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Fire Behaviour Modelling in Exotic Pine Plantations: Testing the Queensland Department of Forestry 'Prescribed Burning Guide Mk III'

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Abstract

Since 1972 the Queensland Department of Forestry has used guides for the planning and execution of prescribed burning in exotic pine plantations. In this study, regression equations were developed to represent the fire behaviour tables of the current Mk III Burning Guide. Weather and fuel data collected from 88 experimental fires were used to examine the components of these equations and to compare observed with predicted values of fire behaviour. Predicted results were generally poor. This was probably due to variation within the fuel type in which the Guide was originally designed to be applicable. Modifications to plantation establishment and management practices have resulted in a change in average fuel type, thereby limiting the field application of the Guide.

Because of its empirical derivation, further improvement and expansion of the Guide appear limited. The development of future burning guides should allow for changes in environmental variables such as fuel composition, and this suggests that a theoretical rather than empirical approach to fire behaviour modelling is warranted.

[O.D.C. 436:432.16--015.5:174.7 *Pinus* spp.]

Introduction

Prescribed burning for fuel reduction began on a trial basis in the exotic pine plantations of south-east Queensland in the late 1960s. The success of these early trials led to the introduction of burning on a buffer-strip basis in the early 1970s. Now virtually all exotic pine plantations are burnt at least once during a rotation. This expansion took place following the development and widespread use of burning guides containing information on fuel drying times, fire behaviour and lighting techniques. These guides were empirically developed using the methodology employed by McArthur (1958, 1967) in producing fire danger meters for forested areas. The field use of burning guides has been extremely successful in Queensland. Of the 22 000 ha of pine plantation prescribed burnt up to 1979, almost 97% was free of scorch and 70% was classed as 'perfect' burns (Byrne 1980).

However, in recent years it has become obvious to field users that increasing areas reaching burnable age contain fuel types not readily applicable to the burning guide. Establishment and silivicultural practices have altered since the original guides were developed. For example, changes in site preparation techniques (Pegg 1967) have allowed the establishment of plantations on 'wetter' sites which inherently support different vegetation types. There has also been a trend to burn areas as early as 8 years old compared with 15 years old in the past. These factors combined with wider interrows and reduced stockings have resulted in a gradual shift in average fuel type. The amounts of grass and understorey shrubs have increased, whereas, in the past, pine needle litter was the major component of the ground fuel.

The changes observed in fuel composition in pine plantations prompted a further program of experimental fires between 1979 and 1981 for the collection of fire behaviour data. The aims of this program were: (1) to evaluate the current Burning Guide with regard to its accuracy and application to fuel types commonly present; (2) to extend and refine this Guide to cover a range of fuel types; and (3) if warranted, to examine the application of a theoretically based fire behaviour model (Rothermel 1972, 1983) to exotic pine fuel types. The present paper examines the first aim of this program. It reports on an evaluation of the fire behaviour tables of the Queensland Mk III Burning Guide (Queensland Department of Forestry 1976) using data collected from 88 experimental fires during the study period.

Description of the Queensland Burning Guide

The original Mk I Burning Guide was developed from fuel drying and fire behaviour data from experimental fires in south-east Queensland supplemented by similar data from Western Australia. The Guide was refined with the collection of further local data. The current Guide in use, the Mk III version, was produced in 1974. This Guide is in three parts: an introduction, a series of drying tables, and a series of fire behaviour tables.

The introduction opens with a brief description of the five fuel-type classifications specified for plantations of slash pine (*Pinus elliottii* Engelm. var. *elliottii*). In particular, the Guide applies to slash pine plantations not previously burnt and carrying an 'average fuel condition', that is, fuels classed as 'Fuel Type 2'. This type was selected as the standard because of its prevalence when the Guide was originally compiled. The remainder of the introduction covers the application of the drying and fire behaviour tables and the recommended lighting techniques.

The drying tables of the Guide predict drying conditions for a temperature range of 20–30°C, the normal range occurring in Queensland in the autumn–winter burning season. The number of days since known amounts of rainfall and the mean daily maximum temperature during the drying period are used to predict the amount of available fuel and, indirectly, the moisture content of the top 1 cm of the fuel profile (Byrne 1980). Four loadings of available fuel, 8, 12, 16 and 18 t ha^{-1}, correspond to four fuel moisture levels representative of the 'first', 'second', 'third' and 'fourth suitable burning day after rain' respectively. Burning is not attempted until at least 7 mm of rain is registered on the burn area.

Predictions of fire behaviour in the Guide vary with suitable burning days. Four tables predict rate of spread and flame height for each suitable burning day using the inputs of relative humidity and wind strength. Predictions for both the interior and exposed edges of plantations are given. Relative humidity is a choice of eight possible values, 15–85% in steps of 10%, while wind strength is one of four force categories, 1–5, 6–11, 12–18 and 19–29 km h^{-1}.

Methods

Fire Behaviour Equations

In order to produce a working model that would yield predicted fire behaviour as opposed to the categories in the fire behaviour tables of the Mk III Burning Guide), a datafile containing the inputs and the subsequent predicted fire behaviour results, for both interior and exposed edges, was created from the tables of the Guide. Compatible with the format of these tables, wind strength and fuel moisture were treated on four levels. Relative humidity was treated as a continuous variable rather than as the eight categories of the tables. The GLIM generalised least squares statistical package (Baker and Nelder 1978) was used to derive multiple linear regression equations for the fire behaviour tables of the Mk III Burning Guide.

Predictions of fire intensity are not available from the Mk III Burning Guide. These were therefore obtained using the formula (Albini 1976, p. 86) $I=230\,L^{3/2}$, where I (kW m^{-1}) is Byram's intensity and L (m) is flame length. Flame height was used as the input for flame length.

Experimental Fires

Between 1979 and 1981, 88 fires were ignited in the interior of slash pine plantations at Toolara State Forest (lat. 26°00′ S, long. 152°50′ E) near Gympie. Plantations, ranging in age from 9 to 12 years and containing flat uniform areas of Type 2 fuels, were selected. These areas were divided into square blocks of about 1 ha and isolated by 2-m-wide fuel breaks.

Rainfall was measured and days since last rain were recorded prior to burning. Fine fuel quantity (t ha^{-1}) of material less than 1 cm diameter was measured and fuel reduction was estimated by measuring the remaining 'fuel' immediately after each fire. Oven-dry fuel moisture (% o.d. weight) was measured for the top 1 cm layer of pine needles only. Temperature (°C) and relative humidity (%) were measured periodically by an aspirated hygrometer, and wind speed (km h^{-1}) at 1·5 m above ground level was obtained from an anemometer. All weather data were collected from a similar adjacent site isolated from fire influences. Each fire was lit at a single point and, after the initial build-up stage, the fire perimeter was marked periodically to provide estimates of forward rate of spread (m h^{-1}). Eye estimates of flame height (m) were recorded. Monitoring lasted from 30 to 60 min. For each fire, the mean fire intensity I (kW m^{-1}) was calculated (after Byram 1959) from $I=Hwr/600$, where H (kJ kg^{-1}) is the heat yield of the fuel, w (t ha^{-1}) is the weight of available fuel, and r (m min^{-1}) is the rate of forward spread.

Comparison of Observed and Predicted Data

As noted above, the Mk III Burning Guide provides fire behaviour predictions for both the interior and exposed edges of plantations, but the 88 experimental fires were conducted in internal areas only. The weather and fuel parameters of these fires were input to the equations derived from the Guide to obtain predicted values of rate of spread and flame height. The predicted fire intensity was calculated for each fire using Albini's (1976) formula as described above. These predicted values were then compared with the observed values of the experimental fires.

For comparisons of each of the fire behaviour variables, regression equations were obtained of the form $y=a+bx$, where y is the predicted value (from the Guide) and x is the observed value (from the experimental fires), with a the intercept and b the slope of the regression line. The equations obtained were then compared with the equation of perfect fit $y=x$ by examining the constants a and b. After this comparison, a number of experimental fires were excluded and similar regression analyses were conducted on predictions for rates of spread only. The first excluded subset of 17 fires had estimated intensities less than 45 kW m^{-1}, the theoretical value at which fires are generally self extinguishing (McArthur 1962). The second subset excluded these same 17 fires plus an additional 14 fires where the observed wind speed exceeded 3.4 km h^{-1}. This value was selected to remove possible anomalies caused by the different measurements of wind speed used in the experimental fires and the Guide. The latter uses Beaufort wind strength which equates approximately to wind speed at 10 m above ground level in the open (Australian Bureau of Meteorology 1984) whereas wind speed was measured at 1·5 m under canopy for the experimental fires. Using a value of 3·4 km h^{-1} effectively removed all fires where the observed wind speed would have exceeded the equivalent of wind strength category 1 (1–5 km h^{-1}) with a 1·6 km h^{-1} allowance for reduction due to canopy (Luke and McArthur 1978, p. 56).

Sensitivity Analysis of the Guide

To assess possible avenues for fine tuning of the Guide, a sensitivity analysis was undertaken using the equations derived to represent the fire behaviour tables of the Guide. Each group of coefficients of the equations in turn was altered by ± 10% while all other coefficient groups were held constant. The weather and fuel data of the 88 experimental fires were then used to recalculate rate of spread, flame height and fire intensity, and the results were compared with those obtained from the original equations.

Results

The regression coefficients for the four equations making up the fire behaviour tables of the Guide are given in Table 1; the form of the equations is shown with the table. The coefficients of determination (r^2) included in Table 1 suggest that all four equations provide a very good fit to these fire behaviour tables.

A summary of the observed values for the experimental fires and the deviations of these values from the predicted values of the Guide equations are presented in Table 2. The mean and range of the observed values are included along with mean relative deviations, calculated using absolute values. The predicted results are generally poor, particularly for fire intensity.

Results of the linear regression comparison of the observed and predicted data are presented in Table 3. None of the regression equations were found to be similar to the line of perfect fit, and the slope of each was significantly greater than zero. These equations are shown superimposed over plots of predicted against observed values in Fig. 1. A similar pattern of overprediction for low observed values and underprediction for higher values is evident for all three variables. Additionally, the relatively wide spread of the datum points about these lines is reflected by the low coefficients of determination r^2 presented in Table 3.

Excluding particular fires from the data set did not improve the accuracy of predictions. The first subset of 71 fires, that is, excluding fires with intensities below 45 kW h^{-1}, produced a coefficient r^2 of 0·128 for the regression of predicted against observed rates of spread. The second subset of 57 fires, excluding both low intensity fires and fires where wind strength exceeded category 1, was similarly unsuccessful, producing an r^2 value of 0·078.

Table 1. Coefficients of derived equations to the fire behaviour tables of the Mk III Burning Guide

Each of the four equations for rate of spread (*ROS*) of the fire and flame height (*FH*) for both the interior and exposed edges of the plantation were of the form

$$y = a + b_1 RH + b_2 FM(2) + b_3 FM(3) + b_4 FM(4) + b_5 WS(2) + b_6 WS(3) + b_7 WS(4)$$
$$+ b_8 RH.FM(2) + b_9 RH.FM(3) + \ldots + b_{22} FM(4).WS(4),$$

where y is the dependent variable (*ROS* or *FM*), a is a constant, the b_i (i = 1–22) are regression coefficients, *RH* is relative humidity, the $FM(j)$ (j = 2–4) are factors with a value of 1 if the fuel moisture content is at the jth level, but zero otherwise, and the $WS(k)$ (k = 2–4) are factors with a value of 1 if the wind speed is at Force k, but zero otherwise. The values of all coefficients, with standard errors (SE) given in parentheses below, are tabulated for each equation, together with the overall coefficient of determination r^2

Parameter in equation	Coefficient group	Coefficient (SE) for: *ROS* interior	*ROS* edges	*FH* interior	*FH* edges
Constant (a)		35·6 (1·0)	44·3 (1·4)	0·892 (0·028)	0·966 (0·035)
RH	1	−0·372 (0·017)	−0·444 (0·022)	−0·0063 (0·0005)	−0·0068 (0·0006)
FM(2)	2	6·0 (1·2)	7·6 (1·6)	0·090 (0·034)	0·123 (0·042)
FM(3)	2	16·8 (1·2)	20·5 (1·6)	0·229 (0·034)	0·313 (0·042)
FM(4)	2	20·6 (1·2)	28·7 (1·6)	0·210 (0·034)	0·334 (0·042)
WS(2)	3	5·1 (1·2)	10·2 (1·6)	0·063 (0·034)	0·190 (0·042)
WS(3)	3	17·5 (1·2)	22·2 (1·6)	0·223 (0·034)	0·325 (0·042)
WS(4)	3	36·2 (1·2)	60·1 (1·6)	0·494 (0·034)	0·917 (0·042)
RH.FM(2)	4	−0·052 (0·018)	−0·047 (0·024)	−0·0010 (0·0005)	−0·0010 (0·0006)
RH.FM(3)	4	−0·150 (0·018)	−0·185 (0·024)	−0·0023 (0·0005)	−0·0030 (0·0006)
RH.FM(4)	4	−0·150 (0·018)	−0·269 (0·024)	−0·0010 (0·0005)	−0·0027 (0·0006)
RH.WS(2)	5	−0·025 (0·018)	−0·086 (0·024)	−0·0003 (0·0005)	−0·0015 (0·0006)
RH.WS(3)	5	−0·155 (0·018)	−0·136 (0·024)	−0·0015 (0·0005)	−0·0017 (0·0006)
RH.WS(4)	5	−0·350 (0·018)	−0·409 (0·024)	−0·0044 (0·0005)	−0·0058 (0·0006)
FM(2).*WS*(2)	6	0·5 (1·6)	0·3 (1·5)	0·025 (0·033)	0 (0·040)
FM(2).*WS*(3)	6	1·6 (1·6)	2·9 (1·5)	0·050 (0·033)	0·075 (0·040)
FM(2).*WS*(4)	6	4·4 (1·6)	11·6 (1·5)	0·113 (0·033)	0·200 (0·040)

Table 1 (*Continued*)

Parameter in equation	Coeff-icient group	Coefficient (SE) for: *ROS* interior	*ROS* edges	*FH* interior	*FH* edges
FM(3). *WS*(2)	6	1·5 (1·6)	6·4 (1·5)	0·037 (0·033)	0·087 (0·040)
FM(3). *WS*(3)	6	6·6 (1·6)	7·4 (1·5)	0·125 (0·033)	0·150 (0·040)
FM(3). *WS*(4)	6	11·5 (1·6)	25·1 (1·5)	0·213 (0·033)	0·400 (0·040)
FM(4). *WS*(2)	6	5·1 (1·6)	7·4 (1·5)	0·075 (0·033)	0·087 (0·040)
FM(4). *WS*(3)	6	9·4 (1·6)	11·3 (1·5)	0·137 (0·033)	0·187 (0·040)
FM(4). *WS*(4)	6	16·0 (1·6)	30·7 (1·5)	0·237 (0·033)	0·450 (0·040)
Coefficient r^2		0·994	0·996	0·979	0·987

Table 2. Summary of observed values of fire behaviour and their deviations from the predicted values of the Guide equations

The results are from 88 experimental fires in interior plantation areas

Variable of fire	Mean (range) of observed values	Mean deviation[A] Overall	(%)
Rate of spread (m h^{-1})	24·6 (10·8–79·2)	10·8	43·8
Flame height (m)	0·6 (0·1–1·7)	0·3	50·7
Intensity (kW m^{-1})	112·8 (3·0–514·0)	61·9	154·9

[A] The mean overall deviation is the sum of the absolute differences between the predicted (p_i) and observed (o_i) values divided by the number (n) of observations, that is, $\Sigma_i|p_i - o_i|/n$; the mean percentage deviation is $\Sigma_i(|p_i - o_i| \times 100/o_i)/n$.

Table 3. Linear regression comparison of observed and predicted fire behaviour

The results are from fits of linear regressions of the form $y = a + bx$, where y is the predicted variable and x the corresponding observed variable, to the data for 88 experimental fires in interior plantation areas. The coefficient of determination r^2 for each equation is shown together with the results of three tests of hypotheses (H_0) for the values of the regression coefficients: *, hypotheses rejected at $P < 0·05$; **, hypotheses rejected at $P < 0·01$

Variable of fire	Regression coefficient Intercept a	Slope b	Coefficient r^2	Tests on coefficients H_0: $a=0$	H_0: $b=0$	H_0: $b=1$
Rate of spread	0·224	0·196	0·119	**	**	**
Flame height	0·537	0·076	0·052	**	*	**
Intensity[A]	92·57	0·104	0·089	**	**	**

[A] Predicted intensities were calculated from flame height predictions.

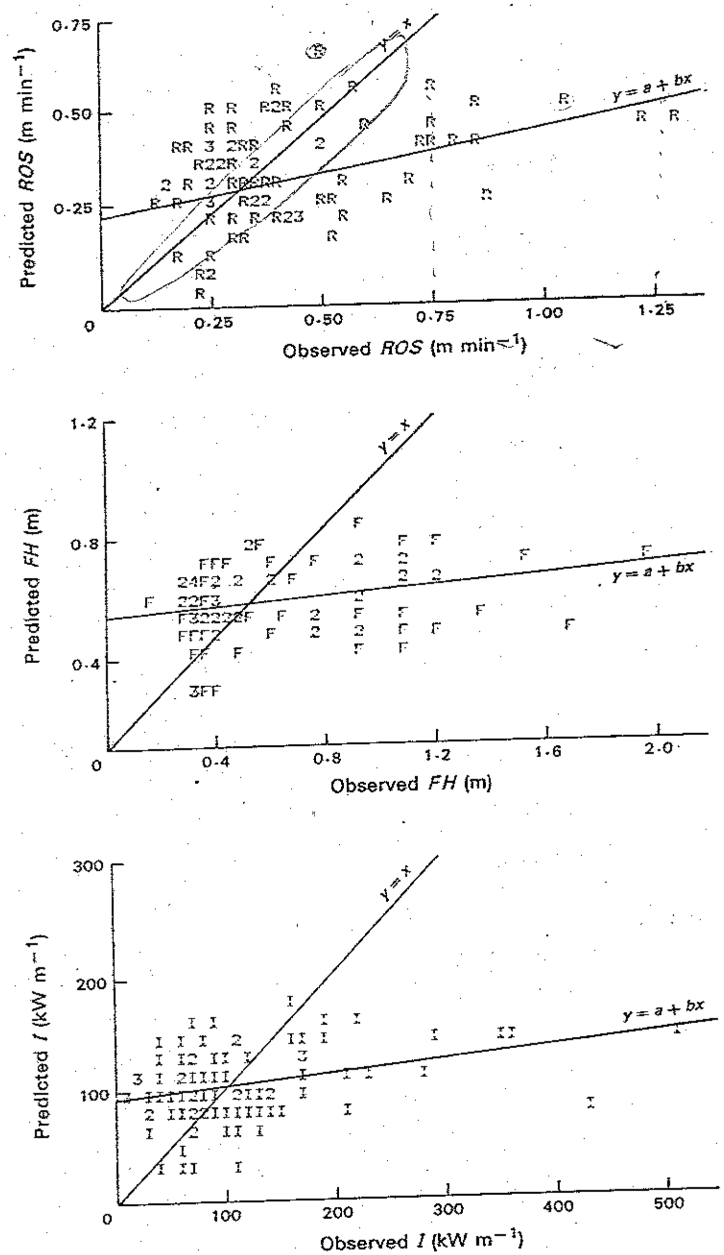

Fig. 1. Linear regression fits of the form $y = a + bx$ to the predicted (y) and observed (x) data for rate of spread (*ROS*), flame height (*FH*) and fire intensity (*I*) from the 88 experimental fires in interior plantation areas. The lines of perfect fit ($y = x$) are included for comparison in each plot.

Table 4. Sensitivity analysis of predictions of Mk III Burning Guide

The results show the changes in the mean relative deviation between the predicted fire behaviour from the Guide equations and the data for the 88 experimental fires in interior plantation areas brought about by changes of ± 10% in the coefficient groups of the Guide equations (see Table 1). As before, the coefficients are relative humidity (*RH*), fuel moisture (*FM*) and wind speed (*WS*), and the fire variables are rate of spread (*ROS*), flame height (*FH*) and fire intensity (*I*)

Coefficient group	Change in coefficient (%)	Change in mean deviation (%) *ROS*	*FH*	*I*
RH	+10	+0·87	−3·59	−21·20
	−10	+0·97	+4·82	+17·79
FM	+10	+1·04	+1·96	+4·38
	−10	−0·40	−1·75	−4·33
WS	+10	−0·01	−0·01	+0·05
	−10	0·00	+0·02	−0·05
RH.FM	+10	+0·16	−0·89	−2·32
	−10	+0·12	+1·04	+2·33
RH.WS	+10	0·00	+0·01	−0·01
	−10	0·00	0·00	+0·01
FM.WS	+10	−0·01	−0·01	−0·01
	−10	0·00	+0·01	+0·01

The sensitivity analysis presented in Table 4 shows changes in mean relative deviation of rate of spread, flame height and intensity for internal areas. The results suggest that altering the humidity coefficient may reduce the mean relative deviation for intensity. However, an examination of Table 4 in conjunction with Table 2 shows that any improvement would be minimal, as the mean relative deviation for intensity would still be of the order of 130% (i.e. 154·9 − 21·2).

Discussion

The four derived equations (Table 1) provided a very good fit of the fire behaviour tables of the Mk III Burning Guide. The coefficients of determination of all equations exceeded 97% and suggested that the predictive ability of these equations was more than adequate to represent the Burning Guide for the comparison of predicted and observed fire behaviour data. This result was not unexpected, as similar regression equations would have been compiled in the development of the Guide, and rounding errors would account for the slight variations.

The deviations between the predicted and observed data presented in Table 2 suggest that the Guide provides relatively poor predictions of rate of spread and flame height and even poorer predictions of fire intensity. The result for fire intensity could be due to two factors: firstly, the predicted flame height was used to calculate 'predicted' fire intensity and, secondly, the formula of Albini (1976) used calculation may not apply. The poor overall predictive results are supported

by the linear regression test of the Guide (Table 3 and Fig. 1). In all cases, the regression equations were found to differ significantly from the line of perfect fit and their slopes were significantly greater than zero. Additionally, their low coefficients of determination preclude any alteration of the Guide's coefficients to produce equations similar to the line of perfect fit. Rothermel and Rinehart (1983) recommend coefficients of determination of at least 0·75 before any adjustments are attempted to improve predictions.

Although various burning guides have been developed for exotic plantations (e.g. Sneeuwjagt and Peet 1976), little evaluative work is available for comparison with this study. An exception is the evaluation by Andrews (1980) who regressed predicted values against observed values of four separate studies of Rothermel's (1972, 1983) fire behaviour model. The r^2 value, and hence goodness of fit, of each study is compared with the r^2 value of the present study in Table 5. The poor predictive ability of the Guide equations is very evident.

Table 5. Comparison of predictions from Rothermel model and Mk III Burning Guide

The coefficients of determination (r^2) found by Andrews (1980) from four previous tests of the Rothermel (1972, 1983) model for predicted rates of spread of fires in different fuel types are compared with the corresponding r^2 value from the present test of the Mk III Burning Guide

Fuel type	Reference for test	Coefficient r^2
Grass	Sneeuwjagt and Fransden (1976)	0·92
Slash	Brown (1972)	0·80
Slash	Bevins (1975)	0·43
Southern rough	Hough and Albini (1978)	0·89
Pine plantations	Present test of Mk III Burning Guide	0·12

Albini (1976), in his discussion of the limitations of accuracy for fire behaviour modelling in general, listed three principal reasons for error:

(1) the model's inherent accuracy may be at fault;
(2) the data used to test the model may be inaccurate;
(3) the model may not be applicable to the situation.

The results with the Guide can be examined in the light of these three possible sources of error. Firstly, the Mk III Burning Guide is empirically derived and has provided acceptable predictions for prescribed burning in the past (Byrne 1980), which suggests that there is no inherent inaccuracy. The results of the sensitivity analysis (Table 4) support this conclusion. Secondly, the fire behaviour data for this study were collected under experimental conditions and are therefore assumed to be accurate. Finally, a number of factors can be considered with regard to the applicability of the Guide in this study. The attempts to improve the applicability of the data set to the Guide failed in both cases: deleting fires of low intensity and fires where wind strength exceeded category 1 did not improve its predictive ability.

One possible explanation for the poor predictive results obtained from the Guide is fuel type variation. Although all of the experimental fires were in areas classified as Type 2, fuel suspension may vary from 50% to 80% within this single type. Additionally, the presence of live or green fuel will directly influence fire behaviour because of its effect on the moisture content of available fuel. Predictions of fuel moisture content by the Guide do not take this live-fuel component into account, nor was this component sampled during the experimental fires (the top 1 cm of pine needles only was sampled). Differences in fuel composition are certain to have occurred on the 88 experimental fire areas.

Conclusions

The poor predictive results obtained with the Mk III Burning Guide are apparently due to variation in fuel composition within Fuel Type 2, the fuel classification most applicable to the Guide's drying and fire behaviour tables. While operational use of the Guide has been very successful in the past (Byrne 1980), changes in plantation management practices in recent years have limited the field applicability of the Guide. The majority of areas now burnt for the first time do not carry Type 2 fuels.

Possible improvement of the Guide to cater for fuel-type variation and shifts in 'average' fuel type appears limited because of the Guide's empirical development. It would not be practical to have to continually modify fire behaviour tables to allow for changing fuel composition. The sensitivity analysis in this study also suggests that fine tuning of the Guide in the short term, by adjusting coefficients within the Guide equations, would not be beneficial. Consequently, it would seem more appropriate for future fire behaviour guides to examine theoretical models such as the Rothermel (1972, 1983) model, and this examination has commenced. Because of their theoretical derivation, these models can be readily adapted to overcome changes in environmental variables.

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