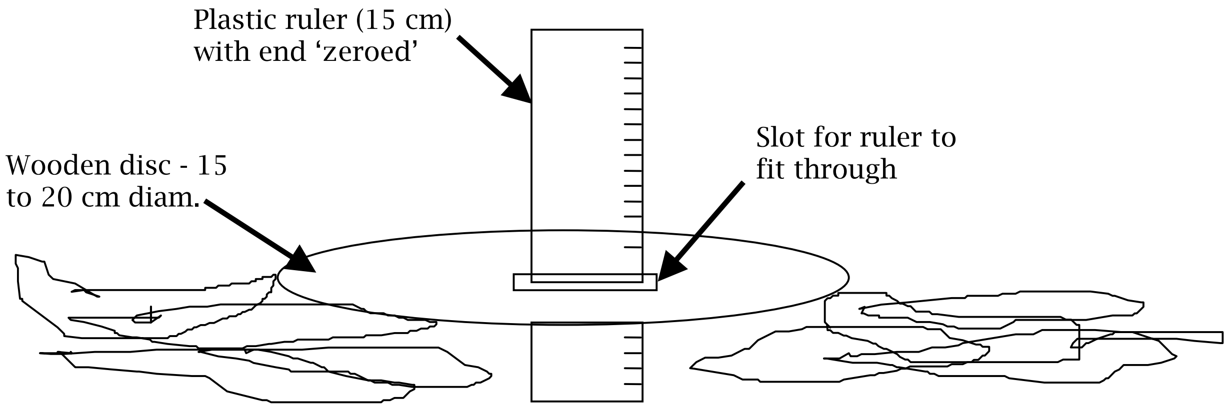

Figure 1.2 Gauge for measuring litter-bed height

Measurements were taken when fuels were dry so that leaf curl was maximised. Any sticks greater than 6 mm thick or stones that projected above the average height of the litter were removed. The disc was pushed down the ruler with light pressure (as described in Tolhurst et. al 1992) until its whole perimeter was in contact with the fuel.

Sixty measurements of litter-bed height were taken within each of the 12, 100 m by 100 m study plots. For each plot, the average of four measurements, taken at a 1 m radius from the centre of each of 15 sample points, was recorded. The litter-bed height for each plot was then calculated as the average of these 15 recorded measurements. Photographs (35 mm format with a 35 mm lens) were taken from the plot corners (facing inward) and of a hardhat placed in the litter-bed (with its rim touching mineral soil). Photographs of the hardhat in position with a sign displaying the average litter-bed height for the study plot were also taken for use as references for a visual surface fine fuel hazard assessment guide. The reference photographs were taken from a kneeling position at a distance of 5 m from the hardhat and in overcast conditions to minimise shadows.

An estimation of the variation in litter-bed height was calculated and this was used to predict an optimal sample size and thus the minimum number of measurements required to obtain an estimate of the mean litter-bed height to within 90% accuracy. The method used was to examine the data with the greatest variation and then to graph the size of the error against the sample size. The size of the 90% error was calculated by multiplying the sample standard error by the 't' statistic appropriate to the 90% confidence level with n-1 degrees of freedom.

Surface fine fuel load

Fifteen samples of surface fine fuel (less than 6 mm thick) were collected from each study plot using a 0.1 m^2 sampling ring. The samples were oven dried at 105°C until they reached a constant weight. This took approximately 48 hours. The average weight of the 15 samples was than calculated to give an average surface fine fuel load for each plot.

Height and cover of near-surface and elevated fuels

Height and projective foliar cover were estimated for both the near-surface and other elevated fuels. Near-surface fuels were defined as those that occurred immediately above the surface litter fuels but were not in direct contact with the soil surface and had a generally more vertical orientation than the surface litter. They consisted of both live and dead material and included grasses, sedges, low shrubs and low bracken. They occurred most commonly in the first 20 to 50 cm above the surface and usually had vertical continuity with the surface fuels, the components of which were both suspended and micro-elevated by the near-surface fuels.

Elevated fuels were classed as material generally greater than 50 cm tall and somewhat discontinuous with the surface and near-surface fuels. The influence that near-surface fuels and, to a lesser extent, elevated fuels had in suspending (or micro-elevating) litter fuels was noted.

Experimental burns

To enable measurements of forward rate of spread (FROS) and flame height, nine of the 12 study plots were burned. Two fires were lit in three of the plots while single fires were lit in the other six.

Within each plot that was burned, either 9, 12 or 16 metal marker pins of known height were set out on a 10 m by 10 m square grid; the number actually used in each plot being enough to permit observation of the fire for between 30 minutes and one hour after ignition. The fires were lit in a line along the upwind side of each plot. For the plots with 16 pins, the line of ignition was 30 m long; on those with 12 or 9 pins, it was 20 m long.

FROS was plotted (and measured) by drawing diagrams of the flame front in relation to the pins at specific time intervals as the fire front travelled through the grid. Flame heights, estimated against the known height of the marker pins, were recorded simultaneously with the drawing of the flame front diagrams. Also at specific time intervals, the headfire was photographed to verify the estimates of flame height.

Weather readings were taken before ignition and after the fire had burned through the grid. As average burning time was between 30 minutes and one hour, the two main weather readings were generally no more than an hour apart. Temperature and relative humidity were measured with a Bacharach sling psychrometer and wind speed was measured with a Dwyer hand-held wind meter.

Surface and profile fuel moisture contents

On a number of the plots (when available resources permitted) surface and profile fuel moisture contents were sampled before and after the experimental burn. Surface fuels were defined as those leaves lying on the top of the litter bed and thereby exposed to the maximum drying influences of the sun and wind. Profile fuels were defined as those leaves occurring through the profile (from the top to the bottom) of the litter bed. The moisture content of the profile fuel should be a gauge for the average moisture content of the whole of the litter-bed.

Samples of approximately 15 g of leaves were collected into airtight jars. The samples were first weighed moist and then dried to a constant weight at 105ºC. Moisture content was calculated as a percentage of oven-dry weight.

Standardisation of forward rate of spread and flame height

FROS and flame height values were standardised to remove the differences due to the particular Forest Fire Danger Index—FDI (McArthur 1973) prevailing at the time of each burn. All FROS values were scaled to correspond to those that would have occurred at a FDI of 5 (e.g. if FROS at FDI of 4 = 50 m/hr, then $FROS_{(FDI5)}$ = 63 m/hr (63=50*5/4)). The basis for the standardisation of FROS was the linear relationship between FROS and FDI found by McArthur (1973). The new variable, $FROS_{(FDI5)}$, was then regressed against litter-bed height. A similar standardisation process was applied to flame height.

Packing ratio

Equation 1 was used to calculate the packing ratio of the fuel on all study plots.

$$\text{Packing Ratio (t / ha / mm)} = \frac{\text{Fuel load (t / ha)}}{\text{Litter} - \text{bed Height (mm)}} \qquad \textbf{\textit{Equation 1}}$$

The relationships between the following parameters were investigated:

- stand height and surface fine fuel load
- stand height and litter-bed height
- litter-bed height and surface fine fuel load
- litter-bed height and standardised forward rate of spread
- surface fine fuel load and standardised forward rate of spread
- litter-bed height and flame height
- surface fine fuel load and flame height
- packing ratio and forward rate of spread
- packing ratio and flame height.

Results

Parameters measured at each study plot

Table 2 sets out the parameters measured at each of the 12 study plots. It reveals that most sites were of medium to high productivity as no average stand heights below 20 m or above 38 m were found.

Table 2 Overstorey height, litter-bed height and surface fine fuel load at the 12 plots

Plot	Stand height (m) (n = 3) Average	(SE)	Litter-bed height (mm) (n = 15) Average	(SE))	Surface fuel load (t/ha) (n = 15) Average	(SE)
Cherry Tree 1	20.3	(1.79)	20.5	(0.58)	6.8	(0.35)
Cherry Tree 2	26.2	(0.84)	21.5	(0.44)	6.9	(0.55)
Waygara 1	28.0	(0.57)	26.7	(0.62)	7.8	(0.69)
Waygara 2	27.0	(0.57)	30.4	(1.88)	5.9	(0.63)
Waygara 3	27.0	(0.06)	30.6	(0.90)	11.4	(0.71)
Colquhuon 1	32.5	(0.50)	41.7	(1.73)	12.5	(0.99)
Colquhuon 2	31.2	(0.44)	36.0	(0.98)	10.7	(1.00)
Colquhuon 3	31.7	(0.33)	46.8	(1.15)	15.3	(0.87)
Mt Beaver	37.8	(1.01)	47.5	(2.45)	19.8	(1.24)
Silvertop 1	32.7	(1.20)	39.2	(1.54)	11.3	(1.09)
Silvertop 2	27.6	(0.33)	30.6	(0.78)	9.9	(0.66)
Old Bonang Hwy	33.8	(0.69)	30.1	(1.71)	15.2	(1.63)

Both litter-bed height and fuel load were found to correlate with stand height. Table 2 shows that, on the sites studied, mean litter-bed heights ranged from 20.5 mm to 47.5 mm and mean surface fine fuel loads ranged from 5.9 t/ha to 19.8 t/ha.

Stand height and surface fine fuel load

The relationship between stand height and surface fine fuel load is shown in Figure 2 and described by the linear regression equation, Equation 2.

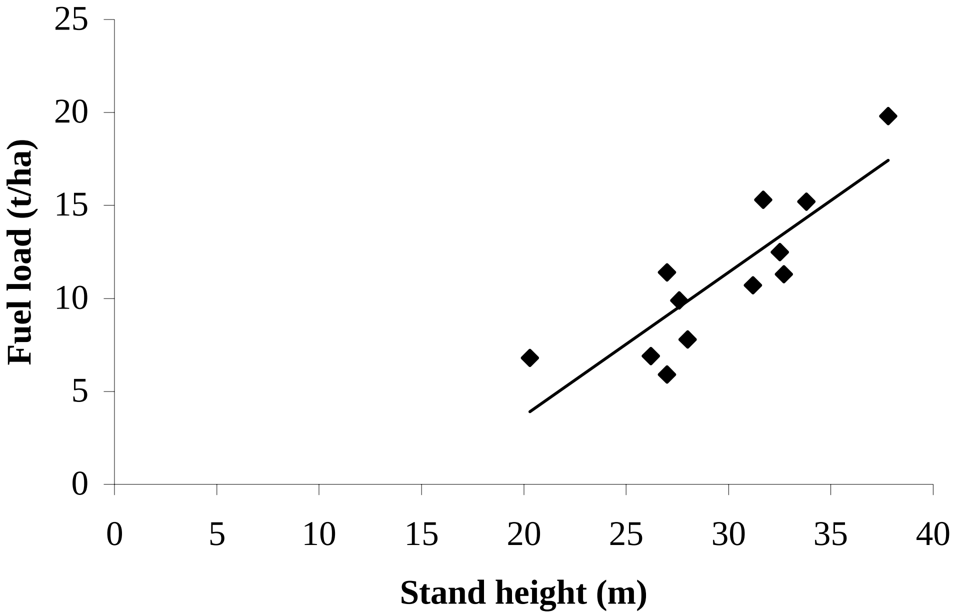

Figure 2 Relationship between stand height and fuel load

— indicates the regression line (Equation 2)

◆ indicates the observed data

$$\text{Fuel load} = (0.77 * \text{Stand height}) - 11.8 \qquad \textit{Equation 2}$$

$(n = 12, r^2 = 0.72, p < 0.001)$

Stand height and litter-bed height

Stand height was found to correlate with litter-bed height as shown in Figure 3 and described by the linear regression equation, Equation 3**.**

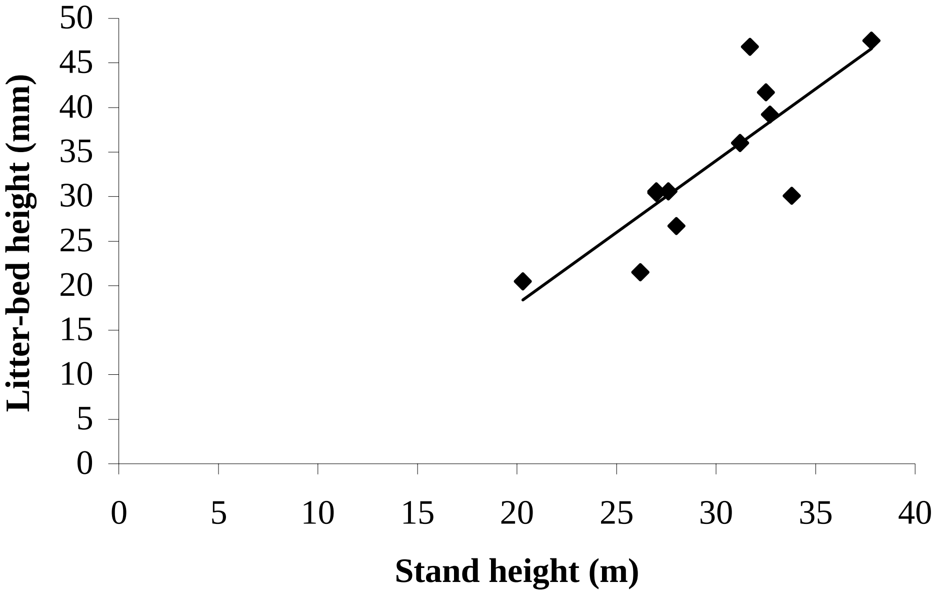

Figure 3 Relationship between stand height and litter-bed height

— indicates the regression line (Equation 3)

◆ indicates the observed data

Litter-bed height = (1.54* Stand height) - 11.7	***Equation 3***
($n = 10$, $r^2 = 0.53$, $p = 0.016$)	

The relationships displayed by Equations 2 and 3 indicate that stand height may be used to predict both surface fine fuel load and litter-bed height. Tolhurst et al. (1992) suggested that this is a realistic estimate for sites that have remained unburnt for more than five years.

Litter-bed height and surface fine fuel load

Litter-bed height and surface fine fuel load were significantly correlated as shown in Equation 4 and Figure 4.

Surface fine fuel load = (0.36*Litter-bed height) - 1.21 ***Equation 4***

($n = 12$, $r^2 = 0.63$, $p = 0.002$)

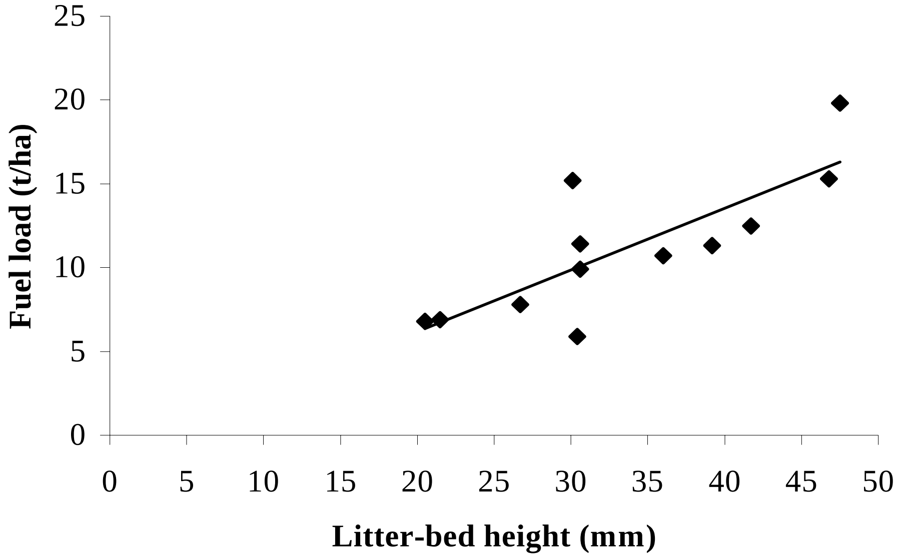

Figure 4 Relationship between litter-bed height and surface fine fuel load

— indicates the regression line (Equation 4)

◆ indicates the observed data

Data from the majority of the study plots suggested that the relationship between litter-bed height and surface fine fuel load was stronger for plots containing only litter (see also Figure 5), and became less precise when near-surface fine fuels (particularly grass tussocks, twiners, low shrubs and dry bracken fronds) occurred amongst the litter.

Litter-bed height and surface fine fuel load – limited near-surface fuels

Figure 5 shows the relationship between litter-bed height and surface fine fuel load for those study plots where there was only a small amount of near-surface fuel. This improved the correlation between the two parameters and is described by Equation 5.

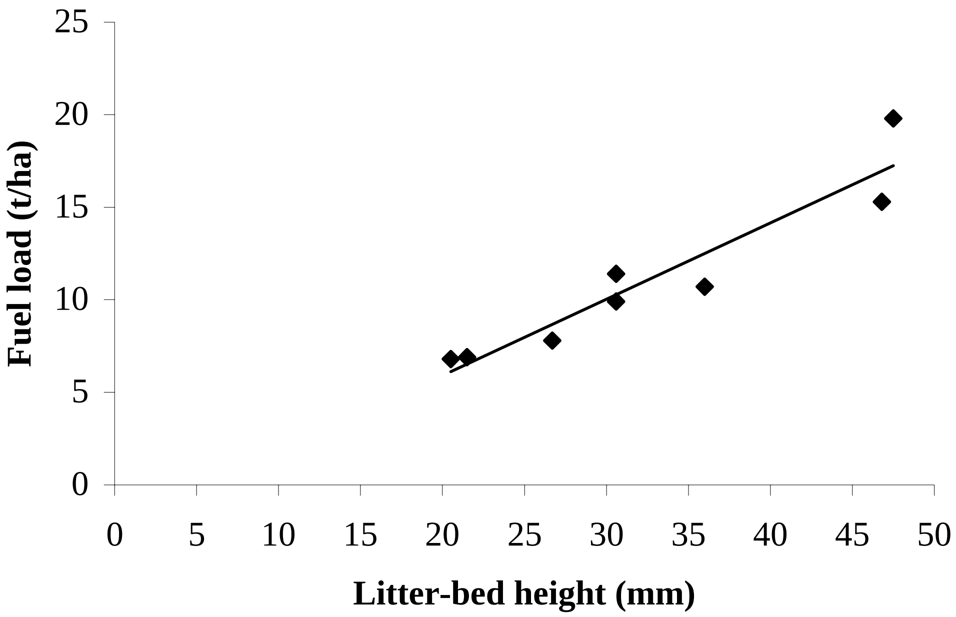

Figure 5 Relationship between litter-bed height and surface fine fuel load for plots with litter fuels only (i.e. only a small amount of near-surface fuels and little micro-elevation)

— indicates the regression line (Equation 5)

◆ indicates the observed data

Fuel load = (0.41*Litter-bed height) - 2.35	***Equation 5***
($n = 8$, $r^2 = 0.89$, $p < 0.001$)	

Sample size for measurement of litter-bed height

Figure 6 graphs the size of the 90% error against sample size for litter-bed height measurement and derives from the data for the most variable study plot (i.e. that where the greatest difference occurred between the maximum and minimum values). It indicates that, above a sample size of five, the reduction in the size of the error is only marginal. It should be noted that, to improve the estimate obtained, this sample size of five requires 20 actual measurements to be taken—four measurements of litter-bed height to be taken at each sampling point and averaged.

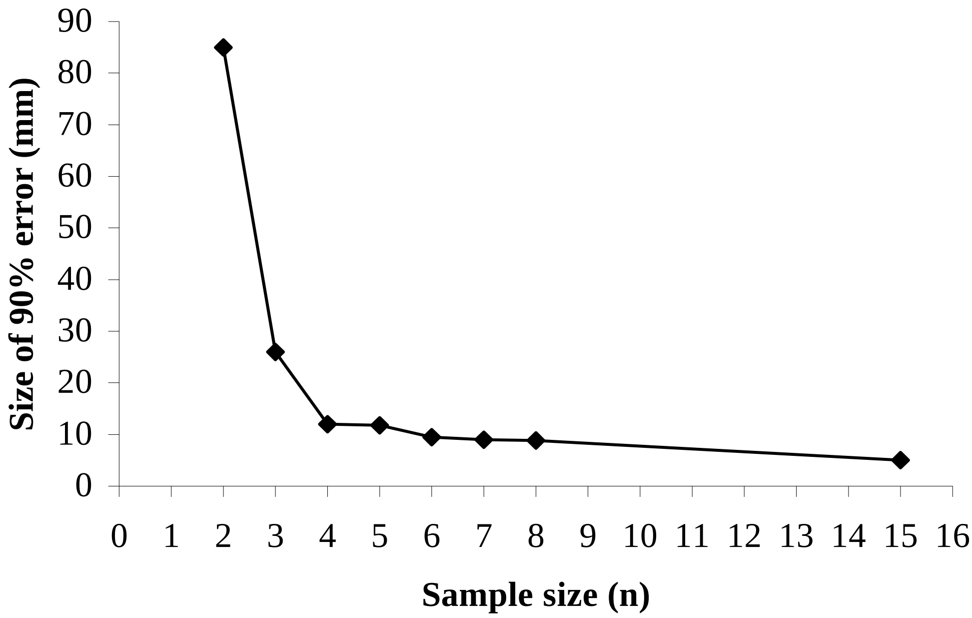

Figure 6 Sample size of litter-bed height measurements with size of error for the most variable plot

Size of error was calculated by multiplying the standard error by 't'

◆ indicates the observed data

Each sample consists of an average of four measurements within a one-metre radius.

Weather conditions during the experimental burns

Table 3 sets out the weather conditions recorded when the nine study plots were burned. Forest Fire Danger Indices during the experimental burns ranged between 2 and 6, which were within the acceptable prescribed burning limit of 0 to 8 (CNR 1996).

Table 3 Weather conditions at 1.7 m above ground level in the forest at the start and end of the experimental burns at the nine study plots

Plot	Temperature		Relative humidity		Wind				FDI
					speed		direction		
	start (°C)	end (°C)	start (%)	end (%)	start (km/h)	end (km/h)	start	end	average
Cherry Tree 2	22	19	59	65	0-7	0-7	SE	SE	4.0
Waygara 1	18	18	68	68	0	0	-	-	2.5
Waygara 2	24	26	48	56	0-2	0-7	E-NE	SE	6.0
Waygara 3	19	20	56	58	0-7	4-7	S-SE	S-SE	5.0
Colquhuon 1	27	24	59	68	0-2	0-3	SW	S-SW	5.0
Colquhuon 3	17	20	58	53	0	4-8	-	NW	5.0
Mt Beaver	20	19	55	50	0-2	0-2	W-SW	S	4.0
Silvertop 2	21	21	68	68	0-2	0-2	W	N-NE	2.5
Old Bonang Hwy	24	23	55	56	0-10	0-10	E	E	5.0

Fire behaviour during experimental burns

Table 4 sets out the fire behaviour data obtained from the nine study plots in which burning was undertaken. The fires were restricted to areas in which prescribed fuel reduction burning was to occur and hence were also restricted to the type of mild and generally stable weather conditions that allow for this activity. This was reflected in the low FDIs during the experimental burns. Forward rates of spread (FROS) ranged from 25 m/hr to 100 m/hr, while average flame heights were between 0.4 and 1.3 m.

Table 4 Fire behaviour during experimental burning at the nine study plots

Plot	Litter-bed height (mm)	Fuel load (t/ha)	FROS (m/hr)	FROS $_{(FDI5)}$ (m/hr)	Flame height (m)	Near-surface fuels
Cherry Tree 2	21.4	6.9	28	34	0.4	Not significant
Waygara 1	26.7	7.8	25	38	0.4	Not significant
Waygara 2	30.4	6.0	72	58	0.8	Tussocks to 200 mm
Waygara 3	30.7	11.4	48	48	0.6	Not significant
Colquhuon 1	41.7	12.0	100	100	1.0	Some shrubs to 150 mm
Colquhuon 3	46.8	15.3	75	75	1.0	Dry bracken, sticks to 100–150 mm
Mt Beaver	47.5	19.8	64	77	1.3	Sticks to 100 mm
Silvertop 2	39.2	11.3	29	58	0.9	Twiners, tussocks to 200 mm
Old Bonang Hwy	30.1	15.2	46	46	0.5	Live and dead bracken

Note: **FROS** $_{(FDI5)}$ indicates the forward rate of spread standardised to correspond to that which would have occurred at a Fire Danger Index of 5.

Two experimental burns were lit within each of the plots at Colquhuon 3, Mt Beaver and Silvertop 2. These burns revealed very similar flame heights and forward rates of spread, indicating a low level of sampling variation.

Plots with greater amounts of near-surface fuels produced generally higher flame heights and faster rates of spread than those that had litter only. Sites with bracken exhibited more erratic fire behaviour with flame heights rising and falling as the fire front encountered clumps of dead and live bracken.

Exposed surface and profile fuel moisture contents

Table 5 sets out the moisture contents of the exposed surface and profile fuels measured in four of the burned study plots. Profile fuel moisture contents were generally relatively low, between 15% to 19% oven-dry weight (ODW). Very little ground fuel was left unburned on any of the plots.

Table 5 Exposed surface and profile fuel moisture contents for four of the burned study plots

Plot	Time (hour of day)	Surface fuel moisture content (%ODW)	Profile fuel moisture content (%ODW)
Waygara 3	1130	14.6 (± 0.3)	16.7 (± 0.4)
	1430	14.4 (± 0.3)	16.6 (± 0.3)
Colquhuon 3	1330	13.7 (± 0.2)	19.5 (± 0.5)
	1515	13.8 (± 0.3)	18.1 (± 0.4)
Mt Beaver	1135	14.7 (± 0.4)	16.1 (± 0.4)
	1440	14.6 (± 0.3)	15.7 (± 0.3)
Silvertop 2	1030	13.9 (± 0.3)	19.9 (± 0.3)
	1430	14.1 (± 0.2)	15.1 (± 0.2)

Litter-bed height and standardised forward rate of spread

The direct relationship between litter-bed height and forward rate of spread showed some significance, but improved considerably when the FROS values were modified to include the variation in FDI at the time of burning. The regression equation, Equation 6, was obtained when FROS values were standardised to a FDI of 5. This relationship is illustrated in Figure 7

$$FROS_{(FDI5)} = (1.96 * \text{Litter-bed height}) - 9.14 \qquad \textbf{\textit{Equation 6}}$$

$(n = 9, r^2 = 0.71, p = 0.004)$

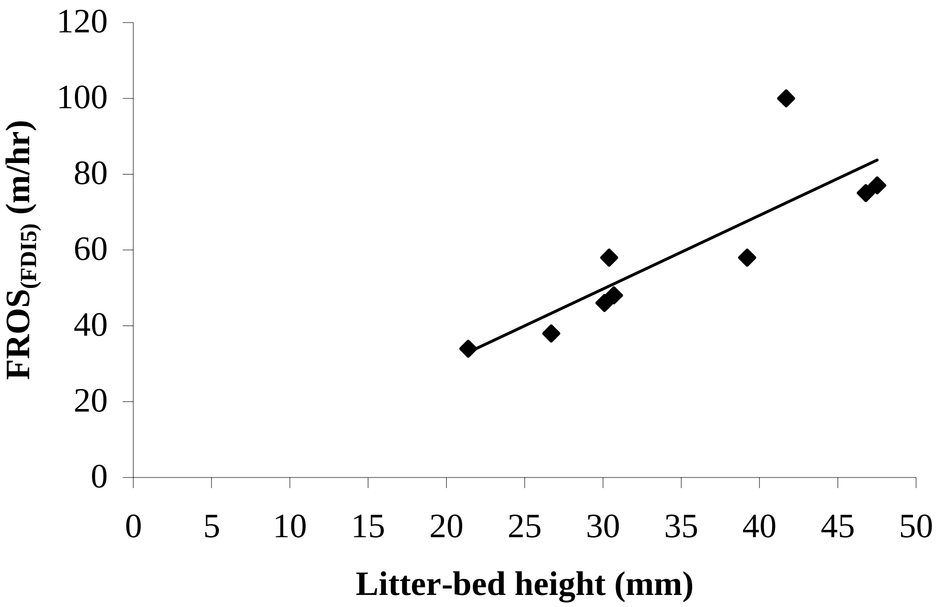

Figure 7 Relationship between litter-bed height and standardised forward rate of spread

— indicates the regression line (Equation 6)

◆ indicates the observed data

Surface fine fuel load and standardised forward rate of spread

Regression of surface fine fuel load against the standardised forward rate of spread ($FROS_{(FDI5)}$) produces a weaker correlation; described by Equation 7.

$$FROS_{(FDI5)} = (4.03 * \text{Fuel load}) + 25.4 \qquad \textbf{\textit{Equation 7}}$$

$$(n=9,\ r^2 = 0.55,\ p = 0.02)$$

This indicated that for the fuel, site and weather conditions experienced, forward rate of spread was better correlated with litter-bed height than with fuel load.

Litter-bed height and flame height

When a simple linear regression was applied to the data for litter-bed height and standardised flame $\text{height}_{(FDI5)}$, a correlation was found with a coefficient (r^2) of 0.62 (Equation 8).

$$\text{Flame height}_{(FDI5)} = (0.03 * \text{Litter-bed height}) - 030 \qquad \textbf{\textit{Equation 8}}$$

$$(n = 9,\ r^2 = 0.62,\ p = 0.01)$$

However, a significantly better correlation was found when the standardisation for FDI was removed and actual flame height was regressed against litter-bed height. It appeared that flame height was affected more by litter-bed height than prevailing weather conditions over the small range of FDIs encountered in the experimental burns. This improved relationship is described by Equation 9 and illustrated in Figure 8.

$$\text{Flame height} = (0.03 * \text{Litter-bed height}) - 0.35 \qquad \textbf{\textit{Equation 9}}$$

$$(n = 9,\ r^2 = 0.86,\ p < 0.001)$$

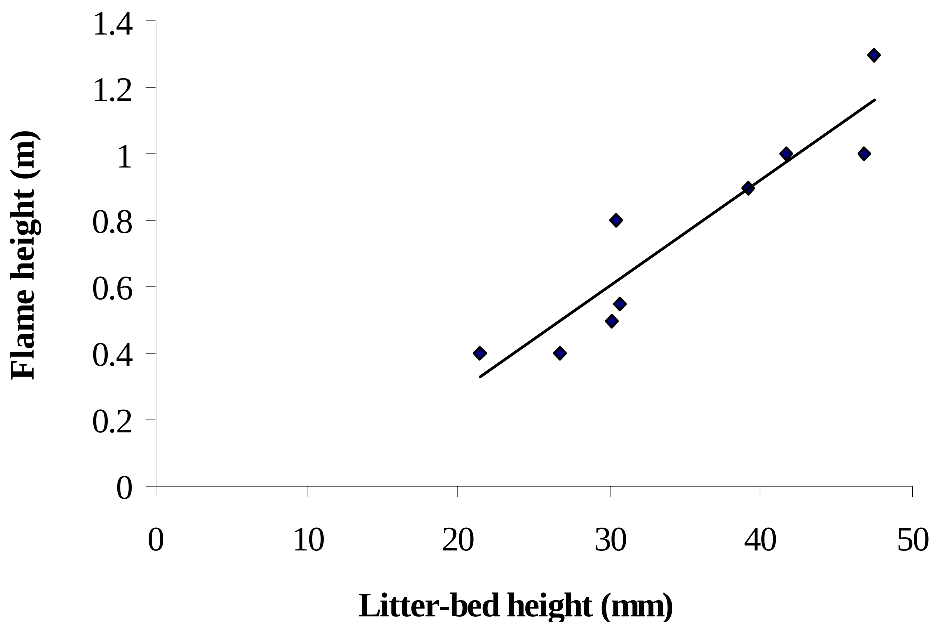

Figure 8 Relationship between litter-bed height and flame height

— indicates the regression line (Equation 9)

◆ indicates the observed data

Surface fine fuel load and flame height

When actual flame height was regressed against surface fine fuel load, a weaker correlation, described by Equation 10, was obtained compared to that found between flame height and litter-bed height.

$$\text{Flame height} = (0.048 * \text{Surface fine fuel load}) + 0.18 \qquad \textbf{\textit{Equation 10}}$$

$(n = 9,\ r^2 = 0.42,\ p = 0.05)$

This indicates that, for the fuel, site and weather conditions experienced, flame height was better correlated with litter-bed height than with fuel load.

Packing ratio and forward rate of spread and flame height

The following relationships were found between forward rate of spread ($FROS_{FDI5}$) and packing ratio, and between flame height and packing ratio.

$$FROS_{(FDI5)} = (-62.7 * \text{Packing ratio}) + 93.9$$ ***Equation 11***

$(n = 9, r^2 = 0.05, p = 0.55)$

$$\text{Flame Height} = (-0.49 * \text{Packing ratio}) + 1.10$$ ***Equation 12***

$(n = 9, r^2 = 0.005, p = 0.85)$

The correlation coefficients and probability values indicate that the correlations between packing ratio and $FROS_{FDI5}$ and flame height and were not significant and will not be discussed further.

Litter-bed height and surface fine fuel hazard classes

Five fine-fuel hazard classes were identified based on the litter-bed heights measured and surface fine fuel structure as determined from the photographs. Descriptions of these classes are as follows, with reference photographs for each class where available.

Low Surface Fine Fuel Hazard

< 15 mm litter-bed height.

Moderate Surface Fine Fuel Hazard

15–25 mm litter-bed height. Small patches of bare earth are visible between the litter.

High Surface Fine Fuel Hazard

25–35 mm litter-bed height. Small patches of bare earth no longer visible between the litter.

Very High Surface Fine Fuel Hazard

35–50 mm litter-bed height. No bare earth visible anywhere between the litter. The increase in the proportion of small to medium sticks is evident. Ground twiners may occur through the litter-bed.

Extreme Surface Fine Fuel Hazard

50+ mm litter-bed height. The increased proportion of small to medium sticks is evident, with sticks greater than 6 mm diameter starting to become more common. Ground twiners may occur through the litter-bed. If ribbon bark species are present, pieces of ribbon bark will start to become more frequent in the litter.

Near-surface fuel hazard

Near-surface fuel hazard is present when grass tussocks, twiners, bracken or other low live fuels occur. These enhance fire behaviour by interacting with the surface fine fuels.

Discussion

The data on mature tree heights indicate that the sampled sites varied in their productivity of biomass. Sites at the extremes of the site productivity range were not sampled. These were, for example, very low productivity sites of White Box (*E. albens*) or Slender Cypress-pine (*Callitris preissii*) with stand heights of less than 10 m, and sites of very high productivity such as Alpine Ash (*E. delegatensis*), Mountain Ash (*E. regnans*) or Cut-tail (*E. fastigata*) with stand heights of 40 m and more. Neither extreme of the productivity range is usually prescribed burned for fuel hazard reduction purposes, so not sampling them was unlikely to greatly affect the findings of this project.

The correlations found between stand height and surface fine fuel load, and between stand height and litter-bed height, indicate that it may be possible to use mature tree stand height as a predictor of the surface fine fuel hazard level which a particular stand may reach if it remains unburned for more than 5–8 years. This may allow for the prediction of expected surface fine fuel hazard levels over large areas through remote-sensing techniques.

The fire behaviour results of this study showed that, for the limited range of sites and conditions examined, measurement of litter-bed height can be used to reasonably predict both flame height and standardised forward rate of spread. For the sites examined, litter-bed height was a better predictor of fire behaviour than was surface fine fuel load. This concurs with the observation of Peet (1972) who, in his work with experimental fires in the Jarrah forests of Western Australia, found that crude visual observations of litter depth and cover were better correlated with forward rate of spread than was litter weight.

The relationship between surface fine fuel load and litter-bed height found in this study accords closely with that found by Chatto (1996) in a study of surface fine fuel load and fuel hazard accumulation in the Chiltern Regional Park in north-east Victoria, and which sampled forests with a similar structure and which had predominantly litter fuels.

The direct correlation between litter-bed height and flame height found in this study indicates that, at low FDIs, small variations in weather conditions had less effect on varying the observed flame height than did the height of the litter-bed. This may not be the case over a wider range of FDIs and further research is required to confirm this. Forward rates of spread, however, did appear to be influenced by small variations in weather conditions (particularly wind variations), as the best correlation between litter-bed height and forward rate of spread was found when FDI was standardised to a common level (FDI = 5).

It is proposed that litter-bed height, measured with a depth gauge at sufficient frequency to include spatial variability, can be a useful indicator of surface fine fuel hazard, at least under low FDI conditions. Plotting the size of the error against sample size indicates a minimum of five measurements (twenty total measurements with four averaged at each sample point) of litter-bed height should be taken at each sample point to ensure that at least 90% of natural variation is accounted for. For a large area, sample points should be of sufficient number to account for variations due to slope, altitude, vegetation type and different burning history. Distances between sample points will vary, but should be in the range of 100 to 500 m.

The highest FDI under which the experimental burns were lit was 6 (i.e. relatively low on the FDI scale of 1 to 100). Although the data from the McArthur Meter Mk V indicates that reasonably linear relationships should exist between increasing FDI and increasing flame heights and forward rates of spread for a given surface fine fuel load, it may be extrapolating too far to say that litter-bed height will be as good a predictor of surface fine fuel hazard at higher FDIs than those encountered in this study.

Beyond FDI 10, fire behaviour studies suggest that it is likely that bark, elevated fuels and fire development dynamics (Burrows 1984; Wilson 1992; Tolhurst et al 1992; Wilson 1993; Burrows 1994; McCarthy & Tolhurst 1998) will have a much greater influence on fire behaviour, and that either measurement or estimation of surface fuel loads alone will have less relevance to predicting fire behaviour. Burrows (1994) found that, for high-intensity fires, there was little relationship between surface fuel and fire behaviour.

It is proposed that, at low FDIs, the relationship found between litter-bed height and fire behaviour is sufficiently good to use litter-bed height as a basis for classifying surface fine fuel hazard. Proposed hazard classes would correspond to those used in the Elevated Fuel Guide (Wilson 1993) but which, for that guide, are based on measurement (or estimation) of litter fuel load. Table 6 sets out the proposed surface fine fuel hazard classes based on litter-bed height.

Table 6 Proposed surface fine fuel hazard rating system based on litter-bed height

Surface fine fuel hazard	Low	Moderate	High	Very High	Extreme
Litter-bed height (mm)	< 15	15–25	25–35	35–50	50 +

Assessing surface fine fuel hazard from litter-bed height became complicated when near-surface fuels with high cover values (such as tussock and sedge grasses, twiners, dead/live bracken and other micro-elevating elements to 30 cm tall) occurred. These both micro-elevate the litter and contribute significantly to fire behaviour. When the data from the three plots with the highest amounts of near-surface fuels—Waygara 2, Silvertop 2 and Old Bonang Hwy—were removed from the data set, the linear correlation coefficient (r^2) of litter-bed height with fuel load was 0.89, compared to 0.63 for the total data set. This strongly indicates that structural changes due to near-surface fuels will be significant in changing the accuracy of estimating total surface fine fuel load from a measure of litter-bed height.

The presence of large amounts of near-surface fuels resulted in greater than average rates of spread and flame heights for two of the above plots—Waygara 2 and Old Bonang Hwy. This concurs with Cheney et al. (1992) who measured discernible increases in both flame height and rate of spread as a result of increased near-surface fuels. Buckley (1992) also reported increased flame heights for bracken fuels, particularly where dead bracken formed a significant near-surface fuel layer.

However, this finding was not reflected in the forward rate of spread observed for the Silvertop 2 study plot. This plot was burned at a very low FDI (about 2 or 3) with a high relative humidity (68%) and this may have significantly influenced the rates of spread. The rates of spread on this plot were also affected by light, variable and occasionally adverse winds that interfered with consistent development and progress of the headfire. Despite these adverse weather conditions and low rates of spread, flame heights were still relatively high (0.9 m), which correlated well with the relatively high litter-bed height of 39 mm and the presence of near-surface fuels.

Sufficient evidence therefore exists to suggest that the assessment of surface fine fuel hazard should take account of any significant near-surface fuel and micro-elevation of the fuel. The extent of this correction could not be determined from the available data, but a subjective judgement is that surface fine fuel hazard is raised between a half and one hazard class on a site where near-surface fuels have cover values greater than 40% and more than 20% of the litter fuels (i.e. leaves and twigs greater than 6 mm in thickness) are micro-elevated. These proposed changes to hazard ratings need to be investigated with further fire-behaviour studies.

As the proposed surface fine fuel hazard categories correspond with those contained in the Elevated Fuel Guide (Wilson 1993), it is suggested that the tables in that guide could be readily modified to use litter-bed height, in conjunction with the set of reference photographs, to assess surface fine fuel hazard and hence Overall Fuel Hazard for a site.

Further, as suggested above, near-surface fuels with cover values greater than 40%, and greater than 20% micro-elevation, should cause the surface fine fuel hazard to be assessed to between half a class and a whole class above what it would otherwise be for the same litter-bed height.

Both this proposed system of measuring litter-bed height as a predictor of surface fine fuel hazard and the proposed system of compensating for the presence of near-surface fuels/micro-elevation on a site, require further fire-behaviour studies to confirm their usefulness. Such studies would need to be undertaken on other geographical sites and under a broader range of FDIs to validate the results obtained in this study.

Conclusions

Litter-bed height showed a good correlation with surface fine fuel load for sites where the fine fuel consists primarily of litter only.

Litter-bed height was a better predictor of forward rate of spread and flame height than was fuel load at FDIs up to 6 (and probably up to 10).

Litter-bed height, in conjunction with a set of reference photographs, can be used to assess surface fine fuel hazard for a site. A minimum of five measurements of litter-bed height should be taken at each sample point (twenty total with four measurements averaged at each of five places around the sample site) and at least five sample points should be sited around a sampling block at a minimum spacing of 100 to 500 m.

It is proposed that significant near-surface fuels and micro-elevation of litter on a site can be compensated for in the assessment of surface fine fuel hazard by increasing the assessed category by between a half and one whole category of hazard. This proposed compensation level requires confirmation by further fire-behaviour studies.

The tables in the Elevated Fuel Guide (Wilson 1993) could be readily modified to use litter-bed height instead of surface fine fuel load to assess both surface fine fuel hazard and also Overall Hazard Rating.

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