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Models for the sustained ignition and behaviour of low-to-moderately intense fires in maritime pine stands

P.M. Fernandes, H.S. Botelho, & C. Loureiro
Departamento Florestal, Universidade de Trás-os-Montes e Alto Douro, Quinta de Prados, 5000-102 Vila Real, Portugal. Tel. (351)259350233, Fax (351)259350480, Email: pfern@utad

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ABSTRACT: In this study we establish quantitative relationships between important fire behaviour descriptors and its environment, that are applicable to low-to-moderately intense fires in maritime pine (*Pinus pinaster*) stands. Sustained fire propagation is presented as a function of fuel moisture content, wind speed, air temperature and fuel type. The thresholds for marginal fire spread depend on fuel moisture, time since rain and propagation mode (backfire or headfire). The available models to predict fire spread rate proved inadequate for operational use in prescribed fire, and an empirical model based on wind speed, dead fuel moisture content, slope, understory height and fuel type is developed, while backing spread rate is satisfactorily predicted by dead fuel moisture content and understory vegetation cover. Flame length is related to Byram's fireline intensity, and, in alternative, to spread rate, fine fuel load and fuel moisture content. Flame tilt angle is described in terms of wind speed and fine fuel load, or as a function of wind speed and flame height.

1 INTRODUCTION

Wildfire is undoubtedly the most important agent of damage to forest resources in the Mediterranean Basin, due to summer weather patterns, poor plantation design and management, and the abundance of ignitions. An average of three percent of the forest area burns each year in Portugal, the highest rate in Europe (Velez 2000). Such area is roughly proportional to the occupation by maritime pine (*Pinus pinaster* Ait.) (Moreira et al. 2001), the prevalent tree species throughout most of the territory.

Maritime pine litter is a popular fuel for laboratory experiments of fire behaviour (e.g. Viegas & Neto 1991; Dupuy 1995; Mendes-Lopes et al. 1998). However, fire behaviour information from field experimentation — frequently a by-product of fire ecology studies — is quite scarce (e.g. Botelho et al. 1994; Cruz & Viegas 2001). Such knowledge gaps poses limitations to proper fire management, including prescribed burning operations.

Prescribed fire in Europe was first used in the maritime pine stands of NW Iberia, where fuel accumulation in the more productive sites is probably unparalleled by pine stands in temperate climates elsewhere (Vega 2001). But the expansion of the technique did not occur, and its use remains localised and suffers from deficient planning, despite an overall positive appreciation (Fernandes et al. 1999). Issues related to prescribed fire effectiveness, impact, operational safety, training, knowledge transfer, and acceptance by potential users all benefit from fire behaviour knowledge. The main objective of this study is, therefore, to relate important fire behaviour descriptors with its environment through empirical modelling, within the range of fire weather situations that occur outside the wildfire season.

2 METHODS

The experimental burning program was conducted in pure maritime pine stands in Northern Portugal, in communal land co-managed by the Forest Services. Six study sites were located in the mountains of Marão, Alvão and Padrela, within an elevation range of 450-970 m. Soils are derived from schist or granite and the mean annual temperature and rainfall in the study area vary from 10 to 14 °C and 500 to 1200 mm, respectively. The stands were established by plantation or regenerated after fire events and were aged 14 to 41 years. Average tree height ranged from 6 to 18 m and basal area varied from 14 to 56 m^2 ha^{-1}.

The fuel-complex in each experimental plot was assigned to one of three types, defined by the dominance of litter, shrubs (mostly *Chamaespartium tridentatum*, *Erica umbellata* and *Ulex minor*) or non-woody understory (*Pteridium aquilinum* and/or grasses). The quantitative, pre-burn description of fuels was achieved by destructive and non-destructive sampling, respectively in quadrats outside the burn plots and along line transects inside the burn plots. The fine fuel elements (Ø<6 mm) were individualised according to their layer of origin: shrubs, herbs and ferns, surface litter (forest floor L layer) and upper duff (forest floor F layer). Fuel load estimates were derived from average bulk density values determined for each fuel layer in each site after processing the collected samples in the laboratory.

Fire sustainability was addressed in one of the six experimental sites, by carrying ignition litter tests early in the morning and in the first days following rainfall episodes. Since the amount of energy available as an ignition source affects the outcome of an ignition test (Blackmarr 1972; Latham & Schlieter 1989), we tried to replicate the operational procedure involved in prescribed fire, by using a drip-torch with a 2:1 mixture of diesel and gasoline. A 2 m fire line was observed for 5 min. before classifying separately its back and head sections as sustained or non-sustained (unsuccessful ignition or self-extinguishment). Ground slope, mean wind speed at 1.7 m height, ambient temperature and relative humidity were measured for each test; a qualitative appreciation of cloudiness was also made. A sample from the top 2 cm of surface litter was collected for moisture content determination, which was expressed as a % of oven-dry weight. A permanent weather station located within 500 m of the test site contributed with additional information on the number of days since the last rainfall >0.5 mm.

Experimental fires for fire behaviour measurement were conducted in square plots 10-15 m wide. We are aware that headfire behaviour will not develop to its full potential (as determined by the prevailing fire environment) in these small-sized plots, except possibly in low intensity fires where heat transfer is dominated by radiation (Wotton et al. 1999), i.e. for light winds and/or gentle slopes. The results should however emulate the behaviour of an infinite fireline conducted as a back fire, as well as be representative enough for practical purposes of a strip head prescribed fire. Rate of spread of the former is independent of scale (e.g. Johansen 1987; McAlpine & Wakimoto 1991).

94 experimental fires were carried during 1999-2001 in the months of November to June. Each fire was contained within the experimental plot by 0.3 to 1.2 m control strips assisted by a hose line. Alignment between slope and the dominant wind direction (permitting deviations up to 20°) was required before ignition. The ignition line was established at 2 m from the windward edge of the plot, to allow both back and head fire propagation and observation. A continuous wind speed record was taken upwind (1.7 m height), approximately at 10 m from the plot. Samples for fuel moisture content evaluation were randomly harvested near the plot immediately before ignition: three composite samples of fine dead fuel from the existing surface fuel layers, one upper duff sample, and one live fuel (Ø<0,3 cm) sample.

Fire behaviour measurement took metal poles (height=1.5 m) as references, located at regular distances along the plot axis. Fires displaying discontinuity in the flame front were classified as

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marginal. Rate of fire spread was determined by registering the time at which the base of the fire front reached the poles. Flame height, the vertical distance from the level of the ground to the extremity of the flame, and tilt angle, the angle formed by the flame axis (defined by the middle point of the flame base) and the horizontal, were estimated visually and sometimes adjusted after comparison with photographs taken during the fire. Flame height estimates were made to the nearest 0.05 m (for flames up to 0.5 m), 0.1 m (flames with 0.6-2 m), 0.2 m (flames with 2-3 m) and 0.5 m (flames taller than 3 m). Flame tilt angle was evaluated according to 5º classes, with vertical flames assigned to 0º. Flame length was calculated by trigonometry from flame height and inclination and taking terrain slope into account.

The multiplication of rate of spread, heat of combustion and fuel consumption yielded fireline intensity (Byram 1959). Estimates for the second variable were based on published values for the low heat content of the fuel-complex components (Elvira & Hernando 1989; Vega et al. 2000), with corrections for moisture content (Alexander 1982). For the purpose of fireline intensity calculation we assumed that only surface fine fuels contributed to flaming combustion and that such consumption occurred entirely in the reaction zone. Consequently, fuel reduction was the difference between surface fuel load estimates based on the inventories carried before and after the fire. The remaining litter was collected inside six random 0.07 m^2 quadrats. Residual shrub biomass was harvested inside a 1 m^2 quadrat subjectively located to represent the average post-burn shrub condition.

3 RESULTS AND DISCUSSION

3.1 *Fire sustainability*

Data from ignition tests and fire behaviour experiments was joined for the purpose of modelling fire sustainability. Sustained (n=208) and non-sustained (n=57) fire propagation observations were classified as 1 and 0, respectively, and logistic regression was used:

$$P = \frac{1}{1 + \exp\left[-\left(b_0 + b_1 x_1 + b_2 x_2 + \ \ldots\ + b_k x_k\right)\right]} \tag{1}$$

where P is the probability of sustained ignition, a continuous and non-linear estimate in the]0,1[interval, b_0 to b_k are the regression coefficients estimated by maximum likelihood, and x_1 to x_k are the independent variables. Modelling of marginal fire propagation was handled the same way.

Moisture content of the surface dead fuel, weather variables (wind speed, temperature, relative humidity), fuel type, understory vegetation cover, fuel-complex bulk density and fuel load all have a highly significant effect (p<0,0001) on fire sustainability. Fuel moisture reduces the residual deviance in 44% and, as expected, is the variable more closely related to ignition success or failure. A logistic model based on fuel moisture results in a 87.9% agreement between the observed and the predicted values, and estimates (taking P=0.5 as the decision threshold) a moisture of extinction value of 35%. After adjusting this model, the effects of wind speed, air temperature and fuel characteristics remain significant. The interaction between wind and moisture is not significant (p=0.2323). The most practical model is

$$P = \frac{1}{1 + \exp\left[-\left(6.883 - 0.244\ M_{sd} + 0.711\ U + 0.209\ T + 1.728\ F\right)\right]} \tag{2}$$

where M_{sd} =moisture content of the surface dead fuel (%), U=wind speed (km hr^{-1}, zeroed in back-wind propagation), T=ambient temperature (ºC), and F=fuel type (-1, litter; 0=litter and shrubs; 1=litter and grass/ferns). Standard errors (s.e.) of the coefficients by the order they appear in the equation are 1.685, 0.041, 0.185, 0.101 and 0.497. Equation (2) estimates a moisture of extinction variation of 22% to more than 50%, depending on U, T and F.

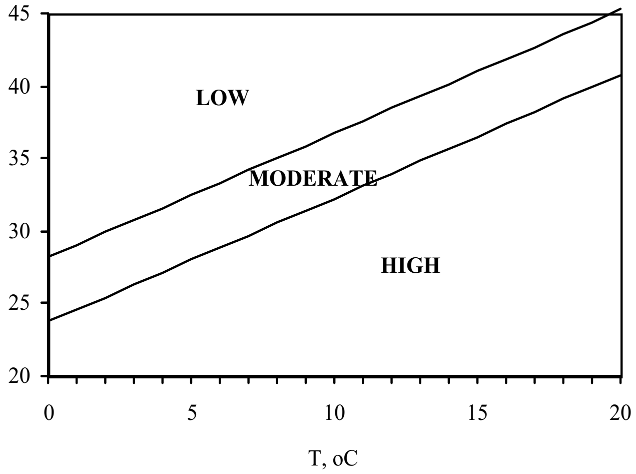

Figure 1. Graphical display of model 2: combinations of surface dead fuel moisture content and ambient temperature that result in low (P<0.5), moderate (0.5<P<0.75) and high (P>0.75) probability of sustained backfire propagation in the maritime pine litter-shrub fuel type.

Wind speed is intuitively perceived as a variable important to fire sustainability, and is used as a predictor in several empirical models (e.g. Bryant et al. 1983; Lawson et al. 1994; Lin 1999; Marsden-Smedley et al. 2001). The presence of T in equation (2) is questionable, given its correlation with M_{sd} (r=0.55, p=0.0000), but it was maintained in the model, because it is a reasonable surrogate for fuel temperature, which is related to the heat of pre-ignition (Schroeder 1969). Slope should also be expected to affect fire sustainability to some degree, which could not be established using this data set, possibly because of correlation with wind speed (r=0.29, p=0.0006) and relatively small variation (average slope was 12%, with a maximum of 30%). Under equal weather circumstances the likelihood of fire extinction will decrease from pure litter to the dominance by grass/fern; given the physical properties of the assemblage of litter and herbaceous vegetation this agrees with the dependence of the 'marginal burning state' of Wilson (1985) on fuel surface area.

The flame front of marginal fires was typically interrupted up to 30% of its extension. Again, fuel moisture is the most relevant independent variable and reduces the residual deviance by 51%, correctly classifying 87.9% of the observations. M_{sd}=27% is, according to this model, the threshold between marginal and non-marginal burning. Analysis of the influences of the other variables results in

$$P = \frac{1}{1 + \exp\left[-\left(9.067 - 0.495\ M_{sd} + 0.137\ P + 1.989\ D\right)\right]} \tag{3}$$

with s.e. values of 1.929, 0.088, 0.055 and 0.693, and where P is the number of days since last rainfall and D stands for back (1) or head (2) fire propagation. Since P and M_{sd} are naturally correlated, adding the former to the equation would appear superfluous, but its significance (p=0.0048) in the presence of the other two variables is undeniable. P probably reflects the high spatial variation in fuel moisture subsequent to a rainfall event. D is preferred to U since it simplifies the equation without loosing predictive capability.

Accuracy — the fraction of the observations that is correctly predicted — of equations (2) and (3) is 0.902 and 0.907. A better performance measure of a logistic model is c, the area under a rela-

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tive operating characteristics (ROC) curve. Both equations have c=0.96, which indicates a very good discrimination ability. Equation (2) was tested with previously existent data, concerning 24 sustained experimental fires conducted with M_{sd}>20%. All these fires are predicted to burn, i.e. in all cases the model generates a P>0.5.

3.2 *Fire behaviour*

Table 1 gives the ranges for fire environment and behaviour variables in the experimental burns. Wind speed, dead fuel moisture content and slope are not significantly different (p>0.05) between the three fuel types. Fire behaviour was quite variable, from creeping fires to flames reaching the tree crown layer. The average ratio between head and back spread rate in the same fire was 15, with a variation of 1.4 to 59.7.

Table 1. Variation in selected descriptors of the fire environment and behaviour in the experimental burns (n=94).

Variable	Min. - Max.	Variable	Min. - Max.
S, %	0 - 30	W_s, t/ha	2.8 - 18.5
U, km/hr	1 - 23	W_F, t/ha	3.2 - 30.1
T, ºC	2 - 22	R_b, m/min	0.06 - 0.60
RH, %	26 - 96	R_h, m/min	0.25 - 13.88
M_{sd}, %	8 - 56	w, %	49 - 100
M_F, %	11 - 296	L_b, m	0.1 - 1.9
M_L, %	82 - 158	L_h, m	0.1 - 4.3
COV, %	0 - 100	I_b, m	8 - 255
H, m	0.2 - 0.7	I_h, m	32 - 3608

S = slope; RH = relative humidity; M = fine fuel moisture content (F = upper duff; L = live fuel); COV = understory vegetation cover; H = understory vegetation height; W = fine fuel load (s = surface fuel, F = upper duff). Fire behaviour (b = back fire, h = head fire): R = rate of fire spread; L = flame length; I = Byram's fire intensity. w = surface fine fuel consumption. The remaining symbols were previously defined.

3.2.1 *Rate of fire spread*

Fire modelling efforts should be preceded by the examination of the existing models. Three potentially interesting alternatives to predict fire spread rate in maritime pine stands were identified, respectively the Forest Fire Behaviour Tables for Western Australia (FFBT) (Sneeuwjagt & Peet 1985; Beck 1995), the Canadian Forest Fire Behaviour Prediction System (CFFBPS) (Forestry Canada Fire Danger Group 1992), and the model of Rothermel (1972). The CFFBPS estimates were obtained using the fuel type C-6 as input. Custom fuel models (Burgan & Rothermel 1984) describing the average fuel characteristics of each fuel type were built for use with Rothermel's model; moisture of extinction was set at 45% based on the previous section results.

Performance of the three systems is unsatisfactory. They all tend to underestimate fire spread rate and to produce biased estimates, and paired t-tests indicate significant differences between observations and predictions. According to the CFFBPS only 53% of the fires would propagate and the mean predictions are eight times lower than the observed values. The corresponding values for the FFBT and the Rothermel model are five, and three (headfires) or two (backfires), respectively. Modelling efficiency (EF, proportion of variation explained by the model in relation to the line of perfect fit) was negative in all cases, except for Rothermel's model predictions of headfire spread rate (EF=0.17). None of the systems can be recommended for use in prescribed burning operations.

Rate of fire spread was modelled using non-linear least squares. After quantifying the effect of a variable, the non-explained variation was checked against the remaining variables to assess the significance of their influences. The damping effect of fuel moisture content on spread rate is usually described by an exponential function (e.g. Cheney et al. 1993). After fitting this model only 11% of the variation in backfire rate of spread (R_b) had been explained. The residual variation is significantly related to fuel-complex descriptors only, with understory vegetation cover providing the best result:

$$R_b = 0.0063 \ \exp \ \left(-0.031 \ M_{sd}\right) \left(COV^{0.951} + 28.831\right) \tag{4}$$

with s.e. of 0.0060, 0.004, 0.207 and 29.618. Moisture content of the upper duff is significant (p=0.047) after fitting (4), but its correlation with M_{sd} is high (p=0.0005) and its explaining capability (R^2=0.05) does not warrant inclusion in the model. Although *COV* is an appealing variable from the operational viewpoint a real effect on R_b cannot be proven, given the collinearity with other fuel characteristics — e.g. r=0.77 (p<0.0001) between *COV* and surface fine fuel load. An analysis of the fuel type litter-shrubs, with higher structural variability, shows association (r=0.83, p<0.0001) between *COV* and fuel load of *Erica umbellata*, the shrub species with higher surface area-to-volume ratio. R_b in the data sub-set is not affected by fuel load or shrub fuel load after consideration of the effect of moisture. Thus it is likely that higher spread rates occur because of higher shrub continuity and thinner shrub particles.

Correlation analysis of headfire rate of spread (R_h) attributes major influences (p<0.0001) to slope and wind speed, with dead fuel moisture content in a secondary role (p<0.05). A model of the form $R_h=aU^b$ explains 45% of the observed variation, with b=0.803. This coefficient increases to 0.996 if wind speeds below 3 km hr^{-1} are excluded. Slope explains 30% of the variation, with R_h proportional to $e^{0.070S}$. U, S and M_{sd} account for 64% of the variability in R_h. Surface fuel load is superior to the other fuel descriptors after adjusting a model for those variables:

$$R_h = 0.594 \ U^{0.662} \exp \ \left(-0.037 M_{sd} + 0.058 S\right) W_s^{0.429} \tag{5}$$

with s.e.=0.168, 0.068, 0.006, 0.007 and 0.108, and where S is in degrees. Current knowledge does not support the use of fuel load as a predictor of fire spread (Cheney et al. 1993; Catchpole et al. 1998a; Burrows 1999). In our data base W_s shows some correlation with U (p=0.0519) and S (p=0.0136). The analysis per fuel type, after considering the other variables, does not show any fuel load effect. In fact, 56% of the variation in W_s is explained by fuel type, and fuel load is significantly different between the litter fuel type and the fuel types dominated by understory vegetation.

The litter-shrubs fuel type was analysed in separate, since it is the general case in maritime pine stands and is also more represented in the data set (n=38). The slope effect — with a coefficient in-between McArthur (1962) and van Wagner (1977) — seems solid enough to be retained. The following model is obtained after the fitting process is repeated:

$$R_{h(s)} = 1.906 U^{0.868} \exp\left(-0.035 M_{sd} + 0.058 S\right) H^{0.635} \tag{6}$$

with s.e.=0.545, 0.145 (U), 0.010 (M_{sd}) and 0.367 (H), and where $R_{h(s)}$ is the spread rate of the headfire in a complex of *Pinus pinaster* litter and shrubs, and H is understory vegetation height (m). H is readily assessed by a manager, and, because it varies inversely with packing ratio or bulk density (Fernandes & Rego 1998) can be interpreted as a surrogate for the overall fuel-complex structural effect on rate of spread. In laboratory experiments, Wolff et al. (1991) and Catchpole et al. (1998*a*) report that fire spread rate is proportional to $1/\beta^{0.5}$, where β is the packing ratio. Equation (6) indicates a fairly linear effect of wind speed on fire spread, as in other contemporary empirical studies of fire behaviour (e.g. Cheney et al. 1993; Marsden-Smedley & Catchpole 1995; Catchpole et al. 1998*b*).

The adaptation of equation (6) to predict headfire spread rate in the fuel types litter-non woody understory ($R_{h(h)}$) and pure litter ($R_{h(L)}$) gives:

$$R_{h(h)} = 2.578 \ U^{0.868} \exp \ \left(-0.035 M_{sd} + 0.058 S\right) H^{0.635} \tag{7}$$

$$R_{h(L)} = 0.603 \ U^{0.868} \exp \ \left(-0.035 M_{sd} + 0.058 S\right) \tag{8}$$

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with s.e. of 0.169 and 0.049, respectively. Equation (7) predicts for the same vegetation height and environmental conditions a headfire spreading 35% faster in a grassy understory than in a shrubby understory.

No acceleration pattern is detected, since propagation distance is not significantly correlated ($0.1718 \le p \le 0.9186$) with the residuals of equations (6) to (8). The influence of live fuel moisture of the woody (p=0.4038) and non-woody (p=0.9895) understories is also undetected. Statistical information concerning fire spread equations (4 to 8) is contained in Table 2, while Fig. 2 gives a scatterplot of observed and predicted values with equation (6), including independent pre-existent data.

Table 2. Statistical measures of performance for the rate of fire spread models.

	Fitting data			Validation data		
Equation	R^2	MAE	MA%E (std. dev.)	EF	MAE	MA%E (std. dev.)
(4)	0.76	0.05	24.0 (24.7)	0.73	0.05	28.7 (23.4)
(5)	0.68	0.86	38.0 (33.4)	0.62	0.65	39.3 (60.0)
(6)	0.72	0.54	33.6 (22.6)	0.74	0.49	19.5 (12.7)
(7)	0.67	1.21	27.6 (20.3)	-	-	-
(8)	0.46	0.75	36.2 (25.9)	-	-	-

MAE=mean absolute error; MA%E=mean absolute % error; EF=modelling efficiency

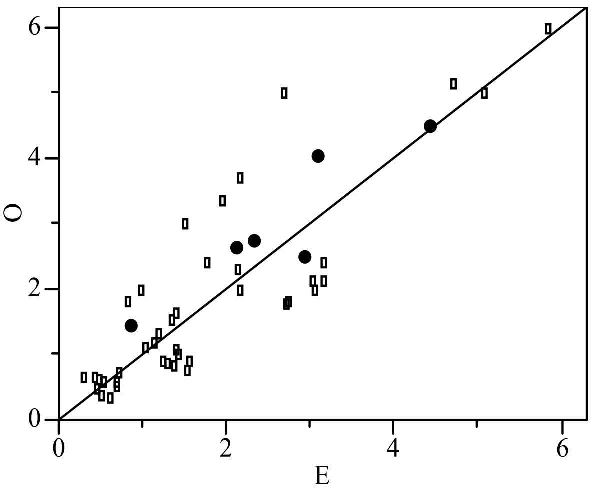

Figure 2. Observed versus estimated (equation 6) headfire spread rates in the maritime pine litter-shrub fuel type. Black circles respect to validation data.

3.2.2 *Flame characteristics and fire intensity*

Flame length (L) modelling was first approached as a function of Byram's fireline intensity. Data analysis supports the use of different relationships for backfires and headfires:

$$L_b = 0.0386\, I_b^{0.680} \tag{9}$$

with s.e. of 0.0079 and 0.049, and

$$L_b = 0.0533\, I_b^{0.542} \tag{10}$$

with s.e. of 0.0140 and 0.0418. As found by most studies, headfire flame length varies with the square root of fireline intensity, while backfire flame length is proportional to the 2/3 power of I (Thomas 1963; Nelson 1980). Underestimates of L_h with the original and widely applied Byram's (1959) flame model would not be operationally relevant within the fireline intensity range of prescribed burning. However, that would not be the case for L_b, with serious underprediction and, consequently, considerably higher crown scorch levels than what expected. The use of equations (9) and (10) require estimates of the determinants of I, that is, R, heat of combustion and fuel consumption. 20000, 19800 and 19000 J g^{-1} are reasonable mean values for the former, respectively for litter, litter-shrubs and litter-grass/ferns. If equations (9) and (10) are solved for fireline intensity we get

$$I_b = 119.741\, L_b^{1.470} \tag{11}$$

$$I_b = 224.585\, L_b^{1.847} \tag{12}$$

Table 3. Statistical measures of performance for the flame length models.

Equation	R^2	MAE	MA%E (std. dev.)
(9)	0.73	0.18	35.2 (38.9)
(10)	0.55	0.46	34.4 (46.1)
(13)	0.79	0.30	37.0 (49.9)

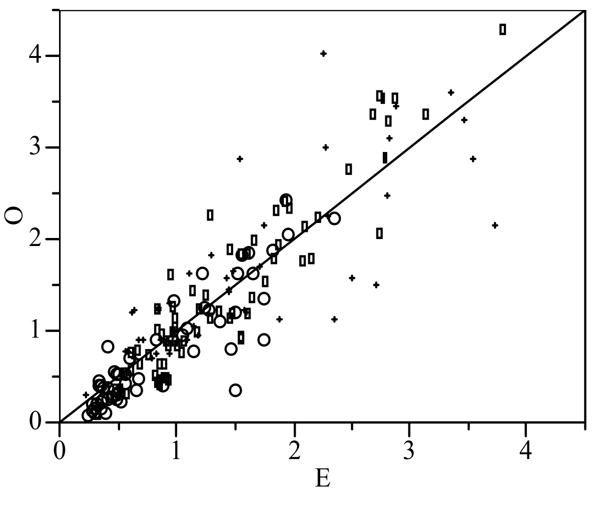

Figure 3. Observed versus estimated backfire and headfire flame lengths by equation 13. Circles, rectangles and crosses respect to litter, litter-shrubs, and litter-grass/ferns, respectively.

Equation (10) has a poorer fit to data than equation (9) (Table 3). Combining head and backfire observations to produce a single equation and using non-linear least squares gives

$$L = 0.653\, R^{0.383}\, W_s^{0.575} \exp\left(-0.030\, M_{sd}\right) \tag{13}$$

with s.e. of 0.113, 0.021, 0.066, and 0.003. Note that the independent variables in equation (13) are the determinants of fireline intensity if heat content is assumed constant. Equation (13) is slightly

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less accurate and precise than equations (9) and (10) but has the advantage of not having fuel consumption as an input, a variable that is a result of the fire. Equation (13) works better for flame lengths within the prescribed burning range, that is below 1-1.5 m (Fig. 3), reflecting the measurement difficulty inherent to larger flames.

Flame height estimates can also be of interest. The mean ratio between flame length and flame height is 1.3 for headfires and 1.4 for backfires. Indirect estimates of flame height from flame length and vice-versa can be derived if flame tilt angle is known. Stepwise regression selected U and W_s as estimators of flame tilt angle α. Slope was also selected for headfires, but its contribution to the total explanation of α was 4.7% only, besides exhibiting correlation with U (p=0.0229) and W_s (p= 0.0004). Excluding S we obtain

$$\alpha_h = 42.579 + 2.490\,U - 1.884 \qquad (R^2=0.52) \qquad (14)$$

$$\alpha_b = 50.165 + 1.240\,U - 1.332\,W_s \qquad (R^2=0.35) \qquad (15)$$

Equations (14) and (15) express the two factors that determine flame angle, the flame deflecting power of the wind and buoyant convection from the fire. These two influences are usually combined into a ratio, such as in Albini's (1981) model of headire flame angle as a power function of the Froude number $U^2/g\,h_F$ (where g is acceleration due to gravity). Taking this approach increases the degree of explanation (R^2=0.59) in relation to (14):

$$\tan\alpha = 1.410\,(U^2/g\,h_F)^{0.281} \qquad (16)$$

The power of the Froude number is lower than the 0.5 value of Albini (1981) and the 0.57 value obtained in the laboratory by Weise & Biging (1996), but is quite similar to the 0.29 value of Nelson & Adkins (1986).

4 CONCLUSION

This study is the first comprehensive experimental program in Europe addressing fire behaviour under field conditions and in forest stands. Equations have been developed that describe and predict fire behaviour in maritime pine stands of NW Portugal under low to moderate fire weather conditions. The results should not be extrapolated beyond the conditions of development and are deemed to be applicable to prescribed burns conducted as backfires or strip headfires. However, the current fire behaviour prescription has been largely exceeded by most of the fires, and, if not affected by scale problems (i.e. small fire size), the models should be able to depict the entire surface fire behaviour range in maritime pine stands.

The results of this study will be integrated in the prescribed fire training process and are being materialised in tools to assist prescribed burning management, hopefully improving the operational effectiveness of the technique. More objective and refined guidelines and prescriptions for burning will be produced by combining the achievements of this study with fire severity models developed from data collected in the same set of burns.

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REFERENCES

Albini, F.A. 1981. A model for the wind-blown flame from a line fire. Combustion and Flame 43: 155-174.

Alexander, M.E. 1982. Calculating and interpreting forest fire intensities. Can. J. Bot. 60: 349-357.

Beck, J.A. 1995. Equations for the forest fire behaviour tables for Western Australia. CALMScience 1(3): 325-348.

Blackmarr, W.H. 1972. Moisture content influences ignitability of slash pine litter. USDA For. Serv. Southeastern For. Exp. Stn. Res. Note SE-173, Asheville.

Botelho, H., J.A. Vega, P. Fernandes and F. Rego. 1994. Prescribed fire behavior and fine fuel consumption in Northern Portugal and Galiza maritime pine stands. In Proc. 2nd Int. Conf. on Forest Fire Research, Viegas, D.X. (Ed.), 21-24 Nov. 1994, Universidade de Coimbra. Vol. I, pp. 343-353.

Bryant, F.C., G.K. Launchbaugh, & B.H. Hoerth. 1983. Controlling mature ashe juniper in Texas with crown fires. J. Range Manage. 36(2): 165-168.

Burgan, R. & R. Rothermel. 1984. BEHAVE: Fire behavior prediction and fuel modeling system - FUEL subsystem. USDA For. Serv. Gen. Tech. Rep. INT-167, Intermt For. and Range Exp. Stn., Ogden.

Burrows, N.D. 1999. Fire behavior in jarrah forest fuels: 2. Field experiments. CALMScience 3(1): 57-84.

Byram, G.M. 1959. Combustion of forest fuels. In Forest fire: control and use, Davis, K.P. (Ed.). McGraw-Hill, New York. pp. 90-123.

Catchpole, W., R. Bradstock, J. Choate, L. Fogarty, N. Gellie, G. McCarthy, L. McCaw, J. Marsden-Smedley, & G. Pearce. 1998*b*. Cooperative development of equations for heathland fire behaviour. In: D.X. Viegas (Ed.), Proc. 3rd International Conf. on Forest Fire Research / 14th Fire and Forest Meteorology Conf., Luso, 16-20 Nov. 1998. ADAI, University of Coimbra, pp. 631-645.

Catchpole, W.R., E.A. Catchpole, B.W. Butler, R.C. Rothermel, G.A. Morris, & D.J. Latham. 1998*a*. Rate of spread of free-burning fires in woody fuels in a wind tunnel. Combust. Sci. and Tech. 131: 1-37.

Cheney, N.P., J.S. Gould & W.R. Catchpole. 1993. The influence of fuel, weather and fire shape variables on fire-spread in grasslands. Int. J. Wildland Fire 3(1): 31-44.

Cruz, M.G., & D.X. Viegas. 2001. Caracterização do comportamento do fogo em complexos combustíveis comuns na região centro de Portugal. Silva Lusitana 9(1): 13-34.

Elvira, L.M., & C. Hernando. 1989. Inflamabilidad y energia de las especies de sotobosque (estudio piloto con aplicación a los incendios forestales). Monografias INIA nº 68, Ministerio de Agricultura Pesca y Alimentacion. Madrid.

Fernandes, P.M., & F.C. Rego. 1998. Equations for estimating fuel load in shrub communities dominated by *Chamaespartium tridentatum* and *Erica umbellata*. Pp. 2553-2564, In Vol. II Proc. 3rd International Conf. on Forest Fire Research / 14th Fire and Forest Meteorology Conf.(Ed. D.X. Viegas), Luso, 16-20 Nov. 1998. ADAI, University of Coimbra.

Fernandes, P.M., H. Botelho, & J.S. Bento. 1999. Prescribed fire to reduce wildfire hazard: an analysis of management burns in Portuguese pine stands. In Proc. Internat. Symposium on Forest Fires: Needs and Innovations, CINAR/European Commission, Athens, pp. 360-364.

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. For. Can. Inf. Rep. ST-X-3, Ottawa.

Johansen, R.W. 1987. Ignition patterns and prescribed fire behavior in southern pine forests. For. Res. Pap. 72, Georgia For. Comm. Res. Division, Macon.

Latham, D.J., & J.A. Schlieter. 1989. Ignition probabilities of wildland fuels based on simulated lightning discharges. USDA For. Serv. Intermt. Res. Stn. Res. Pap. INT-411. Ogden, UT.

Lawson, B.D., O.B. Armitage, & G.N. Dalrymple. 1994. Ignition probabilities for simulated people-caused fires in British Columbia pine and white spruce-subalpine fir forests. In Proc. 12th Conf. on Fire and Forest Meteorology, Oct. 26-29, 1993, Jekyll Island, GA, SAF Publ. 94-02, SAF, Bethesda, MD, pp. 493-505.

Lin, C.C. 1999. Modeling probability of ignition in Taiwan red pine forests. Taiwan J. For. Sci. 14(3): 339-344.

Marsden-Smedley, J.B., & W.R. Catchpole. 1995. Fire behaviour modelling in Tasmanian buttongrass moorlands. II. Fire behaviour. Int. J. Wildland Fire 5(4): 215-228.

Marsden-Smedley, J.B., W.R. Catchpole, & A. Pyrke. 2001. Fire behaviour modelling in Tasmanian buttongrass moorlands. IV Sustaining versus non-sustaining fires. Int. J. Wildland Fire 10: 255-262.

McAlpine, R.S. & R.W. Wakimoto. 1991. The acceleration of fire from point source to equilibrium spread. For. Sci. 37(5): 1314-1337.

McArthur, A.G. 1962. Control burning in eucalypt forest. Comm. Aust. For. Bur., Leaflet No 80. Canberra.

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Mendes-Lopes, J.M., J.M. Ventura, & J.M. Amaral. 1998. Rate of spread and flame characteristics in a bed of pine needles. In Vol. I Proc. 3rd Int. Conf. on Forest Fire Research & 14th Conf. on Fire and Forest Meteorology, Viegas, D.X. (Ed.), Luso, 16-20 Nov., ADAI. pp. 497-511.

Moreira, F., F.C. Rego, & P.G. Ferreira. 2001. Temporal (1958-1995) pattern of change in a cultural landscape of northwestern Portugal: implications for fire occurrence. Landscape Ecology 16: 557-567.

Nelson, R.M. 1980. Flame characteristics for fires in Southern fuels. USDA For. Serv. Res. Paper SE-205, Southeastern For. Exp. Stn. Asheville, NC.

Nelson, R.M., & C.W. Adkins. 1986. Flame characteristics of wind-driven surface fires. Can. J. For. Res. 16: 1293-1300.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA For. Serv. Res. Pap. INT-115, Intermt. For. and Range Exp. Stn., Ogden.

Schroeder, M.J. 1969. Ignition probability. USDA For. Serv. Office Rep. 2106-1, Rocky Mte. For. and Range Exp. Stn., Fort Collins, CO.

Sneeuwjagt, R.J. & G.B. Peet. 1985. Forest fire behaviour tables for Western Australia. 3rd Edition. WA Dept. of Conservation and Land Management, Perth.

Thomas, P.H. 1963. The size of flames from natural fires. In Proc. 9th Symp. on Combustion. The Combustion Inst., Pittsburgh. pp. 844-859.

van Wagner, C.E. 1977. Effect of slope on fire spread rate. Can. For. Serv. Bi-Mon. Res. Notes 33(1): 7-8.

Vega, J.A. 2001. Efectos del fuego prescrito sobre el suelo en pinares de *Pinus pinaster* Ait. de Galicia. Tesis Doctoral, Universidad Politécnica de Madrid, Escuela Técnica Superior de Ingenieros de Montes. Madrid.

Vega, J.A., P. Pérez-Gorostiaga, P. Cuiñas, M. Alonso, M.T. Fontúrbel, C. Fernández, & M.J. Rozados. 2000. Patrones espaciales de temperaturas en el tronco y copa de *P. pinaster* durante fuegos prescritos. Cuadernos de la Sociedade Española de Ciencias Forestales 9: 91-99.

Vélez, R. 2000. Los incendios forestales en la cuenca Mediterránea. In La Defensa Contra Incendios Forestales: fundamentos y experiencias. McGraw-Hill, Madrid. pp. 3.1-3.31.

Viegas, D.X., & L.C. Neto. 1991. Wall shear-stress as a parameter to correlate the rate of spread of a wind induced forest fire. Int. J. Wildland Fire 1(3): 177-188.

Weise, D.R., & G.S. Biging. 1996. Effects of wind velocity and slope on flame properties. Can. J. For. Res. 26: 1849-1858.

Wilson, R.A. 1985. Observations of extinction and marginal burning states in free burning porous fuel beds. Combust. Sci. Tech. 44: 179-193.

Wolff, M.F., G.F. Carrier, & F.E. Fendell. 1991. Wind-aided firespread across arrays of discrete fuel elements. II. Experiment. Combust. Sci. and Tech. 77: 261-289.

Wotton, B.M., R.S. McAlpine, & M.W. Hobbs. 1999. The effect of fire front width on surface fire behaviour. Int. J. Wildland Fire 9(4): 247-253.