

# 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: litter, litter plus shrubs, and litter with a nonwoody 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 :** Les seuils pour la propagation des feux de surface ont été étudiés dans des peuplements de pin maritime (*Pinus pinaster* Ait.) dans le nord du Portugal. La propagation autonome du feu a été évaluée après l'allumage de lignes de feu de deux mètres ou dans des brûlis plus importants effectués dans des parcelles de 10–15 m de large. Les expériences ont été réalisées de novembre à juin dans trois types de combustibles : litière, litière avec des arbustes et litière avec un sous-étage non ligneux. La teneur en humidité des combustibles fins morts, les variables météorologiques sur le site et les descripteurs du complexe de combustibles ont tous eu une influence très significative sur la probabilité de propagation autonome du feu. Un modèle logistique basé seulement sur la teneur en humidité des combustibles a correctement classé le résultat des allumages dans 88 % des cas. Malgré cela, la subjectivité du concept d'humidité d'extinction était apparente et une plus grande exactitude a été obtenue par l'ajout consécutif de la direction de la propagation du feu (vers l'avant ou l'arrière), du type de combustibles et de la température ambiante. La propagation totalement autonome du feu, contrairement aux brûlis marginaux avec un front de feu discontinu, dépendait de la même façon de la teneur en humidité mais était aussi affectée par la direction de la propagation du feu et le temps écoulé depuis la dernière pluie. Les modèles peuvent servir à la recherche sur le feu et aux opérations de gestion des incendies mais ils peuvent être plus pratiques s'ils sont intégrés dans un système d'évaluation des risques d'incendie.

[Traduit par la Rédaction]

## 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).

Fire sustainability can be inferred from the persistence of flame in assemblages of fuel particles burned in laboratory facilities. However, the results do not mimic fire sustainability in the field, unless the natural fuel arrangement is retained and unless enough scale is achieved by allowing some fire development. Ignitability and sustained flaming have been addressed in laboratory-scale fires in fuel beds

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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 that 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. However, Brown (1972) referred to the choice of moisture of extinction as subjective, and Albin (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 et 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 °C and 500–1200 mm. Six locations for the study sites were chosen within a 450–970 m elevation range and at latitudes of 41°20'N to 41°30'N and longitudes of 7°40'W to 7°50'W. Age, mean height, and mean basal area varied from 14 to 41 years, from 6 to 18 m, and from 14 to 56 m<sup>2</sup>·ha<sup>-1</sup>, respectively. The sites are representative of the range in fuel conditions that typifies *Pinus pinaster* forests in northern Portugal.

Preburn quantitative fuel description in the experimental sites considered the fine elements (i.e., <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<sup>-3</sup>) 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<sup>-1</sup>). Because fire in maritime pine stands 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 (litter, litter and shrubs, and litter and nonwoody 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 nonwoody 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 emphasizes 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, preheating 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 nonsustained. The fire was categorized as sustained if the ignition line continued to spread for 5 min.

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 h at 85 °C) and was expressed as a percentage of dry mass 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 variable 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

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

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

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

where  $\beta_0$  to  $\beta_n$  are the regression coefficients estimated by maximum likelihood, and  $x_1$  to  $x_n$  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 nonparametric 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  $\chi^2$  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  $\chi^2$  statistic (H–L) was used to test for dissimilarity between the observed and the expected frequency distributions of fire status; nonsignificant, 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 were calculated (Hosmer and Lemeshow 2000): sensitivity (or the true positive fraction) and specificity (or the true negative fraction), which are the proportions of agreeing observations and predictions for events and non-events, respectively; accuracy, which is 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 (ROC) curve value 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 re-

sponse 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 nonparametric 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, and 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 among 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 from 0.5% to 11.1% and from 4% to 46%, with median values of 1.5% and 13%, respectively. As expected, fuel moisture content is the variable that more closely relates to the success or failure of an ignition attempt, reducing the residual deviance from the null mode by 44%. 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, whereas one experimental fire did propagate with  $M = 56\%$ , thus highlighting the role of additional variables.

Sustained spread of the head of the fire while its back failed to propagate was repeatedly observed under moister conditions. Figure 1 summarizes the relationship between ignition success and fuel moisture content after creating intervals for  $M$  (see Fig. 1 caption) and computing the mean proportion of sustained fires on each moisture class for forward and backward fire propagation. 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 that these variables should be zeroed or given a negative sign for inclusion in the model. However,

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

Variable	Fire spread	
	Unsustained	Sustained
SL		
Mean (SD)	9 (8)a	13 (10)b
Range	0–30	0–30
$U$		
Mean (SD)	2.2 (2.2)a	3.7 (2.9)b
Range	0–9	0–22
$T$		
Mean (SD)	7.3 (2.6)a	11.1 (4.0)b
Range	2.7–13.0	2.0–21.7
RH		
Mean (SD)	67.5 (15.5)a	54.0 (15.4)b
Range	40–96	24–96
$M$		
Mean (SD)	38.5 (10.4)a	21.5 (7.3)b
Range	22–66	8–56
DWR		
Mean (SD)	7 (6.6)a	11 (7.9)b
Range	1–22	1–36
$W_L$		
Mean (SD)	4.0 (1.4)a	4.5 (1.8)a
Range	2.1–12.0	1.8–12.0
$W_{nw}$		
Mean (SD)	0.5 (1.4)a	1.1 (1.8)b
Range	0.0–5.6	0.0–6.3
COV		
Mean (SD)	29.1 (41.9)a	55.2 (42.9)b
Range	0–95	0–100
$W_s$		
Mean (SD)	2.2 (3.8)a	3.7 (3.9)b
Range	0.0–12.2	0.0–12.2
$W_u$		
Mean (SD)	2.7 (4.2)a	4.8 (4.3)b
Range	0.0–12.2	0.0–14.6
$W_{surf}$		
Mean (SD)	6.7 (4.7)a	9.3 (4.1)b
Range	3.0–17.0	2.8–18.5
BD		
Mean (SD)	16.3 (9.9)a	8.9 (8.6)b
Range	2.1 – 30.0	1.1 – 24.0
$W_s/W_1$		
Mean (SD)	0.5 (0.8)a	0.9 (1.0)b
Range	0.0–2.6	0.0–3.6
$W_{nw}/W_1$		
Mean (SD)	0.2 (0.6)a	0.4 (0.8)b
Range	0.0–2.7	0.0–3.5
$W_u/W_1$		
Mean (SD)	0.7 (1.0)a	1.4 (1.4)b
Range	0.0–3.1	0.0–5.2

**Note:** For each variable, values followed by a different letter are significantly different ( $p < 0.05$ ) between sustained and unsustainable fire spread according to both the Student's  $t$  test and the nonparametric Wilcoxon two-sample test. SL, slope (%);  $U$ , mean surface wind speed ( $\text{km}\cdot\text{h}^{-1}$ );  $T$ , air temperature ( $^{\circ}\text{C}$ ); RH, air relative humidity (%);  $M$ , moisture content of surface dead fine fuel (%); DWR, days since last rainfall;  $W_L$ , litter fuel load ( $\text{t}\cdot\text{ha}^{-1}$ );  $W_{nw}$ , nonwoody understorey vegetation fuel load ( $\text{t}\cdot\text{ha}^{-1}$ );  $W_s$ , shrub fuel load ( $\text{t}\cdot\text{ha}^{-1}$ );  $W_u$ , understorey vegetation fuel load ( $\text{t}\cdot\text{ha}^{-1}$ );  $W_{surf}$ , surface fuel load ( $\text{t}\cdot\text{ha}^{-1}$ ); BD, bulk density ( $\text{kg}\cdot\text{m}^{-3}$ ); COV, understorey vegetation cover (%).

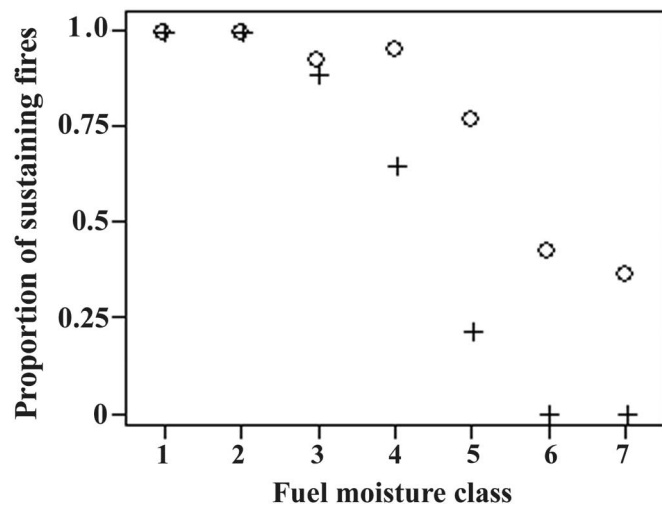


**Table 2.** Univariate logistic regression models for the probability of sustained fire spread ( $n = 265$ ,  $df = 1$ ): variable significance and deviance reduction.

Variable	$p$	Deviance reduction (%)
$F$	<0.001	4
SL	0.0035	3
$U$	<0.001	6
$T$	<0.001	17
RH	<0.001	11
$M$	<0.001	44
DWR	<0.001	4
FT	<0.001	8
$W_L$	0.035	2
$W_{nw}$	0.024	2
COV	<0.001	6
$W_s$	0.006	3
$W_u$	<0.001	4
$W_{surf}$	<0.001	6
BD	<0.001	10
$W_s/W_1$	<0.001	4
$W_{nw}/W_1$	0.046	1
$W_u/W_1$	<0.001	5

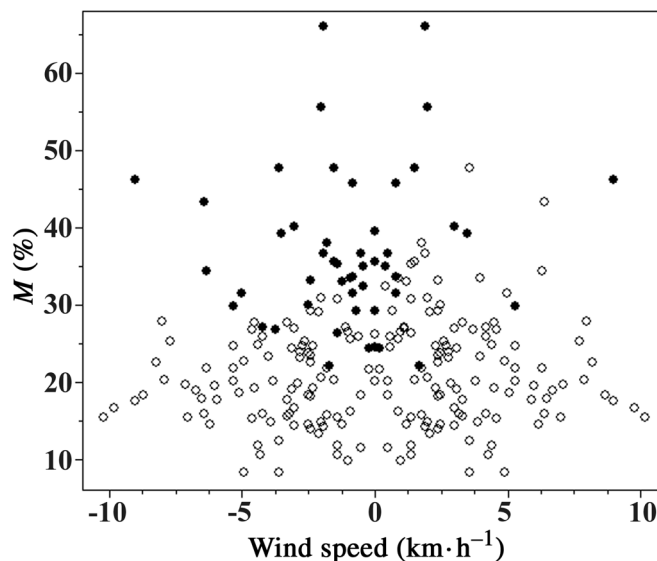
**Note:**  $F$ , fire spread direction (backward and forward); FT, fuel type (litter, litter–shrubs, and litter – nonwoody understorey). See Table 1 for definitions of the other variables.

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



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%, mean 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 model, SS1 in Table 3, reduces residual deviance by 53% from the null model.

**Fig. 2.** Plot of the moisture content of surface fine dead fuel versus wind speed for fires that either sustained ( $\circ$ ) or self-extinguished ( $\bullet$ ). 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, with partial (shrubs and nonwoody understorey) and total fuel loadings, and with the three ratios of understorey vegetation load to litter load. However, these fuel descriptors are 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 dominance by nonwoody understorey vegetation.

The bulk density of a fuel complex can be difficult to quantify, particularly when a high degree of spatial nonuniformity 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 coded FT1 = 1 and FT2 = 0; litter–shrubs is coded FT1 = 0 and FT2 = 1; and litter – non woody understorey is coded with FT1 = FT2 = 0.

Further improvements to model 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). Thus, ambient temperature is 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 5 depicts the discrimination ability of each model for the probability of fire spread. All equations are better

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

Model <sup>a</sup>	Deviance reduction (%)	Coefficient estimate (SE)									
		H-L $p^b$	Intercept	M	F	FT1	FT2	T	DWR		
SS1	52	0.385	9.917 (1.285)	-0.253 (0.035)	-2.264 (0.545)	—	—	—	—	—	—
Wald statistic $p$			<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)	—	—	—	—
Wald statistic $p$			<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)	—	—	—
Wald statistic $p$			<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)
Wald statistic $p$			<0.001	<0.001	0.004	—	—	—	—	—	0.014

<sup>a</sup>The  $p$  value for the likelihood ratio  $\chi^2$  statistic is <0.001 for all models.

<sup>b</sup>H-L, Hosmer-Lemeshow goodness-of-fit  $\chi^2$  statistic. FT1 and FT2 are dummy variables for fuel type (see text). The remaining variables are defined 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	$p$	Deviance reduction (%)
BD	<0.001	62
FT	<0.001	62
COV	<0.001	60
$W_{surf}$	<0.001	59
$W_u/W_1$	<0.001	58
$W_u$	0.001	57
$W_{nw}$	0.003	57
$W_{nw}/W_1$	0.011	56
$W_s/W_1$	0.012	55
$W_s$	0.016	55
$W_1$	0.121	53

**Note:** The  $p$  values are for the Wald statistic for each fuel variable. See Table 1 for definitions of variables.

predictors of sustained fires than of nonsustained 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 >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 nonsustaining 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 database 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 °C, respectively. Model SS1 generated probabilities <0.50 for two fires and, thus, failed to correctly categorize their sustainability status, whereas 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 about 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.

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  $M > 29\%$ : the likelihood of backing fire extinction is very high regardless of other factors. Forward fire spread is assured in the  $M$  range of 30%–38%, except for  $T < 8$  °C

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

Model	Agreement			Disagreement		
	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 with the receiver operations characteristic curve analysis.

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: 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<sup>-1</sup> with a 0.5 m flame length (ranges 0.06–0.45 m·min<sup>-1</sup> and 0.1–1.3 m, respectively), and it is interesting to note the high degree of overlapping with fully sustained back fires (0.07–0.60 m·min<sup>-1</sup> and 0.2–1.9 m, respectively). The spread rate and flame length values for marginal head fires were 0.75 m·min<sup>-1</sup> (0.25–1.85 m·min<sup>-1</sup>) 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  $M$  exceeds 20%, 30%, and 35%, marginal fire propagation is, respectively, possible, dominant, and certain (Fig. 4). In fact,  $M$  offers 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  $M$ . Figure 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  $20% < M < 26%$ . However, the effects of fire direction, slope, and wind speed are confounded, 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 ( $p = 0.0048$ ). Model 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).

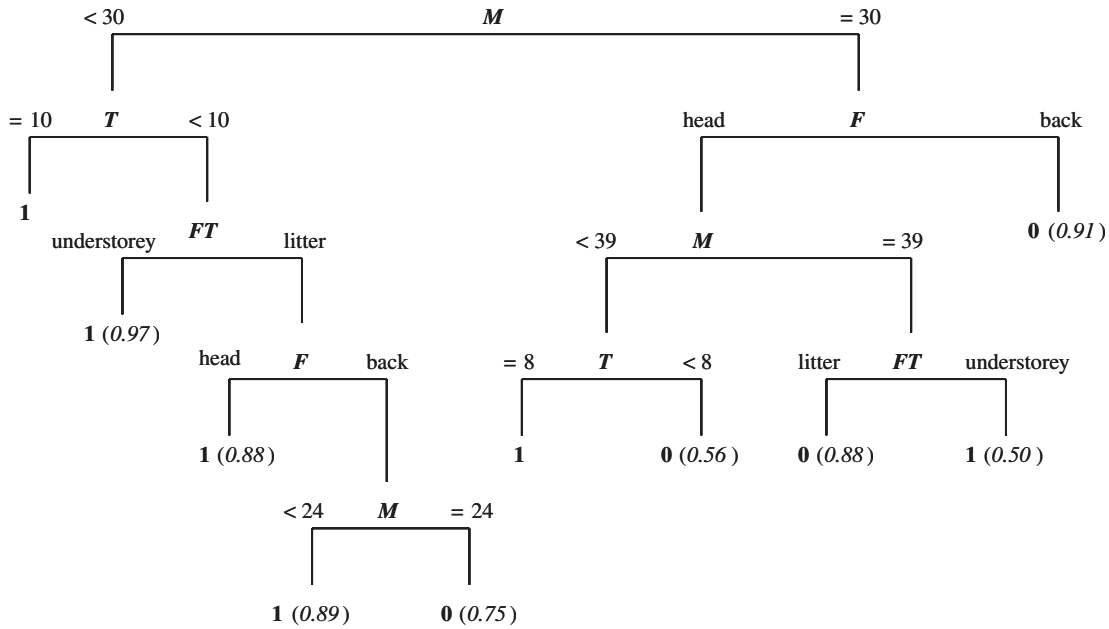
### Discussion

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 agrees with Gillon et al. (1995), who have worked with litter of the same species in laboratory windless burns. However, it was clear that such the  $M$  threshold is merely indicative and subject to variation depending on other factors. Model SS1 predicts sustainable forward and backward fire spread, respectively, at  $M = 39%$  and  $M = 30%$ . Hence, sustained flaming in maritime pine litter is 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 downslope because of differences in the efficiency and mechanisms of heat transfer (e.g., Mendes-Lopes et al. 2003). Although 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  $M$  values, 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 Davis (1973) indicate a general fuel  $M$  thresh-

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



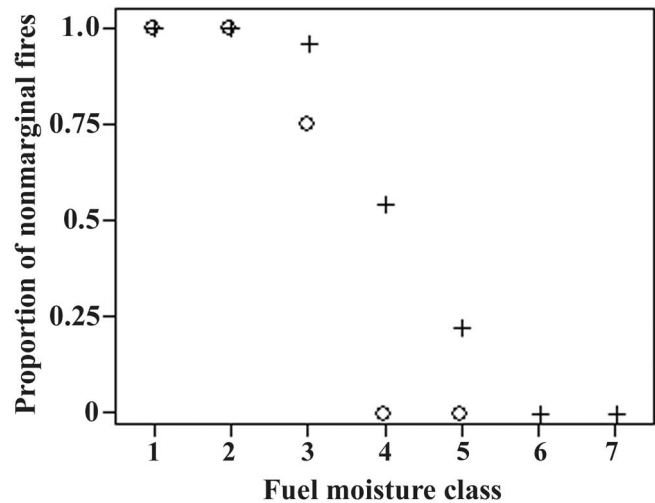
**Table 6.** Univariate logistic regression models for the probability of fully sustained fire spread ( $n = 182$ ,  $df = 1$ ): variable significance and deviance reduction.

Variable	$p$	Deviance reduction (%)
$F$	0.96	0
SL	0.14	4
$U$	0.29	1
$T$	<0.001	14
RH	<0.001	8
$M$	<0.001	51
DWR	0.006	4
FT	0.31	1
$W_L$	0.59	0
$W_{nw}$	0.20	1
COV	0.56	0
$W_s$	0.71	0
$W_u$	0.81	0
$W_{surf}$	0.99	0
BD	0.22	1
$W_s/W_1$	0.29	1
$W_{nw}/W_1$	0.69	0
$W_u/W_1$	0.30	1

Note: See Tables 1 and 2 for definitions of the variables.

old of 25%–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

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



and shrubs and by litter and nonwoody understorey; this is comparable with the 45%  $M$  value indicated by Hough and Albin (1978) for the pine surface fuel complex of the southeastern United States. 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; however, like Marsden-Smedley et al. (2001), the isolation of individual effects of fuel bed properties was



**Table 7.** Fine fuel moisture code thresholds for sustained fire propagation (forward/backward) converted from surface dead fine fuel moisture content.

Fire spread status	Ruas et al. (2001) <sup>d</sup>	FF scale (Van Wagner 1987)
Sustained	74/79	67/74
Fully sustained	80/82	75/78

<sup>d</sup>FFMC =  $(M - 162.1)/1.7$ , with standard errors of 6.2 and 0.1, respectively, and  $R^2 = 0.83$ .

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 nonwoody vegetation, and it has been observed (Plucinski and Catchpole 2001; Tanskanen et al. 2005) that less compacted fuels raise the  $M$  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  $46 \text{ cm}^{-1}$ , whereas the thinner particles ( $<2.5 \text{ mm}$ ) of typical understorey species vary from 47 to  $101 \text{ cm}^{-1}$  (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  $M$  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* Hayata 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 database ( $2^\circ \text{C}$ ) 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 model 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 uni-

form because of 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. Thus, assuming that fire front breaks take place essentially where fuels are damper, the number of days since rain will 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 fully sustained fire spread that is limited to a relatively narrow range in  $M$ . This outcome is natural, because the rainfall effect on the  $M$  of surface dead fine fuels is short lived, e.g., 1 week is assumed in Rothermel et al. (1986). Predictions made by model 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 all burning being 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  $M \leq 23\%$ , respectively, regardless of the time since rain. 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). Thus, fuel moisture is 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 nearly 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 northwestern Spain that involved several empirical and semophysical 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 were not readily available. Nevertheless, fire sustainability is 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, because 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).

This study has addressed the partial and full sustainability of a line-ignited fire by treating its backward and forward propagation separately. 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—nearly complete perimeter and, thereby, is truly a sustained fire. Therefore, we recommend that the equations are set to back fire mode ( $F = 1$ ) when using the results in wildfire management 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); however, 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, as 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 twofold 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 nonmarginal 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.

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