Using fuel and weather variables to predict the sustainability of surface fire spread in maritime pine stands

Paulo M. Fernandes, Hermínio Botelho, Francisco Rego, and Carlos Loureiro

Abstract: Thresholds for surface fire spread were examined in maritime pine (*Pinus pinaster* Ait.) stands in northern Portugal. Fire sustainability was assessed after ignition of 2-m fire lines or in larger burns conducted in 10 - 15 m wide plots. The experiments were carried out from November to June in three fuel types, respectively litter, litter plus shrubs, and litter with a non-woody understorey. Moisture content of fine dead fuels, on-site weather variables and descriptors of the fuel complex all had a highly significant influence on the probability of self-sustaining fire spread. A logistic model based solely on fuel moisture content correctly classified the fire sustainability status of 88% of the observations. Nonetheless, the subjectivity of the moisture of extinction concept was apparent and further accuracy was achieved by the consecutive addition of fire spread direction (forward or backward), fuel type and ambient temperature. Fully sustained fire spread − in opposition to marginal burns with broken fire fronts − was similarly dependent on fuel moisture, but was affected also by fire spread direction and time since rain. The models can benefit fire research and fire management operations but can be made more practical if integrated in a fire danger rating system.

Résumé:

Introduction

Fire behaviour studies have produced a number of models that physically characterize a flame front, but the estimation of these quantities seldom is preceded or complemented by an explicit assessment of fire propagation likelihood or marginal burning status. This potentially implies that fire behaviour estimates are generated for fires that actually will not spread (Plucinski and Catchpole 2001). The correct judgement of whether or not a fire will ignite and spread in a given environment has important operational implications to fire managers, especially for defining initial attack preparedness and resource allocation and to plan for prescribed burning. Anderson (1970) introduced the concept of fire sustainability, a component of flammability that refers to the ability of a fuel complex to maintain flaming combustion after ignition, and thus carry a fire. The proximity to self-extinction of a spreading fire can further be classified, e.g. by an index of marginal burning (Wilson 1985)

Received 13 March 2007. Accepted 17 August 2007.

Paulo M. Fernandes[1], Hermínio Botelho, and Carlos Loureiro. Centro de Estudos em Gestão de Ecossistemas and Departamento Florestal, Universidade de Trás-os-Montes e Alto Douro, Apartado 1013, 5001-801 Vila Real, Portugal.
Francisco Rego.[2] Centro de Ecologia Aplicada "Prof. Baeta Neves", Instituto Superior de Agronomia, Tapada da Ajuda, 1349-017 Lisboa, Portugal.

[1]Corresponding author (e-mail: pfern@utad.pt)
[2]Present address: Direcção-Geral dos Recursos Florestais, Av. João Crisóstomo 28, 1069-040 Lisboa, Portugal.

Fire sustainability can be inferred from the persistence of flame in assemblages of fuel particles burned in laboratory facilities. The results however do not mimic fire sustainability in the field, unless the natural fuel arrangement is retained and enough scale is achieved by allowing some fire development. Ignitability and sustained flaming have been addressed in laboratory-scale fires in fuel beds made of litter (Blackmarr 1972; Plucinski and Catchpole 2001) and shrubs (Plucinski and Catchpole 2002; Weise et al. 2005). Other studies resorted to match ignition field trials, in Canada (Lawson et al. 1994; Beverly and Wotton 2007) and elsewhere (Lin 1999; Tanskanen et al. 2005), especially in needle litter fuels. Finally, research efforts that target the identification of fire spread thresholds for management burns use larger-scale fires to examine how environmental conditions affect fire sustainability, e.g. Marsden-Smedley et al. (2001).

Regardless of fuel type and experimental setting and scale, all studies have identified an important, often dominating or exclusive, role of fine fuel moisture on the likelihood of ignition or sustained fire spread. An increase in moisture content implies that the required heat of ignition is higher and the subsequent release of energy is reduced (Nelson 2001). Rothermel (1972) has defined moisture of extinction as the fuel moisture content at which the heat sink equals the heat source and fire spread will no longer be supported. Brown (1972) however referred to the choice of moisture of extinction as subjective, and Albini (1976) remarked that the moistures of extinction in the US Forest Service fuel models should be viewed as approximate values. Wilson (1985) considered that ‘there is no consistent rationale for assigning a value to moisture of extinction’, and found ample experimental variation of extinction moisture in relation to physical fuel properties. This author tackled the problem of fire sustainability with a probabilistic approach, of which Schroeder (1969) and Blackmarr (1972) constitute early examples.

Wind speed can assist fire sustainability in litter beds (Lawson et al. 1994) but it has also been reported to decrease the moisture content threshold for ignition (Plucinski and Catchpole 2001). In elevated live (Weise et al. 2005) and mixed live-dead fuels (Clark et al. 1985; Marsden-Smedley at al. 2001) wind speed is clearly a driving variable, along with fuel moisture and fuel load. Previous studies in live woody vegetation types (Bruner and Klebenow 1979; Bryant et al. 1983) had already highlighted the relevance of wind to sustained flaming.

Maritime pine (*Pinus pinaster* Ait.) is an important conifer from southwestern Europe that is prone to large and severe wildfires. Fuel accumulation and stand structure in maritime pine stands often promote high-intensity and destructive fire, which can occur even under relatively mild weather conditions (Fernandes and Rigolot 2007). If the extent of fire-caused damage is to be limited by prompt and aggressive fire suppression, a key element in the decision-making process is the capability to forecast when sustained fires are likely. The identification of thresholds for successful ignition and satisfactory fire propagation would also benefit prescribed burning. In the maritime pine stands of Portugal prescribed fire usually takes place between late fall and early spring, when fuel hazard reduction can proceed without detrimental site and tree impacts but marginal burning conditions are common. The resulting difficulties in fire spread have been recognized as a major operational problem and the single most important reason to cancel a planned or ongoing burn (Fernandes and Botelho 2004).

The objective of the current study was to identify the environmental variables that decide if a line-ignited fire can propagate in the surface fuel complex of a maritime pine stand, and to model the probabilities of sustained fire spread from those variables. To do so we have analysed experimental field data collected in the frame of a research project on the behaviour and effects of surface fire in maritime pine stands

Methods

Experimental procedures

The experimental fires were conducted in communal land co-managed by the Forest Service in the mountains of Marão, Alvão and Padrela, northern Portugal. The study area has soils derived from schist or granite and a mediterranean-type climate, with mean annual temperature and rainfall varying in the ranges of 10-14 ^{o}C and 500-1200 mm (Agroconsultores-COBA 1991). Six locations for the study sites were chosen within a 450-970 m elevation range and at latitudes of 41^{o} 20' N to 41^{o} 30' N and longitudes of 7^{o} 40' W to 7^{o} 50' W. Stand age and stand mean height and basal area varied respectively from 14 to 41 years, 6 to 18 m, and 14 to 56 m^{2} ha^{-1}. The sites are representative of the range in fuel conditions that typifies *Pinus pinaster* forests in northern Portugal.

Pre-burn quantitative fuel description in the experimental sites considered the fine elements (i.e. less than 6 mm in diameter) and fuel layers that play a role in surface fire ignition and sustainability. From fuel harvesting in quadrats outside the burn plots mean bulk density (kg m^{-3}) values were derived for surface litter (the forest floor L layer), shrubs, and non-woody vegetation (herbs and ferns). The combination of plot-level assessments of each stratum depth and cover with their respective bulk densities yielded estimates of fuel loads (t ha^{-1}). Because in maritime pine stands fire is simultaneously carried by the contiguous layers of litter and understorey, their combined bulk density was used to describe the overall structure of the surface fuel complex. The mean bulk density of each plot was computed by dividing fuel load by fuel depth, which was taken as the sum of mean understorey vegetation height and L-layer litter depth. Each plot was assigned to one of three fuel types, respectively litter, litter and shrubs, and litter and non-woody vegetation; a minimum ground coverage of 30% by understorey vegetation was required for classification as one of the two mixed fuel types. The shrubs *Pterospartum tridentatum* (L.) Willk, *Erica umbellata* L. and *Ulex minor* Roth. prevailed in sites with a woody understorey, whereas non-woody understoreys were dominated by *Pteridium aquilinum* (L.) Kuhn and grasses of the species *Agrostis curtisii* Kerguelen and *Pseudoarrhenatherum longifolium* Rouy.

Fire sustainability data were obtained from two sources. In one of the experimental sites the sole objective was to classify the sustainability of fire spread in a homogeneous bed of maritime pine needle litter. The tests were done on rain-free days, especially in the first days following a rainfall episode and early in the morning. It is known (e.g., Blackmarr 1972) that the amount of energy available as an ignition source affects the outcome of an ignition attempt. This study emphasis in on the applicability of the results to prescribed burning and therefore we lit the fires with a drip torch carrying a 2:1 mixture of diesel and petrol. A 2-m fire line was established at right angles to the prevailing wind direction and was observed for 5 min. to obtain sound substantiation of fire sustainability, by allowing the fire to grow and the drip torch fuel to burn out. Areas totally shaded or totally exposed to sunlight were avoided when laying down the ignition line. The assessment of fire sustainability individualized the forward (the head fire) and backward (the back fire) sections of the fire front. In low-intensity fires, pre-heating from flame radiation should be comparable between a 2-m fire line and an infinitely wide fire front (Wotton et al. 1999). Whenever the fire went out by itself or became increasingly weaker to the point of near extinction the trial was declared unsuccessful, i.e. fire spread was deemed non-sustained. The fire was categorized as sustained if the ignition line continued to spread for 5 minutes.

Terrain slope was measured for each fire sustainability test, as well as within-stand weather variables at a 1.7-m height. One sample weighing approximately 50 g and comprised of needles from the top 2 cm of surface litter was collected for fuel moisture determination throughout the plot immediately before ignition and sealed. The moisture content was calculated after oven drying (24 hours at 85°C) and was expressed as a percentage of dry weight by using a digital balance accurate to 0.01 g. Ambient temperature and relative humidity were registered at the beginning of the trial. A hand-held digital anemometer continuously measured wind speed, providing a mean value for the duration of the test. 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.

Fire sustainability data was also acquired in a set of experimental fires burning at the remaining five sites. In fact these fires provided the bulk of the data for this study, even if their primary purpose was the measurement of fire behaviour and severity. The plots were 10-15 m wide and were burned in the months of November to June. Fuel moisture sampling consisted in the random harvest of three composite samples (50 g) of the fine dead fuels − needles, twigs, leaves − present in the surface fuel layers, just prior to ignition and in the vicinity of the plot. After oven drying, a mean moisture content value per fire was obtained by averaging the three values obtained.

Each fire was ignited with a drip torch along the windward side of the plot at a 2-m distance from its edge, to permit both forward and backward fire propagation and observation. Fernandes et al. (2002) describe the measurement and estimation of fire behaviour in these fires. Records were kept of self-extinguishing fires and of the conditions leading to fire spread failure. Weather variables measurement and criteria to classify a fire as unsustained were the same as in the previously described trials. Sustaining fires can burn marginally, i.e. present broken fire lines caused by localized flame extinction. In these larger-scale trials, self-sustaining fire lines were further categorized as fully sustained when the flame front was continuous or almost uninterrupted.

Data analysis and modelling

We have assembled the available data from fire sustainability trials and fire behaviour experiments. The likelihoods of sustained and fully sustained fire spread were modelled by logistic regression analysis (Hosmer and Lemeshow 2000). The general form of the logistic function is:

$$[1] \qquad P = \left(1 + e^{-g(x)}\right)^{-1}$$

where P is the conditional probability of an event, a continuous and non-linear estimate in the]0,1[interval, and $g(x)$ is the logit:

$$[2] \qquad g(x) = \ln\left(\frac{P}{1-P}\right) = \beta_0 + \beta_1 x_1 + \ldots + \beta_n x_n$$

where β_0 to β_n are the regression coefficients estimated by maximum likelihood, and x_1 through x_n are the explanatory independent variables.

Means for each independent variable by fire sustainability status were computed and tested for significant differences with the Student's t-test and the non-parametric Wilcoxon two-sample test (Sokal and Rohlf 1995). The individual significance of each independent variable in explaining fire sustainability was first examined. Categorical variables were automatically replaced by a set of k-1 design (or dummy) variables with k levels. Model building was assisted by stepwise procedures and used standard statistics and tests based on the χ^2 distribution (Hosmer and Lemeshow 2000): the likelihood ratio test to evaluate model significance, the Wald statistic to assess the significance of an independent variable in the presence of the other variables in the model, and the reduction in residual deviance from the null hypothesis as a goodness of fit measure. The Hosmer-Lemeshow goodness-of-fit χ^2 statistic (H-L) was used to test for dissimilarity between the observed and the expected frequency distributions of fire status; non-significant, higher *p*-values mean that the predictions fit the data well.

The chosen cut-off point to convert a probability of sustaining fire to dichotomous 0-1 data was P=0.5, i.e. below this threshold probability all estimates are assumed to correspond to unsustained fires. Model predictions and observations were cross-classified and indices of classification performance calculated (Hosmer and Lemeshow 2000): sensitivity (or the true positive fraction) and specificity (or the true negative fraction), the proportions of agreeing observations and predictions, respectively for events and non-events; accuracy, the overall fraction of the sample that is correctly classified by the model; and the false positive and false negative fractions that measure the proportions of disagreeing observations and predictions. However, and because it is independent of any arbitrary decision criterion, the Receiver Operating Characteristic curve value (ROC) was preferred to evaluate how accurate were the predictions of the logistic models (Hosmer and Lemeshow 2000). The ROC curve is a plot of the probability of a true positive prediction versus the probability of a false positive prediction and gives a measure of the comparative discrimination ability of alternative models when applied to independent data.

Similarly to Marsden-Smedley et al. (2001), the logistic regression models of fire sustainability have been complemented by recursive partitioning or classification tree modelling (De'ath and Fabricius 2000). Recursive partitioning reveals structure in data through a top-down approach based on a hierarchical decision scheme. Variation of a single response variable is explained by repeatedly splitting the data set into more homogeneous groups using combinations of independent variables. Establishment of a set of logical if-then conditions then allows accurate classification and ease of interpretation.

Results

Fire spread sustainability

An ignition attempt results either in a sustained fire or in self-extinction. A total of 265 assessments of fire sustainability, of which 57 correspond to fire spread failure, were available for analysis from 44 litter trials and 90 experimental fires. Both the parametric and non-parametric mean comparison tests indicate a significant difference between the two possible outcomes for all continuous variables but surface litter loading (Table 1). Table 2 reinforces this impression of discrimination ability: all variables have a significant ($p < 0.05$) statistical influence on ignition success. Moisture content of the fine and dead surface fuel (M), site weather variables (wind speed, temperature, relative humidity), fuel type, understorey vegetation cover, fuel load and the fuel complex bulk density have a especially pronounced effect ($p < 0.001$) on the potential for fire initiation.

Dead fuel moisture content variation between trials was in the 8 - 66% range (Table 1). The standard error and coefficient of variation for the moisture content of each larger-scale test (n=3) varied respectively from 0.5 to 11.1% and between 4 and 46%, with median values of 1.5% and 13%. As expected, fuel moisture content is the variable that more closely relates with the success or failure of an ignition attempt, reducing by 44% the residual deviance from the null model. If the estimated probability P = 0.5 is taken as the cut-off to assign group membership, a logistic model fit based on fuel moisture results in an 88% agreement between observed and predicted fire status, and estimates a moisture of extinction value of 35%. However, fire did not sustain with M = 22% in one of the tests, while one experimental fire did propagate with M = 56%, thus highlighting the role of additional variables.

Table 1. Site, weather and fuel characteristics for the observations of unsustained (0, n = 57) and sustained (1, n = 208) fire spread.

Variable	0	1	Variable	0	1
SL	9 (8)a 0 - 30	13 (10)b 0 - 30	*COV*	29.1 (41.9)a 0 - 95	55.2 (42.9)b 0 - 100
U	2.2 (2.2)a 0 - 9	3.7 (2.9)b 0 - 22	W_s	2.2 (3.8)a 0.0 – 12.2	3.7 (3.9)b 0 – 12.2
T	7.3 (2.6)a 2.7 – 13.0	11.1 (4.0)b 2.0 – 21.7	W_u	2.7 (4.2)a 0.0 – 12.2	4.8 (4.3)b 0.0 - 14.6
RH	67.5 (15.5)a 40 - 96	54.0 (15.4)b 24 - 96	W_{surf}	6.7 (4.7)a 3.0 – 17.0	9.3 (4.1)b 2.8 – 18.5
M	38.5 (10.4)a 22 – 66	21.5 (7.3)b 8 – 56	*BD*	16.3 (9.9)a 2.1 – 30.0	8.9 (8.6)b 1.1 – 24.0
DWR	7 (6.6)a 1 - 22	11 (7.9)b 1 - 36	s:L	0.5 (0.8)a 0.0 – 2.6	0.9 (1.0)b 0.0 – 3.6
W_L	4.0 (1.4)a 2.1 – 12.0	4.5 (1.8)a 1.8 – 12.0	nw:L	0.2 (0.6)a 0.0 – 2.7	0.4 (0.8)b 0.0 – 3.5
W_{nw}	0.5 (1.4)a 0.0 – 5.6	1.1 (1.8)b 0.0 – 6.3	u:L	0.7 (1.0)a 0.0 – 3.1	1.4 (1.4)b 0.0 – 5.2

Note: Values are given as the mean, standard deviation (in parentheses) and range. For each variable, values followed by a different letter are significantly different ($p < 0.05$) between fire status 0 and 1 according to both the Student's t-test and the non-parametric Wilcoxon two-sample test.
SL = slope, %; *U* = mean surface wind speed, km h^{-1}; *T* = air temperature, °C; *RH* = air relative humidity, %; *M* = moisture content of surface dead fine fuel, %; *DWR* = no. of days since last rainfall; *W* = fuel load, t ha^{-1}; L = surface litter; nw = non-woody understorey vegetation; s = shrubs; u = understorey vegetation; surf = surface fuel; *BD* = bulk density, kg m^{-3}; s:L = shrub to litter load ratio; nw:L = non-woody to litter load ratio; u:L = understorey vegetation to litter load ratio; *COV* = understorey vegetation cover, %.

Sustained spread of the head of the fire while its back failed to propagate was repeatedly observed under moister conditions. Fig. 1 summarizes the relationship between ignition success and fuel moisture content after creating intervals for M (see Fig. 1 legend) and computing – for the forward and backward directions of fire propagation – the mean proportion of sustained fires on each moisture class. S-shaped curves fit the observed trends well, with the probabilities of sustained backward and forward spread in clear disagreement for M > 25%, and a very high probability of ceasing back fire spread when M > 30%.

The likelihood of a sustained head fire increased with stronger winds and steeper terrain (Table 2). A plot of dead fuel moisture content against wind speed (Fig. 2) shows that fire sustainability for $M \geq 32\%$ was restricted to the forward section of the fire, and suggests that increases in wind speed raise the moisture of extinction of the head fire. Backward fire spread is either unresponsive (Weise and Biging 1997) or adversely affected (Van Wagner 1988) by wind and slope, suggesting these variables should be zeroed or given a negative sign for inclusion in the model. However, neither wind speed nor slope are statistically significant ($p = 0.052$ and $p = 0.20$, respectively) in a logistic model with fuel moisture. Furthermore, a significant correlation ($r = 0.30$, $p < 0.001$) exists between slope angle and wind speed, and slope terrain varies in a relatively narrow range (0 - 30%, with a mean value of 12%). In view of the difficulties in quantifying how wind and slope contribute to fire sustainability, we just add the fire direction – coded 0 for forward spread (the head fire) and 1 for backward spread (the back fire) – to dead fuel moisture in the model. The resulting equation, SS1 in Table 3, reduces residual deviance by 53% from the null model.

Table 2. Univariate logistic regression models for the probability of sustained fire spread ($n = 265$, *d.f.* = 1): variable significance and deviance reduction (%).

Variable	*p*-value	Red.	Variable	*p*-value	Red.	Variable	*p*-value	Red.
F	<0.001	4	DWR	<0.001	4	W_u	<0.001	4
SL	0.0035	3	FT	<0.001	8	W_{surf}	<0.001	6
U	<0.001	6	W_L	0.035	2	BD	<0.001	10
T	<0.001	17	W_{nw}	0.024	2	s:L	<0.001	4
RH	<0.001	11	COV	<0.001	6	nw:L	0.046	1
M	<0.001	44	W_s	0.006	3	u:L	<0.001	5

Note: *d.f.* = degrees of freedom; *F* = fire spread direction (backward, forward); *FT* = fuel type (litter; litter-shrubs; litter-non woody understorey). See Table 1 for the remaining variables explanation.

Fig. 1. Plot of the proportion of sustaining fires in each fuel moisture class by fire spread direction (o – forward; + - backward). Fuel moisture classes: 1 – 0-15%; 2 – 16-20%; 3 – 21-25%; 4 – 26-30%; 5 – 31-35%; 6 – 36-40%; 7 –>40%.

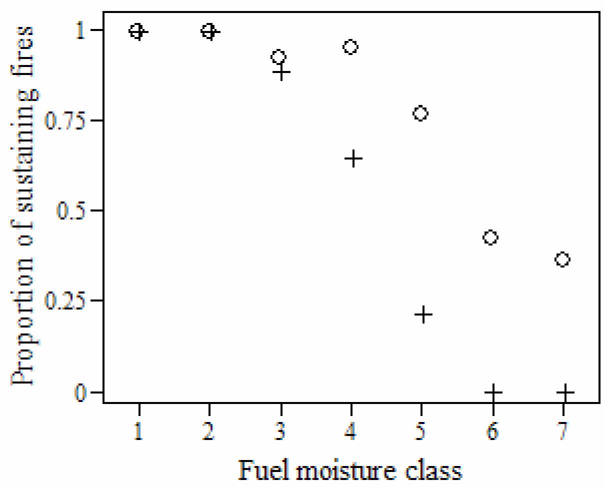
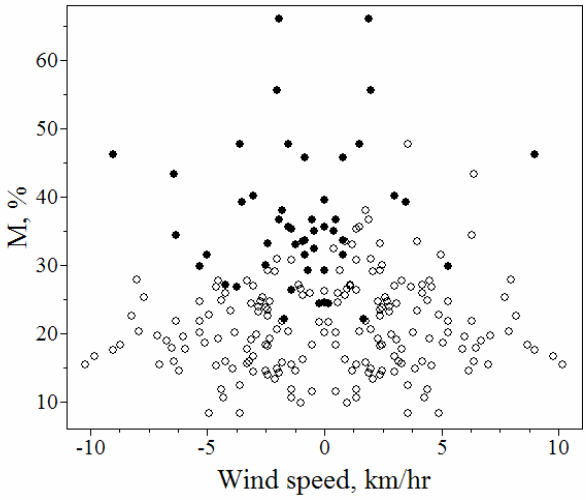


Fig. 2. Plot of the moisture content of surface fine dead fuel versus wind speed for fires that either sustained (white circle) or self-extinguished (black circle). Negative and positive wind speed values imply backward and forward fire propagation, respectively. Two extreme wind observations are not displayed.



The fuel-complex role on fire sustainability was examined next, by adding fuel variables in turn to the two-variable model (Table 4). The probability of a sustained fire significantly increases with understorey vegetation cover, partial (shrubs, non-woody understorey) and total fuel loadings, and with the three ratios of understorey vegetation load to litter load. These fuel descriptors are however outperformed by bulk density and fuel type, which increase the reduction in deviance by 9% each. Under equal fuel moisture circumstances the likelihood of a successful ignition attempt increases with the bulk density decrease, or from pure litter to the dominance by non-woody understorey vegetation.

The bulk density of a fuel-complex can be difficult to quantify, particularly when a high degree of spatial non-uniformity exists (Brown 1981). A fuel type classification should implicitly account for the various fuel properties that might affect fire sustainability, and fuel type was indeed heavily correlated ($p < 0.001$) with all fuel descriptors. Considering the simplicity of use of a fuel type classification, we opt for a three-variable model (SS2 in Table 3) with M, fire spread direction and fuel type as independent variables. The design variables $FT1$ and $FT2$ describe fuel type for the model: the litter fuel complex is assigned $FT1 = 1$ and $FT2 = 0$, while $FT1 = 0$ and $FT2 = 1$ stand for litter-shrubs, and litter-non woody understorey is coded with $FT1 = FT2 = 0$.

Further improvements to equation SS2 are possible if air temperature is included in the model, despite its correlation with fuel moisture ($r = 0.55$, $p < 0.001$). Fuel particles at higher temperatures require less heat to ignite (Schroeder 1969). Ambient temperature is thus justifiable as a fire ignition predictor, if taken as a practical surrogate for the temperature of the air in direct contact with the fuel. The four-variable model SS3 (Table 3) decreases residual deviance by 64%, which is a minor gain over SS2.

Table 3. Multivariate logistic regression models for predicting the probabilities of sustained (SS, n = 265) and fully-sustained (FSS, n = 182) fire spread.

[a] Model	[b] Red.	[c] H-L p-value	Coefficient estimates (std. error) and Wald statistic p-values						
			Intercept	*M*	*F*	*FT1*	*FT2*	*T*	*DWR*
SS1	52	0.385	9.917 (1.285)	-0.253 (0.035)	-2.264 (0.545)	-	-	-	-
			<0.001	<0.001	<0.001				
SS2	62	0.775	14.975 (2.363)	-0.294 (0.044)	-2.668 (0.622)	-4.393 (1.205)	-2.920 (1.227)	_	_
			<0.001	<0.001	<0.001	<0.001	0.017		
SS3	64	0.862	12.249 (2.459)	-0.270 (0.045)	-2.862 (0.658)	-4.206 (1.192)	-2.869 (1.208)	0.245 (0.101)	_
			<0.001	<0.001	<0.001	<0.001	0.017	0.015	
FSS	60	0.978	13.046 (2.352)	-0.495 (0.088)	-1.989 (0.693)	-	-	-	0.136 (0.055)
			<0.001	<0.001	0.004				0.014

[a] The p-value for the likelihood ratio χ^2 statistic is <0.001 for all models. [b] Red. is the deviance reduction (%). [c] H-L is the Hosmer-Lemeshow goodness-of-fit χ^2 statistic. *FT1* and *FT2* denote dummy variables for fuel type (see text). The remaining variables are explained in Tables 1 and 2.

Table 4. Deviance reduction (%) after single addition of fuel variables to the two-variable logistic model (SS1 in Table 3) for predicting fire sustainability.

Variable	p - value	Reduction	Variable	p - value	Reduction
BD	< 0.001	62	W_{nw}	0.003	57
FT	< 0.001	62	nw:L	0.011	56
COV	< 0.001	60	s:L	0.012	55
W_{surf}	< 0.001	59	W_s	0.016	55
u:L	< 0.001	58	W_L	0.121	53
W_u	0.001	57			

Note: the p – values refer to the Wald statistic for each fuel variable. See Table 1 for variables explanation.

Table 5. Predictive capabilities of the models for the probability of sustained fire spread (SS) and fully-sustained fire spread (FSS).

	Agreement			Disagreement		
Model	Sensitivity	Specificity	Overall (accuracy)	False positive	False negative	ROC
SS1	0.97	0.70	0.91	0.30	0.03	0.94
SS2	0.97	0.75	0.92	0.25	0.03	0.96
SS3	0.96	0.81	0.93	0.19	0.04	0.97
FSS	0.96	0.70	0.91	0.30	0.04	0.96

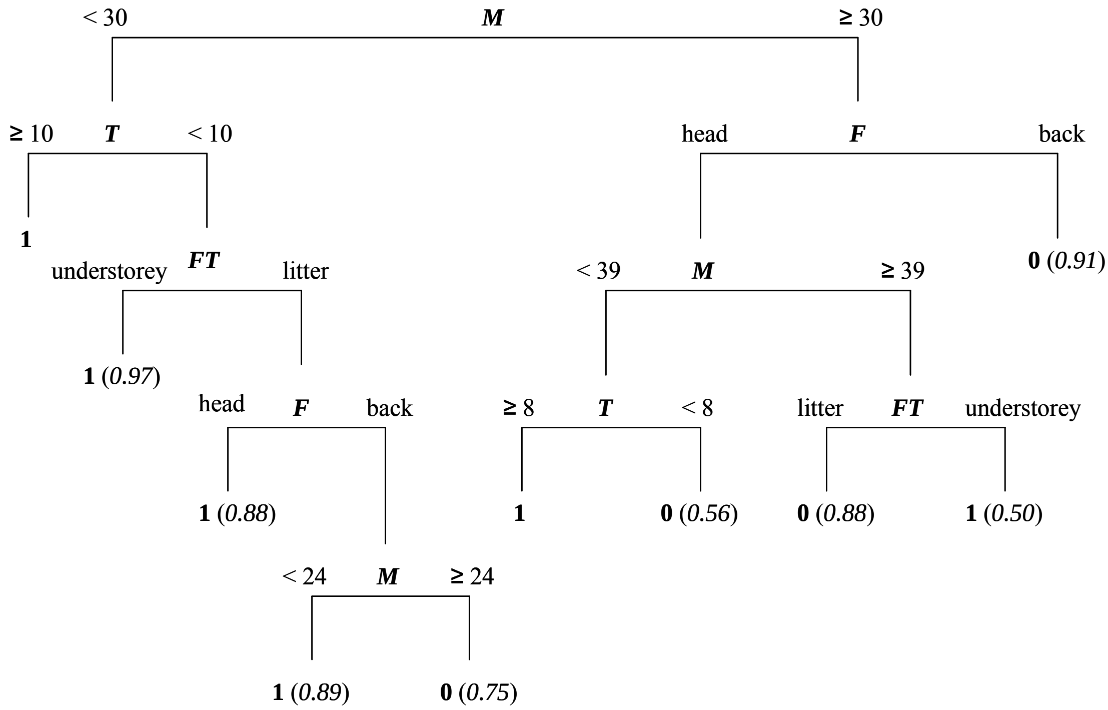
Note: ROC is the value associated to the receiver operations characteristic (ROC) curve analysis.

Table 5 depicts the discrimination ability of each model for the probability of fire spread. All equations are better predictors of sustained fires than of non-sustained fires. Correct categorization – i.e. agreement between the observed and the predicted fire status – exceeds 90% for all three models. The ROC value shows the models can correctly distinguish between sustained and unsustained fires more than 90% of the time, which is considered outstanding discrimination (Hosmer and Lemeshow 2000). Classification errors are mostly due to overestimation of fire sustainability. Equation SS3 has the highest accuracy, essentially because it classifies better the non-sustaining fire cases by providing less inflated estimates of fire spread likelihood.

The equations for the probability of sustained fire spread were evaluated with a limited data set of 24 sustained experimental fires conducted in maritime pine stands and reported in Botelho et al. (1994, 1998) and Cruz and Viegas (2001). The evaluation data base included the two fire spread directions and the three fuel types, with M and ambient temperature varying in the ranges of 21 - 38% and 5 -17 ^{o}C, respectively. Equation SS1 generated probabilities below 0.50 for two fires, and so failed to correctly categorize their sustainability status, while models SS2 and SS3 correctly predicted that all fires in the evaluation database would propagate.

Results of the classification tree modelling (Fig. 3) should grant additional insight on the influence of the various factors that affect fire sustainability, especially in view of the poor clarification of temperature's role. We used as independent variables those in model SS3. The recursive partitioning process selects *FT1* but leaves *FT2* out, hence discriminating between the dominance of litter or understorey in the fuel complex, but not between the woody and grassy nature of the understorey vegetation.

Fig. 3. Fire sustainability rules obtained by recursive partitioning (9 splits, R^2=0.70). *M* = dead fuel moisture, %; *T* = air temperature, °C; *F* = direction of fire spread; *FT* = fuel type. 1 = sustaining fires, 0 = non-sustaining fires. The proportion of fires that sustain or extinguish is indicated in brackets whenever the separation is not complete at the end of the splitting process.



The fire sustainability rules of Fig. 3 are consistent with the modelling results. Fire is generally sustained when *M* < 30%, unless the ambient temperature is below 10 °C and the fire is propagating in fuel beds of pure litter. However, even under these conditions, most head fires and back fires (at *M* < 24%) will sustain.

The fire spread direction influence is more noticeable when *M* exceeds 29%: the likelihood of backing fire extinction is very high regardless of other factors. Forward fire spread is assured in the *M* range of 30 to 38%, except for *T* < 8 °C where the probability of burning decreases to 56%. When *M* reaches 39%, a head fire has a 50% chance of sustaining in understorey, but will most likely go out in litter.

Classification tree modelling of fire sustainability was also attempted with the fuel moisture classes in Fig. 1 in lieu of *M*. The resulting decision tree was less efficient and parsimonious, as three more splits were needed to reach the same level of discrimination.

Full fire spread sustainability

The marginal burning classification was ascribed to 20% of the fire fronts categorized as sustained (n = 182). The flame front of marginal fires was typically interrupted between 10 and 30% of its extension, frequently in coincidence with shade – thus with moister and cooler fuels – and obstacles such as rocks, fallen cones, and branches with live needles attached. On average, a marginal back fire had a spread rate of 0.18 m min^{-1} with a 0.5-m flame length (ranges: 0.06 – 0.45 m min^{-1}; 0.1 – 1.3 m), and it is interesting to note the high degree of overlapping with fully-sustained back fires (0.07 – 0.60 m min^{-1}; 0.2 – 1.9 m). The spread rate and flame length values for marginal head fires were 0.75 m min^{-1} (0.25 – 1.85 m min^{-1}) and 0.6 m (0.1 – 1.4 m), respectively.

The distinction between marginal and fully sustained burning in terms of environmental variables is not as striking as between self-extinction and sustained propagation. The only continuous variables that are significantly different between the two outcomes are *M* and *M*-related variables (relative humidity, temperature, and days since rain). These are the same variables that can be used to discriminate between the two fire spread classifications (Table 6).

When dead fuel moisture content exceeds 20%, 30% and 35%, marginal fire propagation is respectively possible, dominant and certain (Fig. 4). *M* offers in fact the single most relevant explanation for marginal burning, decreasing the residual deviance by 51%, correctly classifying 88% of the observations, and estimating a threshold of M = 27% between marginal burning and fully-sustained fire spread.

The logistic model is improved if fire spread direction (p = 0.0034), slope (p < 0.001), wind speed (p = 0.0055) and days since rain (p = 0.025) are individually combined with *M*. Fig. 4 shows that all backward fire propagation is marginal at M > 25% and that the fraction of fully sustained fires differs between the head and the back fire sections for 20% < M < 26%. The effects of fire direction, slope and wind speed are confounded, however, because neither of these variables is significant when simultaneously added to *M* in a model. Because slope and wind do not significantly affect the degree of head fire sustainability we include the fire spread direction in the final model along with *M* and days since rain (equation FSS in Table 5). Although it can be argued that the number of days since rain is redundant in the model – given that its effect should be reflected in *M* and the two variables are correlated (r = 0.27, p = 0.0029) – its significance in the presence of the other two variables is undeniable (p = 0.0048). Equation FSS reduces residual deviance by 60%, predicts a fire status that concurs with the observation in 91% of the cases, and has a very good discrimination ability (ROC = 0.96). As with the equations for sustained fire spread, fully-sustained fires are better predicted than marginal burns (Table 5).

Discussion

The fuel moisture content that corresponds to a 50% probability of a fire sustaining is interpretable as the boundary between fire extinction and sustained combustion. We have determined a value of 35% for this critical moisture content for the surface fuel complex of maritime pine, which generically corresponds to fiber saturation (Cheney 1981) and coincides with Gillon et al. (1995), who have worked with litter of the same species in laboratory windless burns.

Fig. 4. Plot of the proportion of non-marginal fires, i.e. fully-sustained fires, in each fuel moisture class by fire spread direction (o – forward; + - backward). Fuel moisture classes: 1 – 0-15%; 2 – 16-20%; 3 – 21-25%; 4 – 26-30%; 5 – 31-35%; 6 – 36-40%; 7 –>40%.

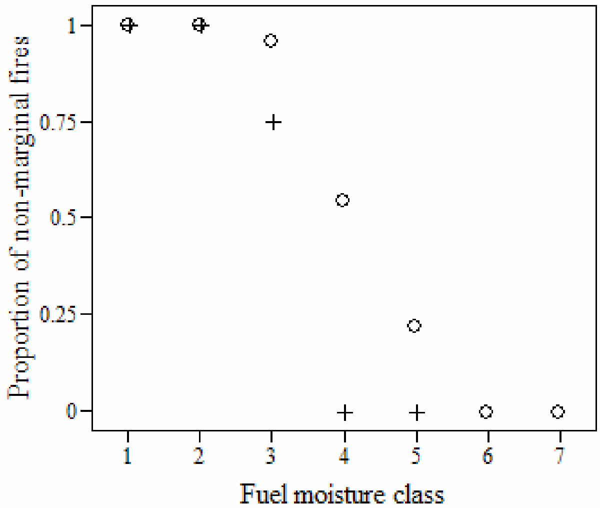


Table 6. Univariate logistic regression models for the probability of fully-sustained fire spread (n = 182, $d.f.$ = 1): variable significance and deviance reduction (%).

Variable	*p*- value	Red.	Variable	*p*-value	Red.	Variable	*p*-value	Red.
F	0.96	0	*DWR*	0.006	4	W_u	0.81	0
SL	0.14	4	*FT*	0.31	1	W_{surf}	0.99	0
U	0.29	1	W_L	0.59	0	*BD*	0.22	1
T	<0.001	14	W_{nw}	0.20	1	s:L	0.29	1
RH	<0.001	8	*COV*	0.56	0	nw:L	0.69	0
M	<0.001	51	W_s	0.71	0	u:L	0.30	1

[a]See Tables 1 and 2 for explanation of the variables acronyms.

It was however clear that such moisture content threshold is merely indicative and subject to variation depending on other factors. Equation SS1 predicts sustainable forward and backward fire spread respectively at M = 39% and M = 30%. Sustained flaming in maritime pine litter is hence possible for M > 35%, and others have also reported this, both in the laboratory (Ward 1971) and in the field (Cruz and Viegas 2001).

The significance of fire spread direction in the models arises from the fact that wind-driven or upslope fires have their propagation enhanced in relation to fires propagating against the wind or down slope, due to differences in the efficiency and mechanisms of heat transfer (e.g. Mendes-Lopes et al. 2003). While the primary heat-transfer mechanism in a back fire is radiation through the fuel bed (Van Wagner 1968), a head fire also propagates by preheating fuels by flame radiation and convection. Wind is intuitively perceived as a relevant factor in fire spread sustainability, and at high fuel moisture contents enhances the role of convective heat transfer in particle ignition (Zhou et al. 2005). Several studies have integrated wind speed in probabilistic models of ignition success, including a few carried in conifer litter (Lawson et al. 1994; Lin 1999). Although the data hinted at a wind speed influence on the likelihood of forward fire propagation we were not able to demonstrate or quantify such effect.

Brown and Davies (1973) indicate a general fuel moisture content threshold of 25% to 30% for the development of point-ignited fires. However, for some pine species the steady spread of fire in litter is still probable within this moisture range (Luke and McArthur 1978), which is corroborated by specific studies carried in the field (Van Wagner 1968; Lin 1999) and in the laboratory (Blackmarr 1972; Plucinski and Catchpole 2001). Objective comparisons with other pine species are not warranted, but using equation SS2 for litter gives *M* thresholds for a sustaining fire of 27% (back fire) and 36% (head fire). Equation SS2 estimates moistures of extinction of 41% and 51%, respectively for head fires carried by litter and shrubs and by litter and non-woody understorey; this is comparable with the 45% *M* value indicated by Hough and Albini (1978) for the pine surface fuel-complex of the south-eastern US. Thus, fire can spread in maritime pine fuels under relatively damp conditions, probably because of the physical and chemical characteristics of the species needles, which are relatively coarse but long and curled and form a litter bed with a high air flow capability (Fernandes and Rigolot 2007).

The fuel complex structure influence on fire sustainability was evident but, like Marsden-Smedley et al. (2001), the isolation of individual effects of fuel bed properties was not possible. In fact, from the operational point of view it is an advantage to use a fire spread probability model that expresses the fuel effect through a qualitative variable, and the discrimination of three fuel types − litter, litter with shrubs, litter with herbs and (or) bracken fern − in models SS2 and SS3 is physically sound. Bulk density decreases from pure litter to litter over layered by non-woody vegetation, and it has been observed (Plucinski and Catchpole 2001; Tanskanen et al. 2005) that less compacted fuels raise the moisture content threshold for fire propagation. Fuel packing ratio − which for a fuel layer with a given nature and composition is basically a function of bulk density (Rothermel 1972) − is an important determinant of conductivity, the rate of gas diffusion through the fuel bed (Scarff and Westoby 2006). The heat release rate increased with conductivity in the litter experiments of Scarff and Westoby (2006), thus supporting the role of bulk density in fire sustainability.

In maritime pine stands the forest floor needles have a surface area-to-volume ratio of 46 cm^{-1}, whereas the thinner particles (< 2.5 mm) of typical understorey species vary from 47 to 101 cm^{-1} (Fernandes and Rego 1998). Consequently, an understorey stratum increases both fuel depth and fuel fineness and thereby the fuel surface area per horizontal unit area of the fuel bed, hence increasing the moisture content at which it ceases to burn (Wilson 1985). Surface area affects heat transfer and absorption by fuel particles, fuel drying, rate of volatiles production by pyrolysis, and air flow (Zhou et al. 2005). Fine fuel load – in this study higher where understorey vegetation was present – has also been reported to favour fire sustainability (see the Introduction), because it increases fuel consumption and so the amount of heat transferred by radiation (Zhou et al. 2005).

Classification tree modelling supported the inclusion of ambient temperature in equation SS3. Lin (2005) conducted laboratory ignition trials in *Pinus taiwanensis* fuel beds and detected a positive effect of air temperature on the probability of ignition at moderate (60%) and high (90%) levels of air relative humidity. By taking air temperature into account, the modelled moisture of extinction range for a surface fire in a maritime pine stand expands even more. If the minimum ambient temperature in the data base (2 ^{o}C) is combined with the most unfavourable circumstance for fire spread, i.e. a back fire in pure litter, moisture of extinction is estimated at 21% by equation SS3.

The occurrence of ruptures in the fire front at a generic moisture content of 27% is congruent with Gillon et al. (1995) and Hernando and Guijarro (1998). These authors report marginal fire propagation respectively at *M* = 27 and *M* = 30 % for *Pinus pinaster* litter fires in the laboratory. Continuity in the fire line was additionally influenced by the fire direction, in agreement with what was found for sustained fire spread, and by the number of days without rain. The rate of fuel drying after a rain event is not spatially uniform, due to heterogeneity in the degree of shading and exposure to wind and because of structural variability in the fuel complex itself. The resulting spatial variation in dead fuel moisture content within short distances is not portrayed by the mean value for dead fuel moisture content determined by sampling. Assuming that fire front breaks take place essentially where fuels are damper, the number of days since rain will thus reflect the extent of small-scale variation in fuel moisture conditions, and consequently the representativeness of localized wetter fuels that will not ignite or sustain combustion.

The burning status classification of model FSS points to a time since rain effect on full-sustained fire spread that is limited to a relatively narrow range in M. This outcome is natural, because the rainfall effect on the moisture content of surface dead fine fuels is short-lived, e.g. one week is assumed in Rothermel et al. (1986). Predictions made by equation FSS with the decision threshold at P = 0.5 and an allowance of 15 days for the maximum number or rainless days − to accommodate the extended drying period required by more shaded and sheltered stands − results in that regardless of time since rain all burning is marginal if $M \geq 31\%$ or $M \geq 27\%$, for the forward and backward directions of spread respectively, and all fires are fully-sustained when $M \leq 27\%$ or $M \leq 23\%$. This is consistent with an early maritime pine underburning prescription (Botelho et al. 1994) that restricted the effectiveness of back firing to $M < 23\%$.

The fire sustainability equations rely on the ability to estimate fuel moisture either by field procedures or the use of mathematical models. The moisture content of fine, dead, surface fuels is controlled by air humidity and temperature, solar radiation, wind, precipitation, condensation and soil moisture (Viney 1991). Fuel moisture is thus dependent on site conditions, including stand structure, which accordingly can have an effect on the outcome of an ignition attempt (Tanskanen et al. 2005). Fire danger rating systems − such as the Canadian Forest Fire Danger Rating System (CFFDRS) (Stocks et al. 1989) − that translate routinely acquired weather data into easily accessible fuel moisture content surrogates are a valuable asset to plan fire management operations. Correlation with wildfire activity led, like elsewhere in the world, to Portugal adopting the Canadian Forest Fire Weather Index (FWI) System module of the CFFDRS, which has been proven useful to appraise potential fire behaviour in maritime pine (Palheiro et al. 2006). Canadian studies that relate the success of ignition trials on surface or subsurface fuels with the codes of the FWI System and site-specific measurements of weather variables and fuel moisture show the former can perform near as well (Lawson and Dalrymple 1996) or even better (Beverly and Wotton 2007), despite the obvious influence of local conditions on fuel moisture.

The Fine Fuel Moisture Code (FFMC) component of the FWI System is designed to represent the moisture content of fine, dead surface fuels (Van Wagner 1987). The FFMC provided the most accurate estimates of *Pinus pinaster* litter moisture in a comparative study conducted in NW Spain that involved several empirical and semi-physical models of dead fuel moisture content (Ruiz et al. 2002). A logistic model fit to predict fire sustainability from the FFMC was not attempted in this study. For a given site, day and test, noon code readings would have to be adjusted for the hour of the day and spatially interpolated between weather stations (Lawson et al. 1996), and such weather data was not readily available. Fire sustainability is nevertheless easily formulated in terms of the FFMC. For this purpose the FFMC was converted from M by alternatively using an equation that correlates *Pinus pinaster* litter moisture with the code value (Ruas et al. 2001), and the FF scale (Van Wagner 1987). Table 7 contains the resulting FFMC thresholds for sustained fire propagation. These limits offer broad guidelines for management applications, but some caution is advisable, as the FFMC is not meant to represent elevated dead shrub fuel and has been shown to be poorly correlated with its moisture content (Fogarty et al. 1998).

Table 7. Fine Fuel Moisture Code thresholds for sustained fire propagation (forward / backward), converted from surface dead fine fuel moisture content.

Fire spread status	[a]Ruas et al. (2001)	FF scale (Van Wagner 1987)
Sustained spread	74 / 79	67 / 74
Fully-sustained spread	80 / 82	75 / 78

[a] FFMC = (M-162.1)/1.7, with standard errors of 6.2 and 0.1, respectively, and R^2=0.83.

This study has addressed the partial and full sustainability of a line-ignited fire by treating separately its backward and forward propagation. The approach conforms to the interests of prescribed burning planning, because the ignition pattern is central to the control of fire intensity. However, only a fire that is able to propagate against the wind and down the slope can develop a complete or − when flame front disruptions occur − near complete perimeter, and thereby is truly a sustained fire. Use of the results in wildfire management therefore recommends that the equations are set to back fire mode (F = 1) to avoid overestimation of fire activity. The equations' classification errors are largely dominated by overestimating, rather than underrating, fire sustainability. Because the ignition source adopted in this study was a drip-torch, the models are also likely to overestimate the likelihood of fire sustainability for most point-ignited fires caused by accident or negligence. From the point of view of fire danger rating the costs of predicting false fire days are favoured over the underestimation of potential fire events (Taylor and Alexander 2006), but for prescribed burning the opposite may well be preferable, depending of the relative impacts of deploying resources for unsustained fires and ignoring suitable days to burn. Depending on the type of operational decision and its consequences, users can adopt a higher, more conservative P value threshold or, like in Lawson et al. (1994), resort to probability classes for better guidance.

Conclusion

In this study we have addressed the environmental conditions leading to successful surface fire spread in maritime pine stands in Portugal. Moisture content of the fine dead fuels in the surface fuel complex largely determines whether or not a fire ignited by a drip-torch will be self-sustained. Nevertheless, and in contrast to what often is proposed, the moisture content threshold for fire spread varies considerably. An approximate two fold range in moisture of extinction was found, depending on the direction of fire spread (forward or backward) in relation to wind and terrain slope, the fuel complex nature, and ambient temperature. Fuel moisture content is also the major factor in assuring non-marginal burning in the form of a fully sustained fire front, with fire spread direction and time since the last rain fall − presumably expressing within-site fuel moisture variation − as secondary influences.

The above variables were integrated in probabilistic models for sustained and fully-sustained fire spread. These can be used in simulation-based research studies and have the potential to improve the decision-making process by offering fire managers a measure of uncertainty that is useful to weigh the alternatives and associated risks. Future in-depth work examining how fire danger rating indices relate to fuel moisture content would render the models more convenient for fire management use and broaden their scope of application.

Acknowledgments

We are grateful to Délio Sousa for field assistance, and to two reviewers whose comments substantially improved the manuscript. This research was supported by a grant (SFRH/BD/3277/2000) awarded to P. Fernandes by Fundação para a Ciência e Tecnologia, and by projects PEAM/IF/0009/97 and FIRE TORCH (ENV4-CT98-0715/DGXII/CE).

References

Albini, F.A. 1976. Estimating wildfire behavior and effects. USDA For. Serv. Gen. Tech. Rep. INT-30.

Beverly, J.L., and Wotton , B.M. 2007. Modelling the probability of sustained flaming: predictive value of fire weather index components compared with observations of site weather and fuel moisture conditions. Int. J. Wildland Fire, **16**(2):161-173.

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

Botelho, H., Vega, J.A., Fernandes, P., and Rego, F. 1994. Prescribed fire behavior and fine fuel consumption in Northern Portugal and Galiza maritime pine stands. *In* Proceedings of the 2nd International Conference on Forest Fire Research. *Edited by* D.X. Viegas. Universidade de Coimbra. pp. 343-353.

Botelho, H., Fernandes, P., and Ruas, L. 1998. Modeling *Pinus pinaster* trees damage induced by up-slope wind-driven prescribed fires in Northern Portugal. *In* Proceedings of 13th Conference on Fire and Forest Meteorology. IAWF. pp. 473-476.

Brown, A.A., and Davis, K.P. 1973. Forest Fire: Control and Use. 2nd ed. McGraw-Hill. New York.

Brown, J.K. 1972. Field test of a rate-of-spread model in slash fuels. USDA For. Serv. Res. Note INT-116.

Brown, J.K. 1981. Bulk densities of nonuniform surface fuels and their application to fire modeling. For. Sci. **27**(4): 667-683.

Bruner, A.D., and Klebenow, D.A. 1979. Predicting success of prescribed fires in pinyon-juniper woodland in Nevada. USDA For. Serv. Res. Pap. INT-219.

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

Cheney, N.P. 1981. Fire behaviour. *In* Fire and the Australian Biota. *Edited by* A.M. Gill, R.H. Groves, and I.R. Noble. Australian Academy of Science, Canberra. pp. 151-175.

Clark, R.G., Wright, H.A., and Roberts, F.H. 1985. Threshold requirements for fire spread in grassland fuels. *In* Proceedings of the Symposium on Rangeland Fire Effects. *Edited by* K. Sanders and J. Durham. BLM/University of Idaho, Boise. pp. 27-32.

Cruz, M.G., and Viegas, D.X. 2001. Caracterização do comportamento do fogo em complexos combustíveis comuns na região centro de Portugal [Fire behaviour characterization in fuel complexes common in central Portugal]. *Silva Lusitana* **9**(1): 13-34. [In Portuguese. English summary available.]

De'ath, C., and K. Fabricius. 2000. Classification and regression trees: a powerful yet simple technique for ecological data analysis. Ecology, **81**(11): 3178-3192.

Fernandes, P.M., and Botelho, H.S. 2004. Analysis of the prescribed burning practice in the pine forest of northwestern Portugal. J. Env. Manage. **70**(1): 15-26.

Fernandes, P., H. Botelho, and C. Loureiro. 2002. Models for the sustained ignition and behavior of low-to-moderately intense fires in maritime pine stands. *In* Proceedings of the 4th International Conference on Forest Fire Research & 2002 Wildland Fire Safety Summit, Luso, Portugal, Nov. 18-23, 2002. [CD-ROM] *Edited by* D.X. Viegas. Millpress Science Publishers, Rotherdam, the Netherlands.

Fernandes, P.M., and Rego, F. 1998. A new method to estimate fuel surface-area-to-volume ratio using water immersion. Int. J. Wildland Fire, **8**(3):121-128.

Fernandes, P.M., and Rigolot, E. 2007. The fire ecology and management of maritime pine (*Pinus pinaster* Ait.). For. Ecol. Manage. **241**(1-3): 1-13.

Fogarty, L.G., Pearce, H.G., Catchpole, W.R., and Alexander, M.E. 1998. Adoption vs. adaptation: lessons from applying the Canadian Forest Fire Danger Rating System in New Zealand. *In* Proceedings of the 3rd International Conference on Forest Fire Research & 14th Conference on

Fire and Forest Meteorology. *Edited by* D.X. Viegas. ADAI. pp. 1011-1028.

Gillon, D., Gomendy, V., Houssard, C., Marechal, J., and Valette, J.C. 1995. Combustion and nutrient losses during laboratory burns. Int. J. Wildland Fire, **5**(1):1-12.

Hernando, C., and Guijarro, M.. 1998. Temperature regime in *Pinus pinaster* and *P. halepensis* trunks. *In* Proceedings of the 3rd International Conference on Forest Fire Research & 14th Conference on Fire and Forest Meteorology. *Edited by* D.X. Viegas. ADAI. pp. 801-813.

Hosmer, D.W., and Lemeshow, S. 2000. Applied Logistic Regression. 2nd edition. John Wiley & Sons Inc. New York.

Hough, W.A., and Albini, F.A. 1978. Predicting fire behaviour in palmetto-galberry fuel complexes. USDA For. Serv. Res. Pap. SE-174.

Lawson, B.D., and Dalrymple, G.N. 1996. Probabilities of sustained ignition in lodgepole pine, interior Douglas-fir, and white spruce-subalpine fir forest types. Supplement 1 to: field guide to the Canadian Forest Fire Behavior Prediction (FBP) System. FRDA Handbook 012. Can. For. Serv., Natural Resources Canada, Victoria.

Lawson, B.D., Armitage, O.B., and Dalrymple, G.N. 1994. Ignition probabilities for simulated people-caused fires in British Columbia pine and white spruce-subalpine fir forests. *In* Proceedings of the 12th Conference on Fire and Forest Meteorology, SAF Publ. 94-02, Soc. Am. For., Bethesda. pp. 493-505.

Lawson, B.D., Armitage, O.B., and Hoskins, W.D. 1996. Diurnal variation in the Fine Fuel Moisture Code: tables and computer source code. FRDA report 245. Canada – BC Partnership Agreement on Forest Resource Development. B.C. Ministry of Forests.

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

Lin, C.C. 2005. Influences of temperature, relative humidity, and heat sources on ignition: a laboratory test. Taiwan J. For. Sci. **20**(1): 89-93.

Luke, R.H., and McArthur, A.G. 1978. Bushfires in Australia. Aust. Govt. Publ. Serv. Canberra, Australia.

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

Mendes-Lopes, J.M., Ventura, J.M., and Amaral, J.M. 2003. Flame characteristics, temperature–time curves, and rate of spread in fires propagating in a bed of *Pinus pinaster* needles. Int. J. Wildland Fire, **12**(1): 67-84.

Nelson, R.M. 2001. Water relations of forest fuels. *In* Forest Fires Behavior and Ecological Effects. *Edited by* E.A. Johnson and K. Miyanishi. Academic Press, San Diego. pp. 79-149.

Palheiro, P., Fernandes, P., and Cruz, M.G. 2006. A fire behaviour-based fire danger classification for maritime pine stands: comparison of two approaches. *In* Proceedings of the 5th International Conference on Forest Fire Research. [CD-ROM]. *Edited by* D.X. Viegas. Elsevier B.V., Amsterdam, the Netherlands.

Plucinski, M.P., and Catchpole, W.R. 2001. Predicting ignition thresholds in litter layers. *In* MODSIM 2001 International Congress on Modelling and Simulation, vol 1. *Edited by* Ghassemi, F., Post, D.A., Sivapalan, M. and Vertessy, R. Modelling and Simulation Society of Australia and New Zealand. pp. 967-971.

Plucinski, M.P., and Catchpole, W.R. 2002. Vertical development of fire in shrubland fuels. *In* Proceedings of the 4th International Conference on Forest Fire Research & 2002 Wildland Fire Safety Summit, Luso, Portugal, Nov. 18-23, 2002. [CD-ROM] *Edited by* D.X. Viegas. Millpress Science Publishers, Rotherdam, the Netherlands.

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

Rothermel, R.C., Wilson, R., Morris, G., and Sackett, S. 1986. Modeling moisture content of fine dead wildland fuels: input to the BEHAVE Fire Prediction System. USDA For. Serv. Res. Pap. INT-359.

Ruas, L., Santos, C., and Fernandes, P. 2001. Calibração dos índices de humidade do Sistema Canadiano de Indexação do Perigo de Incêndio para pinhal bravo [Calibration for Portugal of the Canadian Forest Fire Danger Rating System fuel moisture codes]. *In* Resumos das Comunicações do 4º Congresso Florestal Nacional. SPCF, Lisboa. p. 78. [In Portuguese].

Ruiz, A.D., Maseda, C.M., and Lourido, C. 2002. Possibilities of dead fine fuels moisture prediction in *Pinus pinaster* Ait. stands at “Cordal de Ferreiros” (Lugo, north-western of Spain). *In* Proceedings of the 4th International Conference on Forest Fire Research & 2002 Wildland Fire Safety Summit, Luso, Portugal, Nov. 18-23, 2002. [CD-ROM] *Edited by* D.X. Viegas. Millpress Science Publishers, Rotherdam, the Netherlands.

Schroeder, M.J. 1969. Ignition probability. USDA For. Serv. Office Rep. 2106-1.

Sokal, R.R., and Rohlf, J. 1995. Biometry: the Principles and Practices of Statistics in Biological Research. 3rd edition. W.H. Freeman and Company. New York.

Stocks, B.J., Lawson, B.D., Alexander, M.E., Van Wagner, C.E., McAlpine, R.S., Lynham, T.J., and Dubé, D.E. 1989. The Canadian Forest Fire Danger Rating System: an overview. For. Chron. **65**(6): 450-457.

Tanskanen, H., Venäläinen, A., Puttonen, P., and Granströn, A. 2005. Impact of stand structure on surface fire ignition potential in *Picea abies* and *Pinus sylvestris* forests in southern Finland. Can. J. For. Res. **35**: 410-420.

Taylor, S.W., and Alexander, M.E. 2006. Science, technology, and human factors in fire danger rating: the Canadian experience. Int. J. Wildland Fire, **15**(1): 121-135.

Van Wagner, C.E. 1968. Fire behaviour mechanisms in a red pine plantation: field and laboratory evidence. Can. Dep. For. Rur. Dev. Publ. no. 1229.

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Can. For. Serv., Forestry Tech. Rep. 35.

Van Wagner, C.E. 1988. Effect of slope on fires spreading downhill. Can. J. For. Res. **18**: 818-820.

Viney, N.R. 1991. A review of fine fuel moisture modelling. Int. J. Wildland Fire **1**(4): 215-234.

Ward, D. 1971. A controlled experiment to study factors influencing fire rate of spread in *Pinus pinaster* litter. Forest Notes, **9**(3): 39-47.

Weise, D.R., and Biging, G.S. 1997. A qualitative comparison of fire spread models incorporating wind and slope effects. For. Sci. **43**(2): 170-180.

Weise, D., Zhou, X., Sun, L., and Mahalingam, S. 2005. Fire spread in chaparral − ’go or no-go?’. Int. J. Wildland Fire, **14**: 99-106.

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

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

Zhou, X., Mahalingam, S., and Weise, D. 2005. Modeling of marginal burning state of fire spread in live chaparral live fuels. Combustion and Flame, **143**: 183-198.