

## Empirical modelling of surface fire behaviour in maritime pine stands

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**Abstract.** An experimental burning program took place in maritime pine (*Pinus pinaster* Ait.) stands in Portugal to increase the understanding of surface fire behaviour under mild weather. The spread rate and flame geometry of the forward and backward sections of a line-ignited fire front were measured in 94 plots 10–15 m wide. Measured head fire rate of spread, flame length and Byram's fire intensity varied respectively in the intervals of 0.3–13.9 m min<sup>-1</sup>, 0.1–4.2 m and 30–3527 kW m<sup>-1</sup>. Fire behaviour was modelled through an empirical approach. Rate of forward fire spread was described as a function of surface wind speed, terrain slope, moisture content of fine dead surface fuel, and fuel height, while back fire spread rate was correlated with fuel moisture content and cover of understorey vegetation. Flame dimensions were related to Byram's fire intensity but relationships with rate of spread and fine dead surface fuel load and moisture are preferred, particularly for the head fire. The equations are expected to be more reliable when wind speed and slope are less than 8 km h<sup>-1</sup> and 15°, and when fuel moisture content is higher than 12%. The results offer a quantitative basis for prescribed fire management.

**Additional keywords:** flame length, fuel, Portugal, prescribed fire, rate of spread.

### Introduction

Fire spread rate, flame size and heat release rate determine the difficulty of control and the aboveground impacts of fire and consequently their prediction is at the core of many decisions related to fire management. It has long been recognised that the results of fire behaviour experiments cannot be extrapolated beyond the fuel, weather and topography conditions from which they are derived (Fons 1946). Because a theoretical formulation able to estimate fire behaviour directly, conveniently and reliably seems distant, fire management decisions in the predictable future will continue to be assisted by empirically based fire models (Sullivan 2009). Accuracy in fire behaviour estimation is particularly important in prescribed burning operations, because the predefined burning conditions must lead to site-specific effects (Albini 1976). Regardless of the pursued modelling approach, outdoor experimental fires are a vital element in the study of fire behaviour (Alexander and Quintilio 1990).

Few alternatives are available to estimate surface fire behaviour in pine stands. Peet *et al.* (1971) developed a prescribed burning guide for maritime pine (*Pinus pinaster* Ait.) plantations in SW Australia from point-source ignitions in litter. Building on this work, options for both maritime and radiata pine are included in the Western Australia Forest Fire Behaviour Tables (Sneeuwjagt and Peet 1985). Experimental data covered a modest range of 0.1 to 1.4 m min<sup>-1</sup> in spread rate and

were supplemented with observations of wildfire spread up to 17 m min<sup>-1</sup> (Beck 1995). In Queensland, similar experiments were combined with the west Australian findings to derive a burning guide for slash pine (Byrne 1980). In eastern Australia, there are examples (Alexander 1990) of research applications that assumed similar fire spread rates in radiata pine plantations and dry eucalypt forest, and thus have estimated the former from the Forest Fire Danger Index of McArthur (1967). The Canadian Forest Fire Behaviour Prediction System (Forestry Canada Fire Danger Group 1992) estimates fire behaviour for 16 fuel types, including four types of pure pine stands. Nine experimental fires (spread rate range of 1–6 m min<sup>-1</sup>) – of which six are documented by Van Wagner (1968) – guided the formulation of the surface fire rate of spread equation for fuel type C-6, which corresponds to conifer plantations where litter dominates the surface fuel complex. The semi-empirical fire spread model of Rothermel (1972) and associated models have the potential to predict surface fire behaviour in any fuel type, provided it is described as a fuel model. Such apparent model generality is, however, offset by the necessity of using actual observations of fire behaviour as a benchmark to adjust the predictions (e.g. Van Wagendonk and Botti 1984) or to develop the fuel models (e.g. Hough and Albini 1978).

A close association exists between wildland fire and maritime pine, a widespread conifer from the western Mediterranean Basin. The species survives low-intensity fire, which historically

played an important role in the dynamics of some natural populations in the Iberian Peninsula, but is especially renowned for its high flammability and proneness to stand-replacement wildfire (Fernandes and Rigolot 2007). Proactive hazard reduction by fuel treatments should therefore be an important component of maritime pine management, and fire behaviour assessment offers objective criteria to formulate the treatments. In particular, analysis of the prescribed burning practice in pine stands in Portugal has identified the need for decision-support tools to ensure a planning level commensurate with effective and undamaging burn operations (Fernandes and Botelho 2004). Considerable research on flammability and fire behaviour in maritime pine litter has been conducted in European laboratories (e.g. Dupuy 1995; Mendes-Lopes *et al.* 2003). Fire characteristics in maritime pine stands are documented in several studies of prescribed burning effects, but explicit work on fire behaviour under natural conditions is limited in scope (Vega *et al.* 1993; Botelho *et al.* 1994; Cruz and Viegas 2001; Fernandes *et al.* 2004). Surface fuels, in contrast, have been extensively characterised in maritime pine stands (Fernandes and Rigolot 2007).

Understanding how the fire environment determines the impacts of prescribed fire in maritime pine stands was the primary motivation for an experimental burning program in northern Portugal that included the acquisition of surface fire behaviour data. Preliminary analysis indicated that the existing alternatives (Sneeuwjagt and Peet 1985; Forestry Canada Fire Danger Group 1992; Andrews *et al.* 2008) were inadequate to predict prescribed fire behaviour in maritime pine (Fernandes *et al.* 2002a). Fuel models developed through a robust calibrating procedure increased the performance of the Rothermel model (Cruz and Fernandes 2008), but still underestimated the rate of fire spread at the high end of the fuel moisture content range (Cruz *et al.* 2008). Moreover, fuel models cannot accommodate the variety of local fuel conditions and hence are unsatisfactory to estimate site-specific fire behaviour. The experimental dataset was previously used to describe the thresholds for sustained fire spread in maritime pine stands (Fernandes *et al.* 2008). Here, we document the observed fire behaviour and describe the main surface fire characteristics by means of empirical models that are expected to overcome the predictive shortcomings of tools based on Rothermel's model.

## Methodology

### *Study area and experimental sites*

The study area is situated in northern Portugal at latitudes of 41°20'N to 41°30'N and longitudes of 7°40'W to 7°50'W. The climate is Mediterranean, with mean annual temperature and rainfall varying from 10 to 14°C and from 500 to 1200 mm, and soils are derived from schist or granite (Agroconsultores-COBA 1991). Three communal forests co-managed by the Portuguese Forest Service were selected in the mountains of Marão and Alvão and in the Padrela plateau respectively. Five experimental sites within a 450–970-m elevation range occupied by planted or naturally regenerated maritime pine stands were chosen. Site selection targeted the typical fuel conditions of maritime pine stands in the Mesomediterranean and Supramediterranean bioclimatic levels, where the understorey comprises *Ericion umbellatae* alliance species (Rivas-Martinez 1979). On each site,

trees taller than 2 m were measured for diameter at breast height, height, and live crown base height within one representative 0.05-ha circular plot.

Square plots of 10 to 15 m (a 100–225-m<sup>2</sup> area range) were prepared for the experimental fires at each site. Small-sized plots facilitate fire measurement and can be of benefit to the analysis of fire data by reducing within-plot variability in fuels and weather. A 0.3- to 1.2-m-wide cleared strip was established around each plot, without removing trees to avoid weather-related edge effects. Terrain slope was measured.

Surface fuels consisted of a layer of dead needles and twigs on the forest floor, with or without a contiguous low understorey of live and dead (standing or suspended) vegetation of variable cover and floristic composition. The fuel complex was measured at the plot level and categorised according to the existing assemblages of dominant species. The preburn quantitative characterisation of fuels was non-destructive and considered three layers, namely the understorey vegetation, surface litter (the forest floor L-horizon) and subsurface litter (the forest floor F-horizon). The line-intercept method of Canfield (1941) was employed to assess vegetation ground cover along the plot diagonals. Intercepts of canopies by transects were measured in height, taken as the vertical distance (cm) between the litter surface and the apparent top of vegetation. A mean figure for understorey height was obtained by weighting each measured height by the horizontal extent of the respective canopy. Litter depths were measured to the nearest mm at 10 random locations. Destructive sampling outside the plots resulted in the calculation of site-specific bulk density values for each fuel layer. The mean bulk density of understorey vegetation ranged from 1.63 to 4.81 kg m<sup>-3</sup>, while mean values of 18.4 and 46.2 kg m<sup>-3</sup> were assumed for the L and F layers of litter, because variation between sites was less than within-site variability (Fernandes 2002). Plot estimates of fine fuel loads on a unit area basis (t ha<sup>-1</sup>) were obtained by multiplying the volume resulting from the cover and depth of each fuel layer by the respective bulk density. Coarser (thicker than 6 mm) and downed woody fuels play a minor role in fire spread and were not sampled; in maritime pine stands in the study region, they typically amount to less than one fifth of the total fuel load (Fernandes 1991). Surface fuel depth was calculated as the sum of the mean L-layer litter depth and height of the understorey vegetation, while the weighting of each fuel layer height by its respective cover or load resulted in two effective fuel depths.

### *Experimental fires*

The experimental fires were carried out between November and June and from 1999 to 2001. Burning in these months had been anticipated to result in documentation of the entire surface fire behaviour range. Almost half of the fires were implemented in series of consecutive or near-consecutive days following recent rainfall, to encompass a wide range of fuel moistures. A total of 94 sustained fires were conducted in 41 days. One to four plots were burned on each day. A back fire or head fire qualified as unsustained if it went out – usually within less than 5 min after ignition – and was discarded from further data analysis.

Plot ignition was conditional on the existence of alignment between slope and wind direction (up to a 20° deviation) or when

wind direction was normal to slope. Each fire was lit by a drip torch with a 2 : 1 diesel to gasoline mixture. The ignition line – narrower than plot width to allow unrestrained fire growth – was established inside the plot, parallel to and 2 m away from the windward edge, to permit observation of both forward and backward spread. Most fires were started at the plot lowest elevation and propagated upslope with the wind and downslope against the wind, but two other ignition patterns were also employed: (i) ignition at the top of the plot, resulting in downslope movement of the head fire; and (ii) ignition along a plot side parallel to slope direction, the fire being pushed by a cross-slope wind. Fire suppression, whenever required, made use of hand tools and a vehicle with a slip-on tanker.

Fuels were randomly sampled for moisture content just before ignition in the immediate vicinity of the plot to be burned. Three composite samples – each weighing ~50 g – of fine dead fuels were taken from surface litter and understorey vegetation and their moisture contents averaged to provide a representative value for the dead fuels carrying the fire. Live fuels measuring less than 3 mm in diameter and the F-layer litter were also harvested (one sample each). To better integrate the spatial variability of moisture conditions, every sample comprised fuel material collected from several locations. The samples were bagged, sealed on collection and then oven-dried at 85°C for 24 h. Moisture content was then expressed on a percentage dry-weight basis. Weather data that was taken 1.7 m above the ground in the stand included ambient air temperature and relative humidity. A continuous anemometer measurement of wind speed (to the nearest 0.1 km h<sup>-1</sup>) was acquired either upwind of or parallel to the plot, at an approximate 10-m distance.

The quantification of fire behaviour was based on visual estimates made by experienced observers walking parallel to the flame front. Individual sections for fire observation were defined by metal poles (1.5 m high) positioned along the plot axis at regular intervals, usually 2 or 3 m, and used as references to aid in the assessment of fire characteristics. The time of ignition was registered and the arrival of the fire front base to the rods was timed with stopwatches to determine rate of fire spread. The description of flame dimensions followed Alexander (1982) but the reference for measurement was litter surface instead of the fuel bed top, because under marginal burning conditions (namely in back fires), the flame tip is often below or just above the apparent fuel depth. Flame height was measured as the vertical distance from the middle of the flame base at ground level to flame extremity (e.g. Weise and Biging 1996), and flame tilt angle as the angle between the vertical and the flame front axis, again defined by the flame base midpoint. A mean value per fire segment was estimated for each flame property. Flame height was assessed to the nearest 0.05 m (for flames up to 0.5 m), 0.1 m (flames 0.6–2 m), 0.2 m (flames 2–3 m) and 0.5 m (flames taller than 3 m). Flame tilt angle was evaluated in classes of 5°, with 0° assigned to vertical flames. Photographic imagery was sometimes used to adjust the flame estimates, especially in faster-spreading and higher-intensity fires. Notes were taken on the occurrence of spotting and combustion of ladder fuels and tree foliage. Changes in wind direction were also noted.

Fuel consumption per layer was computed as the difference between the non-destructive assessment of preburn fuel load and the residual fuel load estimated by destructive sampling after

the burn. Sampling of the remaining litter fuels was random and avoided the plot edge vicinity, often disturbed by fire-break construction and fire control operations. Litter was collected from six 0.07-m<sup>2</sup> quadrats and separated *in situ* between the L-layer (when present) and the F-layer. The remaining understorey vegetation was harvested from a 1-m<sup>2</sup> quadrat subjectively located to represent the average preburn understorey structure and post-burn condition.

Burn depth was not significantly different between the areas of the plot that were burned by the forward and the backward sections of the fire, probably because the F-layer availability for combustion was limited in most fires (Fernandes 2002). Accordingly, we have assumed that head fires and back fires removed equal quantities of fuel and thus computed a single fuel depletion estimate per plot.

#### *Data analysis and modelling*

Rate of fire spread for each segment of observation was calculated from the travel time and distance between poles. Plot head fire and back fire spread rate, flame height and flame tilt angle were calculated as the mean values of the segments; sections where wind direction had shifted were not considered. Flame length  $L$  was deduced from flame height  $H$  and tilt angle  $\alpha$  as  $H/\cos\alpha$ . Wind speed was averaged over the same segments and length of time as the head fire and back fire spread rates. A few experiments were excluded from analysis because of erratic wind direction.

Fire intensity as described in Byram (1959) is the product (in kW m<sup>-1</sup>) of spread rate (m s<sup>-1</sup>), net heat of combustion or heat yield (kJ kg<sup>-1</sup>) and the amount of fuel consumed in the flaming front (kg m<sup>-2</sup>). Heat yield was fixed at 18 000 kJ kg<sup>-1</sup> (Forestry Canada Fire Danger Group 1992), and flaming combustion assumed to be restricted to surface fine fuels that were entirely burnt in the active combustion zone. These assumptions are justified by the dominance of spread rate in determining the potential fire intensity range and the uncertainties in quantifying the other components of Byram's intensity (Alexander 1982). Mean values for fire intensity were derived for the back fire and the head fire on each plot.

All experimental data were used in model development. The addition of surface fire data from a subsequent higher-intensity experiment carried out in one of the study sites (Fernandes *et al.* 2004) allowed expansion of the fuel moisture content range to drier summer conditions. Correlation analysis was employed to screen for the influence of site, fuel and weather variables on fire behaviour characteristics. Relevant variables were then plotted against the independent variables to obtain graphical views of the form of the relationships. Least-squares fitting techniques (Myers 1990) were exercised to obtain the best possible model specification and functional formulation. After the effects of the variables with a major influence on a fire behaviour descriptor were accounted for, we used stepwise regression and added the remaining variables in turn to examine their significance and ability to improve the model. As in other empirical fire modelling studies (Cheney *et al.* 1992, 1993; Marsden-Smedley and Catchpole 1995; Fernandes *et al.* 2000; Gould *et al.* 2007), the dependent variables were log-transformed because error variance showed a tendency to increase with fire behaviour

**Table 1. Stand characteristics in the experimental sites**

Variable	Marão	Alvão1	Alvão2	Alvão3	Padrela
Stand age (years)	37	33	14	41	25
Diameter at breast height (cm)	26.1	25.7	11.0	25.3	13.0
Trees ha <sup>-1</sup>	1060	820	1520	480	2458
Basal area (m <sup>2</sup> ha <sup>-1</sup> )	56.5	42.5	14.3	24.5	32.7
Stand height (m)	15.8	16.3	6.1	18.3	10.0
Height to live crown base (m)	9.0	8.4	1.7	8.9	3.7

**Table 2. Mean (standard deviation) plot values for fuel structure descriptors for each fuel type**

Fuel type	Litter depth (cm)		Litter load (t ha <sup>-1</sup> )		Understorey vegetation		
	L-layer	F-layer	L-layer	F-layer	Cover %	Height (cm)	Load (t ha <sup>-1</sup> )
Litter ( <i>n</i> = 30)	3.2 (1.4)	2.8 (1.4)	5.7 (2.4)	12.8 (6.7)	0 (0)	–	0.0 (0)
EU-PT ( <i>n</i> = 38)	2.8 (0.9)	2.8 (0.9)	5.0 (1.6)	12.2 (4.1)	70 (23)	50 (12)	7.0 (2.9)
G-UM ( <i>n</i> = 10)	1.5 (0.2)	2.3 (0.8)	2.8 (0.3)	10.5 (3.6)	97 (5)	31 (7)	9.1 (2.9)
PA-G ( <i>n</i> = 4)	1.1 (0.2)	2.6 (0.9)	2.0 (0.4)	12.1 (4.2)	100 (0)	25 (7)	7.9 (3.5)
PA-S ( <i>n</i> = 6)	2.4 (0.1)	1.7 (0.1)	4.4 (0.3)	8.0 (0.4)	96 (5)	41 (8)	6.7 (3.3)
UM-PT-EU ( <i>n</i> = 2)	1.4 (0.0)	4.3 (1.9)	2.6 (0.0)	19.6 (8.8)	83 (16)	34 (9)	8.1 (1.3)

magnitude. The ratio of arithmetic sample mean and mean of the back-transformed predicted values from the regression was used to correct the logarithmic regression bias (Snowdon 1991). Collinearity among independent variables in a model was inspected with the maximum variance inflation factor (VIF) (Myers 1990). Assessment of the relative strengths of independent variables in a model was based on the standardised partial regression ( $\beta$ ) coefficients (Sokal and Rohlf 2003).

Model evaluation resorted to deviation measures (Willmott 1982), specifically the root mean square error (*RMSE*), the mean absolute (*MAE*) and percentage (*MA%E*) errors, the *MA%E* standard deviation and mean bias error (*MBE*):

$$RMSE = \sqrt{\frac{\sum (y_i - \hat{y}_i)^2}{n}} \quad (1)$$

$$MAE = \frac{\sum |y_i - \hat{y}_i|}{n} \quad (2)$$

$$MA\%E = \frac{\sum \left( \frac{|y_i - \hat{y}_i|}{y_i} \right)}{n} \cdot 100 \quad (3)$$

$$MBE = \frac{\sum (\hat{y}_i - y_i)}{n} \quad (4)$$

where  $y_i$  and  $\hat{y}_i$  are respectively the observed and the predicted values. Model predictions of fire spread rate were checked against independent data from experimental fires in maritime pine stands in Portugal (Rego *et al.* 1993; Botelho *et al.* 1994, 1998; Cruz and Viegas 2001) and France (Rigolot 2000). Modelling efficiency (*EF*), an overall indicator of goodness of fit, was employed to relate model estimates to validation data (Mayer and Butler 1993):

$$EF = 1 - \frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \bar{y}_i)^2} \quad (5)$$

## Results

### Experimental conditions and fire behaviour

Stand characteristics in the experimental sites are given in Table 1. The absence or presence of understorey vegetation and the corresponding dominant species led to the identification of six fuel types, quantitatively characterised in Table 2:

- (1) Litter plots, i.e. where understorey vegetation was absent
- (2) EU-PT. Shrubs *Erica umbellata* L. and *Pterospartum tridentatum* (L.) Wilk. dominate, with *E. cinerea* L., *E. australis* L. and *Halimium ocymoides* (Lam.) as minor components
- (3) G-UM. A matrix of grass (*Agrostis curtisii* Kerguelen, *Pseudoarrhenatherum longifolium* Rouy) and gorse (*Ulex minor* Roth)
- (4) PA-G. Non-woody layer of bracken fern (*Pteridium aquilinum* (L.) Kuhn) and grasses
- (5) PA-S. Bracken fern in combination with various shrubs
- (6) UM-PT-EU. Shrubs of the species *Ulex minor*, *Pterospartum tridentatum* and *Erica umbellata*

Table 3 gives the ranges for site, weather, fuel moisture and fire behaviour variables for head fire ( $n = 90$ ) and back fire ( $n = 76$ ) spread. Not all backward sections of the fire could self-sustain, hence the sample size difference. The burning program covered the autumn–winter weather favourable to prescribed burning – thus relatively stable and moist conditions with light winds prevailed – along with drier, but still mild, periods of spring conducive to more intense fire behaviour. Accordingly, in 24% of the fires, the moisture content of surface fuels, subsurface fuels, or both, does not comply with the burn prescription in Fernandes and Rigolot (2007). The maximum daily Fire Weather Index (Van Wagner 1987) for days with fire trials was 19, reaching a value of 40 in the day of the summer fire included in the

**Table 3. Descriptive statistics for site, weather, fuel moisture and fire behaviour variables**

Data are laid out as follows: mean (standard deviation), [minimum, maximum]. For the moisture content of live fine fuel, head fires,  $n = 58$ ; back fires,  $n = 52$

Variable	Head fires ( $n = 90$ )	Back fires ( $n = 76$ )
Slope ( $^{\circ}$ )	6 (6.5), [-6, 17]	-7 (6.3), [-17, 8]
Wind speed ( $\text{km h}^{-1}$ )	4.1 (3.1), [0.5, 22.0]	4.2 (3.4), [0.5, 23.1]
Air temperature ( $^{\circ}\text{C}$ )	12 (5), [2, 30]	11 (4), [2, 22]
Air relative humidity (%)	53 (17), [24, 96]	52 (16), [26, 87]
Moisture content of fine dead surface fuel (%)	20.6 (8.3), [3.7, 41.7]	19.5 (6.5), [8.4, 41.5]
Moisture content of F-layer litter (%)	147.6 (70.5), [7.3, 296.1]	142.6 (67.5), [11.1, 296.1]
Moisture content of live fine fuel (%)	102.1 (14.8), [82.3, 157.6]	102.8 (15.7), [82.3, 157.6]
Rate of fire spread ( $\text{m min}^{-1}$ )	2.75 (2.26), [0.25, 13.88]	0.26 (0.14), [0.07, 0.60]
Flame height (m)	1.3 (0.9), [0.1, 4.2]	0.5 (0.3), [0.05, 1.5]
Flame length (m)	1.6 (1.0), [0.1, 4.2]	0.6 (0.4), [0.1, 2.0]
Surface fine fuel consumption ( $\text{t ha}^{-1}$ )	8.87 (3.57), [0.77, 16.51]	
F-layer litter consumption ( $\text{t ha}^{-1}$ )	4.35 (4.13), [0, 23.38]	
Byram's fire intensity ( $\text{kW m}^{-1}$ )	692 (618), [30, 3527]	77 (59), [7, 232]

analysis; distance and elevation of the experimental sites in relation to the weather station providing the data were 5–45 km and 20–520 m respectively.

Only a few experimental fires breached plot limits but all were readily extinguished. Fire behaviour variability (Table 3) ranged from creeping, poorly sustained fires, to flames reaching into the lower tree canopy. Broken fire fronts characterised all back fires and most head fires propagating at dead fine fuel moisture contents above 25 and 30% respectively (Fernandes *et al.* 2008). The maximum head fire rate of spread was  $14 \text{ m min}^{-1}$ , but three-quarters of the fires were below  $4 \text{ m min}^{-1}$ . The average ratio between forward and backward spread rate in any one plot was 15.6, with a variation of 1.4 to 59.5; the corresponding values for flame length ratios were 3.6 and 1.0–12.9. Fire intensity exhibited the highest variation of all fire descriptors, mainly as a result of variation in rate of spread, and ranged over two orders of magnitude for head fires, up to more than  $3500 \text{ kW m}^{-1}$ .

The burning program revealed a wide fuel consumption range, due to the large ranges in surface and subsurface dead fuel moisture contents determined by a variation of two to 36 days in time since rain. The lowest-intensity fires did not remove the entire forest floor L-layer and the finest shrub components, and left the F-layer intact. At the opposite end, all fine fuels were eliminated and dead branches in trees were partially combusted up to a 3-m height, which commonly resulted in spotting within a distance of 5 m. Localised torching in the lower third of the canopy was observed in eight plots where crown base height was lower than 4 m and flame length exceeded 2 m.

#### Rate of fire spread

Table 4 provides a list of symbols for the variables appearing in the Results and Discussion sections. The concurrent availability of forward ( $R_f$ ) and backward ( $R_b$ ) fire spread data suggests a two-step modelling approach. A basic rate of fire spread (e.g. Ward 1971) could be determined from fuel characteristics and then used to assess wind and slope effects on  $R_f$ . Rates of spread of the back fire and of a fire front unaffected by wind and slope would have to be assumed equal. However, the approach is

**Table 4. Symbols for variables used in fire behaviour analysis**

Symbol	Variable
Dependent variables	
$R$	Rate of fire spread ( $\text{m min}^{-1}$ )
$H$	Flame height (m)
$L$	Flame length (m)
$I_B$	Byram's fire intensity ( $\text{kW m}^{-1}$ )
Independent variables	
$U$	Wind speed ( $\text{km h}^{-1}$ )
$S$	Slope ( $^{\circ}$ )
$M_S$	Moisture content of fine dead surface fuel (%)
$M_F$	Moisture content of F-layer litter (%)
$FD$	Fuel depth (cm)
$COV$	Understorey cover (%)
$W_S$	Surface fine fuel load ( $\text{t ha}^{-1}$ )

**Table 5. Correlation matrix of the variables dominating the rate of forward fire spread**

Correlations were significant at the 0.1% level; ns, non-significant

	Rate of spread	Slope	Wind speed
Slope	0.44		
Wind speed	0.67	0.20 ns	
Moisture content of fine dead surface fuel	-0.38	-0.02 ns	-0.11 ns

contentious because there should be differences in the prevailing mechanisms involved in forward and backward fire spread (Catchpole *et al.* 1993; Cheney *et al.* 1998), thus in the role played by fuel properties, and because  $R_b = 0$  does not imply that  $R_f = 0$ . Hence we have chosen to model  $R_f$  and  $R_b$  independently.

Wind speed ( $U$ ), terrain slope ( $S$ ) and moisture content of surface fine dead fuels ( $M_S$ ) were the most influential ( $P < 0.001$ ) factors acting on head fire spread (Table 5). Although these independent variables were unrelated ( $P > 0.05$ ),

**Table 6.** The significance, expressed as  $P$ -values, and increase in  $R^2$  (for significant variables,  $P < 0.05$ ) of adding fuel variables to models  $R_f = aU^b \exp(cS + dM_S)$  and  $R_b = a \exp(bM_S)$  respectively for forward and backward fire spread and in their log-transformed form

Variable	$R_f$		$R_b$	
	$P$ -value	$R^2$ increase	$P$ -value	$R^2$ increase
L-layer litter load	0.1031		0.0012	0.107
F-layer litter load	0.8776		0.2728	
Understorey vegetation load	0.0000	0.050	0.0000	0.565
Surface fuel load	0.0001	0.045	0.0000	0.408
Fuel depth	0.0000	0.062	0.0000	0.570
Effective fuel depth (cover weighted)	0.0000	0.067	0.0000	0.639
Effective fuel depth (load weighted)	0.0000	0.069	0.0000	0.505
Understorey vegetation cover	0.0000	0.050	0.0000	0.690

a positive correlation between  $U$  and  $S$  approached significance ( $P = 0.0614$ ). The wind speed influence on  $R_f$  was best described by a power law, while the increasing and decreasing effects of slope and fuel moisture on spread rate were best portrayed by an exponential function. Spread rate was proportional to  $U^{0.82}$ ,  $\exp(0.067S)$  and  $\exp(-0.053M_S)$ , which accounted respectively for 44, 24 and 25% of the existing variation. Combination of the variables into the log-transformed version of model  $R_f = aU^b \exp(cS + dM_S)$  explained 73% of the variation in spread rate.

Table 6 displays the results of adding the fuel-complex descriptors to the three-variable  $R_f$  model. To allow analysis and model inclusion, understorey cover ( $COV$ ) for the litter fuel type was entered as  $COV = 1\%$ . Of the variables in Table 6, all but litter loads were able to explain ( $P < 0.001$ ) part of the remaining variation in  $R_f$ , suggesting that the fuel effect on spread rate is due to understorey vegetation. Rate of spread increased with fuel loads, fuel depths and understorey cover, and the correlation among fuel variables was highly significant ( $P < 0.001$ ), thereby entailing confounded effects on spread rate. The three variants of fuel depth were superior to fuel loads and understorey cover and thus used to build alternative  $R_f$  models. The simplest formulation of fuel depth resulted in an equation that was slightly better adjusted to data, and as such was chosen to integrate the  $R_f$  model. No other independent variables were significant in explaining residual  $R_f$  variation, namely the moisture contents of subsurface litter ( $P = 0.4665$ ) and live fuel ( $P = 0.6510$ ).

The log-transformed version of the  $R_f$  model has  $\beta$  coefficients of 0.57, 0.45,  $-0.37$  and 0.27 respectively for  $U$ ,  $S$ ,  $M_S$  and fuel depth ( $FD$ ) (all significant at  $P < 0.001$ ). A maximum VIF of 1.2 indicates that collinearity among the independent variables is not a concern (Myers 1990). The back-transformed model explained 75.3% of  $R_f$  variance and is given by:

$$R_f = 0.773U^{0.707} \exp(0.062S - 0.039M_S)FD^{0.188} \quad (6)$$

with standard errors of 0.164, 0.064, 0.007, 0.005 and 0.036 respectively. The mean residual per fuel type ranged from  $-0.14 \text{ m min}^{-1}$  (UM-PT-EU) to  $0.70 \text{ m min}^{-1}$  (PA-S) and did not significantly differ between fuel types, according to a Tukey–Kramer HSD mean comparison test.

Back fire rate of spread  $R_b$  was correlated at the 0.1% level with  $M_S$ , surface and understorey fuel loads, fuel depths and

understorey cover. Wind speed and terrain slope were not significant ( $P > 0.05$ ). Fuel structure descriptors and  $M_S$  were uncorrelated, the  $P$ -value varying between 0.2671 and 0.9918, but the association between fuel-complex descriptors was highly significant ( $P < 0.001$ ).

After fitting an exponential function of  $M_S$ , only 14% of the variation in back fire rate of spread had been explained. Exploration of the significance of adding fuel variables to this model (Table 6) showed the fuel complex relative role in fire spread rate to be much higher for a back fire than for a head fire. Understorey cover was selected to join  $M_S$ , yielding a model with  $\beta$  coefficients of  $-0.40$  and  $0.83$  and a maximum VIF of 1.0. The resulting back-transformed equation accounts for 76.1% of the variation in  $R_b$ :

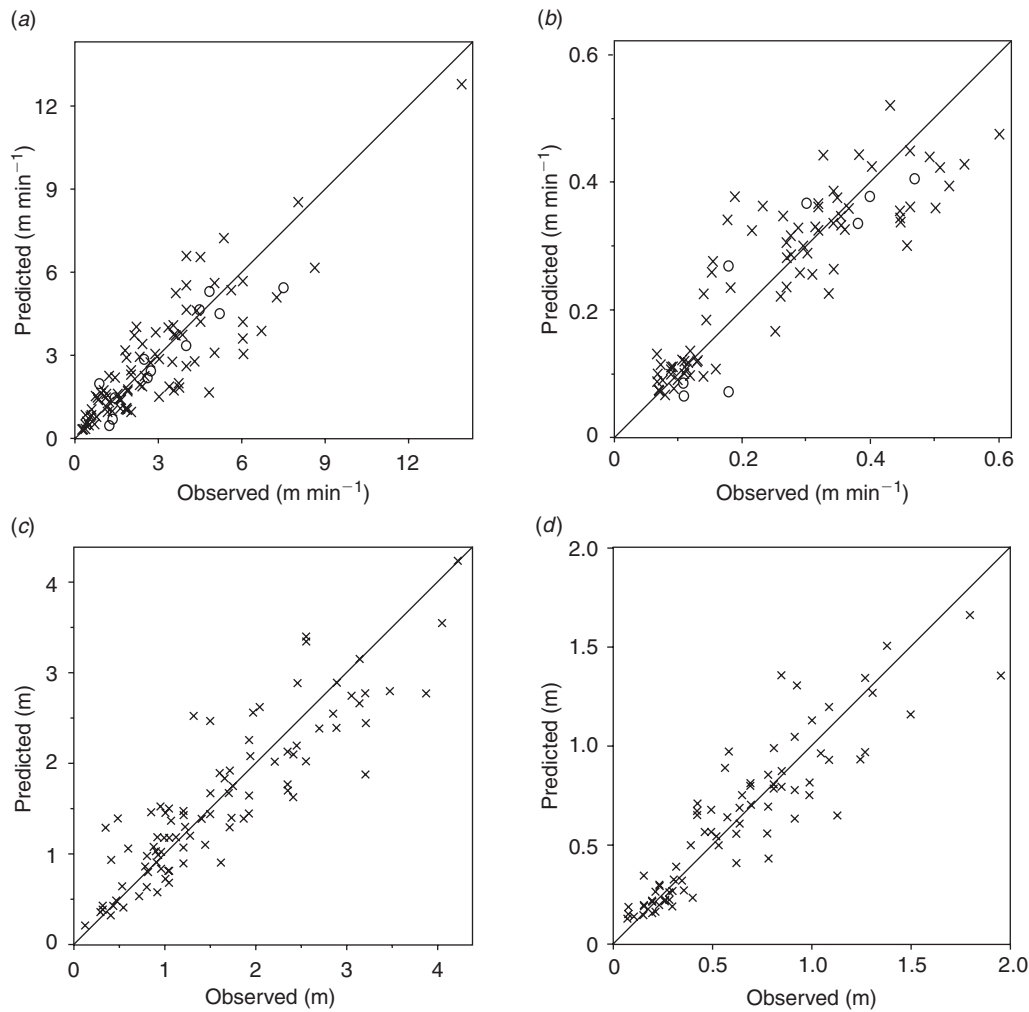
$$R_b = 0.213 \exp(-0.040M_S)COV^{0.264} \quad (7)$$

where  $COV = 1\%$  if understorey vegetation is absent, and with standard errors of 0.023, 0.005 and 0.015 respectively. The mean residual per fuel type varied from  $-0.04 \text{ m min}^{-1}$  (UM-PT-EU) to  $0.05 \text{ m min}^{-1}$  (PA-G) and was not significantly different between fuel types. All the remaining variables, including  $U$ ,  $S$  and  $M_F$  (F-layer litter moisture content) were unsuccessful ( $P > 0.05$ ) in further reducing the existing variation.

Figs 1a and 1b respectively for head and back fire display the observed  $v$ . predicted rates of fire spread; the respective model statistics are in Table 7. Both model fit and model evaluation statistics are better for the back fire equation than for the head fire equation, probably because lower errors are incurred in backward fire spread measurement. Nevertheless, and for the limited evaluation dataset available, all model estimates of head fire spread rate ( $n = 12$ ) are within 25% of the observed values, whereas only 42% of the independent back fire spread observations ( $n = 8$ ) are inside that interval. Mean absolute percentage errors of the models are below or within the 25–50% range that Cruz and Fernandes (2008) indicate as the best that can currently be attained in fire behaviour prediction.

#### Flame dimensions and fire intensity

Flame length is the most obvious manifestation of heat release and is frequently the preferred descriptor of flame size (Rothermel 1991). Flame height, however, is more accurately



**Fig. 1.** Predicted *v.* observed fire behaviour characteristics: (a) forward rate of fire spread (Eqn 6); (b) backward rate of fire spread (Eqn 7); (c) head fire flame length (Eqn 10); (d) back fire flame length (Eqn 11). Data points used in model development and model evaluation are respectively shown as crosses and circles. Model performance statistics are presented in Table 7.

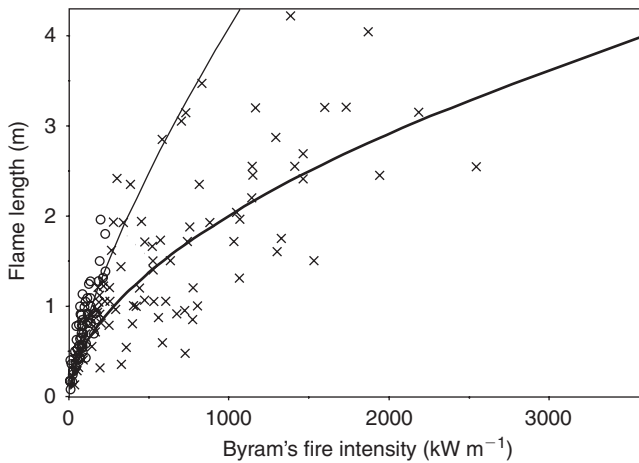
**Table 7.** Statistical measures of performance for the fire behaviour models

*RMSE*, root mean square error; *MAE*, mean absolute error; *MA%E*, mean absolute percentage error; *EF*, modelling efficiency; *MBE*, mean bias error

Model	Development data				Evaluation data				
	$R^2$	<i>RMSE</i>	<i>MAE</i>	<i>MA%E</i> (s.d.)	<i>EF</i>	<i>RMSE</i>	<i>MAE</i>	<i>MA%E</i> (s.d.)	<i>MBE</i>
(6) $R_f$	0.753	1.12	0.81	34.3 (26.7)	0.60	0.81	0.64	37.1 (57.1)	-0.29
(7) $R_b$	0.761	0.07	0.05	22.9 (21.9)	0.74	0.07	0.06	32.5 (22.1)	-0.02
(8) $L_f$	0.573	0.62	0.46	38.7 (47.3)					
(9) $L_b$	0.795	0.19	0.14	30.9 (32.0)					
(10) $L_f$	0.780	0.45	0.34	28.1 (38.5)					
(11) $L_b$	0.801	0.18	0.13	25.4 (25.1)					
(12) $H_f$	0.741	0.44	0.32	36.1 (52.1)					
(13) $H_b$	0.802	0.14	0.10	29.7 (38.2)					

assessed, and its prediction can serve a variety of purposes (Anderson *et al.* 2006). The monitoring of prescribed fire operations in Portugal (Fernandes and Botelho 2004) and elsewhere (e.g. Byrne 1980) resorts to flame height rather than to flame

length. Consequently, both indicators of flame dimensions are considered here. On average, flame length in head fires and back fires was respectively 1.3 and 1.4 times greater than flame height, reflecting the prevalence of low in-stand wind speeds.



**Fig. 2.** Flame length *v.* Byram's fire intensity for head fires (crosses) and back fires (circles). Flame length varies respectively with the 0.54 (thicker line, Eqn 8) and 0.72 (thinner line, Eqn 9) powers of  $I_B$ .

**Table 8.**  $R^2$  values for the log-transformed form of alternative flame length ( $L$ ) models

$I_B$ , Byram's fire intensity;  $R$ , rate of fire spread;  $W_s$ , surface fine fuel consumption;  $W_S$ , surface fine fuel load;  $M_S$ , moisture content of fine dead surface fuel

	Model form	Head fire	Back fire
1	$L = aI_B^b$	0.72	0.71
2	$L = aR^bW_s^c$	0.72	0.79
3	$L = aR^bW_s^c \exp(dM_S)$	0.79	0.79

A power function of Byram's fire intensity ( $I_B$ ) is often fitted to flame length. In agreement with theory (Nelson 1980), visual inspection of data (see Fig. 2) supported the use of different relationships for back fires and head fires, i.e. a single equation would underestimate the flame length of backing fires. Additionally, we have considered two modelling approaches that replace fire intensity with its component variables (Table 8). The model 2 type is based on fire spread rate and surface fuel consumption, while the model 3 form uses rate of spread, surface fuel load and surface dead fuel moisture content. Fuel load and moisture appear in model 3 as determinants of fuel consumption, hence avoiding estimation of this variable. Also, and because fuel moisture affects heat of combustion (Byram 1959), model 3 can potentially improve on the fit provided by the flame size- $I_B$  equations. Table 8 presents the results expressed in terms of  $R^2$  for the three modelling options.

After back transformation of model 1 and correction for bias, flame lengths of the head fire ( $L_f$ ) and back fire ( $L_b$ ) are respectively expressed through (Fig. 2):

$$L_f = 0.049I_B^{0.543} \tag{8}$$

with standard errors of 0.013 and 0.045, and

$$L_b = 0.029I_B^{0.724} \tag{9}$$

with standard errors of 0.008 and 0.045. Eqns 8 and 9 account respectively for 57.3 and 79.5% of the observed variation in

flame length. Model 2 fits  $L_f$  data better than model 1 but it is not advantageous over model 3, which is given by:

$$L_f = 0.451R_f^{0.305}W_S^{0.790} \exp(-0.040M_S) \tag{10}$$

where  $W_S$  is surface fine fuel load, and with  $R^2 = 0.780$  and standard errors of 0.089, 0.046, 0.077 and 0.005 respectively. Despite the influence of  $W_S$  and  $M_S$  on rate of spread, Eqn 10 has no collinearity problems (maximum VIF = 1.32) and all variables are significant at  $P < 0.001$ . Variation in flame length was determined more by fuel load ( $\beta = 0.52$ ) and fuel moisture ( $\beta = -0.48$ ) than by fire spread rate ( $\beta = 0.39$ ). The residuals of Eqn 10 increase slightly ( $P = 0.0438$ ,  $R^2 = 0.045$ ) with the consumption of subsurface litter, thus suggesting that some of the partially decomposed forest floor contributes to flaming combustion. Explanation of  $L_f$  could not be improved by other independent variables, and flame length residuals were not statistically distinct between no-slope, upslope or downslope fire propagation.

Model 3 also yielded a better fit ( $R^2 = 0.801$ ) to back fire flame length than models 1 and 2:

$$L_b = 1.223R_b^{0.870}W_S^{0.361} \exp(-0.018M_S) \tag{11}$$

with a maximum VIF of 1.32 and standard errors respectively of 0.278, 0.091, 0.126 and 0.007. A near-linear effect of spread rate ( $\beta = 0.72$ ,  $P < 0.0001$ ) exerts the major control on  $L_b$  variation, with fuel load ( $\beta = 0.20$ ,  $P = 0.0055$ ) and moisture ( $\beta = -0.15$ ,  $P = 0.0111$ ) in minor roles. None of the other variables could improve Eqn 11.

The ability of Byram's fire intensity to portray head fire flame height  $H_f$  was rather poor.  $H_f$  is proportional to  $I_B^{0.49}$  but only 42% of its variability is accounted for. This is basically the outcome of a weak relationship between  $H_f$  and spread rate. The model of Albin (1981) for the flame height of wind-aided fires is formulated as  $H_f = AI_B/U$ , where  $U$  is in units of  $m\ s^{-1}$ . Use of this approach requires the ambient wind to be combined with the upslope component of the fire's buoyant velocity into  $U_{ws}$ , the effective wind speed (Nelson 2002). After calculating  $U_{ws}$  and excluding downslope head fires ( $n = 7$ ), as well as two influent outliers, we obtained  $A = 1/386$  ( $R^2 = 0.646$ , s.e. = 1/10). The result compares well with the theoretical expectation of 1/360 and the value of 1/385 that Nelson and Adkins (1986) derived from their analysis of wind-tunnel data.

If the model 3 form is fitted to  $H_f$ , rate of fire spread is the least important influence -  $\beta$  is respectively 0.18, 0.61 and -0.53 for  $R_f$ ,  $W_S$  and  $M_S$  - and adds only 2% to the overall explanation of  $H_f$ . The following equation was subsequently fitted after concluding for a linear influence of fuel load on flame height:

$$H_f = 0.401W_S \exp(-0.058M_S) \tag{12}$$

with  $R^2 = 0.741$  and standard errors of 0.079 and 0.005.  $\beta$  coefficients for the log-transformed version of Eqn 12 were respectively 0.62 and -0.63, with a maximum VIF of 1.0.

Back fire flame height, in contrast with the above result for  $H_f$ , could be acceptably predicted from Byram's fire intensity:

$$H_b = 0.016I_B^{0.778} \tag{13}$$

with  $R^2 = 0.802$  and standard errors of 0.003 and 0.042.



If Eqns 8 and 9 are solved for fire intensity, we get:

$$I_{B-f} = 185.2L_f^{1.842} \quad (14)$$

$$I_{B-b} = 117.7L_b^{1.381} \quad (15)$$

which translate a given flame size into its energy-release equivalent.

Table 7 describes the predictive ability of Eqns 8–13, while Figs 1c and 1d display the estimated v. observed flame lengths for the preferred equations, i.e. Eqns 10 and 11. Goodness of fit is comparable between rate of spread models (Table 7, development data) and flame size models, but a lower standard deviation of the *MA%E* of the former indicates higher precision.

## Discussion

### *Wind and slope effects on fire spread rate*

The dependence of fire spread rate on wind speed is commonly formulated through a power or exponential function. The choice of one or the other is often irrelevant, unless model use is extrapolated to strong winds, in which case the exponential form will produce unrealistically high estimates (e.g. Burrows 1999b). Considerable variation can be found in the literature for the *b* coefficient when  $R_f \propto U^b$ , from  $b < 1$  (Pagni and Peterson 1973; Wolff *et al.* 1991) to  $b > 2$  (Rothermel 1972; Beer 1993). Exponential or markedly curvilinear power functions have been derived for eucalypt forest (Cheney 1981; Burrows 1999b) and *Pinus sylvestris* stands (Tanskanen *et al.* 2007) from field data. In contrast, contemporary empirical studies in shrub- or grass-dominated fuels (Cheney *et al.* 1993; Marsden-Smedley and Catchpole 1995; Catchpole *et al.* 1998a; McCaw 1998; Vega *et al.* 1998; Fernandes 2001), as well as in eucalypt forest (Gould *et al.* 2007), indicate a near-linear relationship between  $R_f$  and  $U$ . Based on such evidence, Catchpole *et al.* (1998b) preferred a power function ( $b = 0.91$ ) to account for the wind effect in their laboratory-based model.

A single functional form is probably insufficient to describe  $R_f$  along the whole range of  $U$  variation, and fire response to wind can differ below and above a critical wind speed (Beer 1993). If a model in  $S$ ,  $M_S$  and  $FD$  is fitted, analysis of residuals suggests that winds of  $3 \text{ km h}^{-1}$  are necessary before fire spread is impacted. The prevalence of moist conditions –  $M_S > 15\%$  and  $M_F > 100\%$  in  $\sim 75\%$  of the cases – restricted fuel consumption and the output of convective heat, minimising the resistance to wind, and thus limiting the tendency for  $b > 1$ . In maritime pine needle beds burned in a tray, a curvilinear wind effect on rate of spread was revealed when wind speed changed from  $2$  to  $3 \text{ m s}^{-1}$  at a moisture content of  $10\%$ , but the effect was linear for a moisture content of  $18\%$  (Mendes-Lopes *et al.* 2003). In the present study, we obtained  $b = 0.71$  and it is interesting to note that Cheney *et al.* (1992) report  $b = 0.65$  for comparable conditions of wind, slope and fire width in *Eucalyptus sieberi* stands with a well-developed understorey layer. Mean wind speed did not surpass  $5 \text{ km h}^{-1}$  in  $\sim 70\%$  of our experimental fires, which can affect reliability of the dependence of  $R_f$  on  $U$  (Cheney *et al.* 1998). Also, the short time-span of the fire runs could have increased the error in measuring wind speed (Sullivan and Knight 2001), as well as fluctuation in spread rate caused by wind variability (Albini 1983) and interaction between the wind field and the fire buoyancy.

The current study adds to the sparse body of work tackling the influence of terrain slope on the rate of forest fire spread under field conditions. The slope factor for maritime pine stands,  $\exp(0.062S)$ , equals the factor of Cheney *et al.* (1992) for *Eucalyptus sieberi* stands and, in terms of the relative effect on fire spread, falls between the relationship derived by Van Wagner (1977) from multiple sources and used in Canada,  $\exp(3.533[\tan S]^{1.2})$ , and the Australian factor of Noble *et al.* (1980) after the work of McArthur (1967),  $\exp(0.069S)$ . A fire spreading uphill on a  $20^\circ$ -slope increases its spread rate more than three-fold in relation to level ground, which approaches the laboratory findings of Dupuy (1995) in maritime pine litter.

A wind or slope influence on back fire spread could not be identified, in agreement with the results of laboratory fire experiments in maritime pine litter (Ward 1971; Mendes-Lopes *et al.* 2003). Several other authors have declared  $R_b$  independent of wind speed or practically unaffected by its variation (Van Wagner 1968; McAlpine and Wakimoto 1991; Weise and Biging 1997). Though a back fire moves essentially at the expense of heat transmitted through the fuel complex (e.g. Van Wagner 1968), wind cools the fuel and tilts the flame away from the unburnt fuel. This reduction in preheating efficiency by flame radiation should also explain the observations (Van Wagner 1988; Dupuy 1995; Burrows 1999a) of downslope fires decreasing their rates of spread as slope increases. If the joint influence of wind and slope in  $R_b$  is determined mainly by the angle formed between the flame and the fuel bed, its relatively reduced variation – between  $97^\circ$  and  $149^\circ$ , with a rather stable mean value of  $124^\circ \pm 1^\circ$  – should be involved in the failure to recognise the role of those variables in  $R_b$ .

### *Fuel effects on fire spread rate*

The damping effect of fuel moisture content on fire spread rate is usually described by an exponential curve or other non-linear relationship (Cheney 1981; Cheney *et al.* 1993; Marsden-Smedley and Catchpole 1995; Burrows 1999b; Fernandes 2001). Estimates of the *d* coefficient in the moisture content factor of Eqns 6 and 7,  $\exp(-dM_S)$ , are virtually identical for back ( $d = 0.040$ ) and head ( $d = 0.039$ ) fire spread, agreeing with laboratory experiments that point to a non-existent wind speed effect on *d* (Catchpole *et al.* 1998b). The values of *d* are low in comparison with other vegetation types, where *d* varies from  $0.02$  to  $0.40$  respectively, in Tasmanian moorland (Marsden-Smedley and Catchpole 1995) and in *Eucalyptus sieberi* forest (Cheney *et al.* 1992). The exponential damping effect should depend on physical fuel characteristics, the fire spread rate being less affected when fuel particles are finer (Wilson 1990; Catchpole *et al.* 1998b). Steepness of the exponential curve would certainly be higher if very dry fuels – especially in combination with relatively windy conditions (Burrows 1999b) – were more represented in the database, because fire spread rate increases dramatically when fine fuel moisture content is less than  $6\%$  (Cheney 1981). For the burns carried out in the first days after rainfall, a vertical gradient in dead fuel moisture content was apparent during sampling; under these heterogeneous conditions, it is debatable whether  $M_S$ , an estimate of the profile moisture content of the surface fuel complex, constitutes the best descriptor of the fuel moisture effect on fire behaviour.

Live fuel moisture content could not be identified as a meaningful fire spread factor. Not only were dead fuels important in the fuel complex, but live fuel moisture variation was relatively irrelevant (Table 3), with a mean of  $102 \pm 2\%$  and 80% of the fires within the 90–120% interval. Most of the fires took place in the dormant season, and in these sclerophyllous shrub communities, the water in live tissues does not increase markedly in spring.

Unequivocal modelling of the role of fuel attributes on fire behaviour is restricted to laboratory settings (e.g. Rothermel 1972; Wilson 1990; Wolff *et al.* 1991; Catchpole *et al.* 1998b), essentially because fuel variables are naturally correlated and fuels are heterogeneous and can be difficult to quantify properly in the real world. Like others before (Cheney *et al.* 1992, 1993; Marsden-Smedley and Catchpole 1995; Fernandes *et al.* 2000; Fernandes 2001), the present study identified several fuel descriptors that were statistically relevant to fire spread, but failed to tell apart their respective influences and only one fuel variable could be included in each equation: fuel depth ( $R_f$ ) and understorey cover ( $R_b$ ).

The arrangement of fuel particles in the fuel complex affects  $O_2$  circulation and availability and heat transfer efficiency and thus it plays a fundamental role in preheating, ignition and combustion. Descriptors of the fuel array compactness such as bulk density (Thomas 1971) and packing ratio (Rothermel 1972; Wolff *et al.* 1991; Catchpole *et al.* 1998b) have been inversely related to fire spread rate. A decline in bulk density with an increase in height is common in understorey vegetation, namely for the species *Pteridium aquilinum* (Fernandes *et al.* 2002b), *Ulex minor* (P. Fernandes, unpubl. data on file) and the shrubs *Pterospartium tridentatum* and *Erica umbellata* (Fernandes and Rego 1998). Consequently, fuel depth may well be a surrogate for a bulk density effect on fire propagation. Understorey development in height and cover is also accompanied by increases in total and dead fuel loading, even if the effect of fuel quantity on rate of spread is controversial (Cheney *et al.* 1993; McAlpine 1995; Burrows 1999b). Other empirical studies have included vegetation depth in rate of spread equations, namely in shrubland types in Australasia (Catchpole *et al.* 1998a) and Europe (Vega *et al.* 1998; Fernandes 2001), and in eucalypt forest (Cheney *et al.* 1992; Gould *et al.* 2007). Regardless of the nature of their influence, fuel depth and understorey cover should reflect the overall understorey structure effect on fire spread. Operational use of the equations benefits from reducing the physical effect of the fuel complex to these variables, because their estimation is relatively straightforward.

#### Flame size and fire intensity

Flame size modelling, in particular from field data, faces two basic problems. The unstable nature of flames and difficulty in defining their limits precludes accurate measurement and intensifies the individual bias intrinsic to visual estimation (Johnson 1982). Techniques based on sensors or image analysis can reduce subjectivity in flame geometry measurement. In the present study, a single observer assessed flame characteristics throughout the experiments, which is expected to have produced consistent estimates. The second problem is conceptual and affects the development and use of a relationship between  $L$  and  $I_B$ . It is not feasible to determine either the fuel consumption

fraction or the contribution of each fuel category to flaming combustion, making fuel availability quantification the major source of uncertainty in calculating Byram's (1959) fireline intensity (Alexander 1982; Cheney 1990).

Coefficients for the equation  $L = aI_B^b$  are quite variable in the literature (Byram 1959; Thomas 1963; Nelson 1980; Nelson and Adkins 1986; Weise and Biging 1996; Vega *et al.* 1998; Burrows 1999b; Anderson *et al.* 2006), owing to fuel type, experimental data range, flame size definition and estimation and assumptions made in the calculation of fire intensity. As found by most studies, Eqn 8 ( $b = 0.54$ ) indicates that head fire flame length varies with the square root of Byram's intensity. Eqn 9 ( $b = 0.72$ ) is consistent with the theoretical dependence of still air flame length on the  $2/3$  power of  $I_B$  (Thomas 1963) that also applies to back fires (Nelson 1980).

Part of the scatter around the  $y = x$  line for the flame size models (Fig. 1) should be ascribed to the visual estimation of flame height and tilt angle, particularly on head fires in steeper terrain. The relatively poor relationship between  $L_f$  and  $I_B$  is nevertheless surprising, even if the aforementioned limitations of Byram's intensity to predict flame length are taken into account. Fires under light winds and on flat ground should behave more like back fires (Nelson 1980) and thus could decrease the  $L_f-I_B$  equation fit to data, but analysis of residuals showed no differences between no-slope, upslope and downslope head fires. However, residuals were positively correlated with subsurface litter moisture content and consumption, and negatively associated with surface moisture content, both at the 0.1% level of significance. This suggests that it might be preferable to compute Byram's intensity with total fine fuel consumption in lieu of surface fine fuel consumption, and implies that heat of combustion adjusted for moisture content would have improved the  $L_f-I_B$  relationship. A marginal effect of subsurface fuel on flame size had already been noticed after fitting Eqn 10 and was previously reported by Vega *et al.* (1993): in controlled experimental conditions, the F-layer litter of maritime pine contributed to flame length for moisture contents beneath 60%.

After fitting the model form  $L = aR^b W_S^c \exp(dM_S)$ , the predictability of  $L_f$ , and to a much lesser extent of  $L_b$ , increased over the respective Eqns 8 and 9. In pine needle burns in the laboratory, Catchpole *et al.* (2002) have described combustion efficiency – the fuel fraction subjected to flaming combustion – as an exponential decay of moisture content. Preference of Eqns 10 and 11 to estimate flame length, regardless of the possible improvements in  $I_B$  calculation, is reinforced by the advantage of not depending on assumptions and calculations concerning fuel availability and heat of combustion.

#### Model applicability and use

Line-ignited fires should immediately reach the potential steady-state rate of spread. However, although back fire spread is independent of scale (e.g. Johansen 1987; McAlpine and Wakimoto 1991), fire front width limits the spread rate of wind-driven (Wolff *et al.* 1991; Cheney and Gould 1995) or slope-driven (Morandini *et al.* 2001) fires. Based on Cheney and Gould (1997) and Wotton *et al.* (1999), we consider the 10–15-m plots employed in the present study large enough to reveal the fire behaviour potential of fire lines propagating in forest under mild burning conditions. Reliability of the equations

estimates is expected to be higher for  $U < 8 \text{ km h}^{-1}$ ,  $S < 15^\circ$  and  $M_S > 12\%$ , because the dataset is well populated for combinations of these variables in those regions. The experiments did not cover drier fuel conditions ( $M_S < 10\%$ ) under windier weather ( $U > 6 \text{ km h}^{-1}$ ), a combination that, depending on the fuel load and stand structure, is conducive to crown fire development (Cruz *et al.* 2004). The equations should be used with the companion models for the probability of sustained fire spread (Fernandes *et al.* 2008) when  $M_S > 20\%$  and the likelihood of fire propagation is increasingly uncertain.

Applicability of the equations is limited by fuel nature and structure. Despite the fuel complex secondary role on fire spread variation, model validity in similar fuel types is open to question because the structure of correlation between fuel descriptors might be different. Understorey vegetation in the study sites was representative of western Iberia stands occupying siliceous soils in the transition of Atlantic to Mediterranean climate influences. It is therefore advisable to test the models with data coming from stands with a distinct understorey, namely dominated by *Ulex europaeus* and woody species from the genus *Cytisus*, *Cistus* and *Quercus*. Only in a few study plots did surface fine fuel load exceed  $15 \text{ t ha}^{-1}$ , but fuel accumulation can be substantially higher where the oceanic climate influence prevails (Fernandes and Botelho 2004), especially in unthinned and unpruned dense stands. Likewise, model generalisation to pine stands of other species requires experimental verification of the predictions. Overestimation is to be expected if the equations are used to predict litter-dominated fire behaviour in more packed litter beds formed by pine species with shorter and thinner needles (e.g. *Pinus sylvestris*, *P. radiata*).

Management-related applications of the fire behaviour equations will face difficulties in obtaining proper input values, mostly in relation to fuel variables. Measurement of understorey cover and depth is straightforward after adequate training, while the estimation of fuel loads should be based on rapid non-destructive methods. Fernandes *et al.* (2002b) have developed equations based on structural descriptors (depth, cover) or time since last burn to estimate fuel load per individual component in maritime pine stands in northern and central Portugal. Finally, and as with any fire behaviour model, the ability to estimate fuel moisture content and convert forecast open wind speed to in-stand wind is critical for the application of the equations under operational circumstances.

## Conclusion

Extensive fire behaviour experimentation in forest stands had not been attempted in Mediterranean Europe before the current study. The developed equations describe the behaviour of line-ignited surface fires in maritime pine stands of northern Portugal from wind speed, terrain slope, fuel moisture and fuel structure descriptors. It is worth noting that the effects of site-specific fuel conditions on fire characteristics are accounted for in a user-friendly way, offering a degree of resolution unattainable by a fuel model approach to fire behaviour prediction. The models are adequate to predict forward and backward fire behaviour characteristics, especially in the low to moderate fire danger conditions under which prescribed burning is carried out, i.e. weak to moderate wind and relatively moist fuels. The equations are expected to underestimate fire spread if extrapolated to simultaneously

dry and windy weather. Data from wildfire observations and from future, preferably larger-scale experiments, could be used to extend the equations' scope of application.

The quantitative nature of the results should contribute to higher proficiency in the planning, execution and evaluation of prescribed fire operations in maritime pine stands. More objective and refined burning guidelines have been developed by combining the achievements of the present study with fire severity data collected in the same set of burns, and the fire behaviour equations have been integrated in practical tools to assist prescribed burning management and training.

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