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Fire spread prediction in shrub fuels in Portugal

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Abstract

Expertise and knowledge of forest fire behaviour provide a sound basis to fire management activities. This study examines the possibility of describing fire spread in shrubland by means of a simple empirical model. Rates of fire spread up to 20 m min^{-1} and the associated weather and fuel conditions were measured on a set of experimental and prescribed burns in four different shrub fuel types in Portugal. Shrubland fire spread in flat terrain could be accurately predicted in terms of wind speed, aerial dead fuel moisture content and vegetation height. However, it was not possible to identify individual effects of the fuel-complex descriptors on fire propagation. Preliminary fire spread models are presented but their use should be restricted to mild to moderate burning conditions until more extensive experimentation is carried out.

Keywords: Fire behaviour modelling; Forest fire management; Shrubland; Heathland; Portugal

1. Introduction

Evergreen sclerophyll shrublands dominated by broadleaf or heath species are a prominent feature of Mediterranean landscapes (Di Castri, 1981). Shrubland plant communities are widespread in Portugal and occupy about 1.6 million ha (D.G.F., 1997), an area that represents 18% of the country which is an increase of 2% since a previous inventory (D.G.F., 1993) due to changes in land use and fire regime. Open forests of oak and pine with a continuous shrub understorey are also extensive in several regions of the country.

An increasingly important requirement of forest and land management in fire-prone ecosystems is the ability to predict fire behaviour. Shrub fuel types are known to be exceptionally flammable and capable of sustaining extreme fire intensity even at moderate fire danger levels (e.g. Wouters, 1993; Fogarty, 1996), thus posing a threat to human life and property. The ecological integrity of many shrubland and heathland communities is, on the other hand, maintained by periodic burning, and fire is simultaneously used in these vegetation types to reduce wildfire hazard and protect nearby natural or production forests.

Rate of spread and fireline intensity are the two primary descriptors of fire behaviour and their prediction is crucial to achieve effectiveness in both wildfire control and application of prescribed burning. Fireline intensity is directly related to flame size (e.g. Byram, 1959) and suppression possibility (Andrews and Rothermel, 1982), and can be correlated with ecological impacts of fire such as tree crown damage (e.g. Van Wagner, 1973). Spread rate is one of the variables required to calculate intensity and is the major determinant of its variation (Alexander, 1982), especially within a specific fuel type. Fire

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spread prediction under operational circumstances is currently restricted to the semi-physical model of Rothermel (1972), or to empirical models derived from data collected under natural environmental conditions. Fire behaviour systems that are based on empirical equations (e.g. Noble et al., 1980; Sneeuwjagt and Peet, 1985; Forestry Canada Fire Danger Group, 1992) are user-friendly — they require only a few input variables and can be translated to tables or meters, account implicitly for field heterogeneity and are successful within the range of conditions under which they were developed.

Fire spread prediction in Europe is based on Rothermel's model, whose applicability is rarely questioned or verified, probably because of the immediate needs posed by the extent of the fire problem in the Mediterranean Basin. The model, however, has limitations that are especially relevant in shrub vegetation and arise from its generalization to mixed size (Albini, 1976) and live fuels (Catchpole and Catchpole, 1991). It seems therefore that an empirical approach to fire behaviour modelling can and should be thought of as an alternative in Europe's shrublands.

The objective of the present study was, after analysing the relationships between fire spread and environmental variables, to produce a preliminary model to predict rate of fire spread in shrub fuel types occurring in Portugal.

2. Methods

Data was obtained from two sources, experimental burns designed for fire behaviour study (including small test fires), and management burns for fuel hazard reduction or habitat improvement purposes. Information is equally reliable and, except when mentioned, the methods used to collect the data did not differ between the two kinds of fires. The available information is with respect to 29 burns on flat terrain or in slopes of less than 5% in four fuel types:

1. UE: tall shrubland dominated by gorse (*Ulex europaeus*) in NW Portugal (two fires).
2. EU–CT: low heathland of *Erica umbellata* and winged broom (*Chamaespartium tridentatum*) in northern and central Portugal (19 fires).
3. EA–CT: moderately tall heathland dominated by spanish heath (*Erica australis*) and *C. tridentatum* in NE Portugal (seven fires).
4. Earb: tall mixed heathland of tree heath (*Erica arborea*), *Ulex parviflorus* and gum cistus (*Cistus ladanifer*) in southern Portugal (one fire).

The above plant formations are sequenced according to a gradual shift from oceanic to Mediterranean climate conditions, and comprise species that vary widely in their foliage characteristics and morphology. For example, surface area to volume ratio — a fuel variable with an important role in the model of Rothermel (1972) — is 87 cm^{-1} for *E. umbellata* but only 43 cm^{-1} for *C. tridentatum* (Fernandes and Rego, 1998a).

Basic descriptors of stand structure — vegetation cover and height — were assessed before each burn. Cover % was determined with the line intercept method of Canfield (1941), and height was measured for each homogeneous — in structure and species composition — portion of the transect. Height was taken as the vertical distance (to the nearest 5 cm) between litter and the visually averaged top of the canopy, thus disregarding occasional taller plant elements. Stand height was calculated as the weighted (by cover) average of the individual height measurements.

Fuel weight of each shrub species was evaluated by means of 3–15 quadrats with 0.5 m×0.5 m. All the aerial fuel encompassed by the vertical projections of a quadrat was clipped after height measurement. Litter fuels were judged too sparse or too compact to influence fire behaviour and were not sampled. Biomass was sorted by size class (<6 and >6 mm) and oven-dried at 85°C for 48 h to get dry weights. Combination of quadrat data on individual species with community structure data allowed the estimation of fuel load (fuel weight per unit area) at the stand level. Fuel loadings in the prescribed burning plots were estimated non-destructively using published equations (Fernandes and Pereira, 1993; Pereira et al., 1995; Fernandes and Rego, 1998b). Bulk density was calculated as the ratio between fuel load and the fuel-complex volume (Rothermel, 1972).

Fine (<6 mm) elevated dead fuel and live foliage were sampled for moisture content determination just before igniting a fire. 3–10 and 1–10 samples, respectively, were collected, sealed and later oven-dried at

Table 1
Range of values for rate of fire spread, weather and fuel moisture variables[a]

	R (m min^{-1})	U (km h^{-1})	T (°C)	RH (%)	M_d (%)	M_l (%)	S (%)
Average	4.4	9	14	53	21	85	1
Minimum	0.7	1	6	30	10	72	0
Maximum	20.0	27	22	93	40	113	5

[a] R: rate of fire spread; U: surface wind speed at 2 m height; T: air temperature; RH: air relative humidity; M_d: fine (<6 mm) dead fuel moisture content; M_l: fine live fuel moisture content; S: slope steepness.

85°C for 48 h. Moisture content was expressed on a dry weight percentage basis.

Weather variables (wind speed, air temperature and relative humidity) were recorded at 2 m in the open by a meteorological station placed near the burn plot, or taken upwind with hand-held instruments. The weather measurements were averaged over a period of time matching the measured fire propagation.

One or two operators started the burn by using a drip-torch to rapidly establish a line of fire perpendicular to the dominant wind direction. Length of the ignition line ranged from 10 m, in test fires, to 100 m in some of the fuel reduction burns. The fire was allowed to propagate with the wind and, whenever possible, was not restrained laterally. Rates of fire spread were determined by timing the head fire front arrival to pre-placed poles or natural reference points. Fire containment made use of previously slashed or backfired strips, or took advantage of obstacles such as roads and fire-breaks.

Statistical analysis were all carried with the JMP 3.1.6. package (SAS Institute Inc., 1996).

3. Results and discussion

Tables 1 and 2 display the observed variations in rate of fire spread and environmental variables. Weather conditions during the burns were mild to moderate, primarily reflecting the season (November–March) of the experiments and prescribed burns. Nevertheless, high levels of intensity were attained in a few burns.

Rate of fire spread was significantly correlated at the 1% level with 2 m wind speed, and at the 5% level with air relative humidity, temperature and moisture content of the elevated dead fuel. The linear correlation of spread rate with moisture content was slightly higher ($r=-0.46$) than with air temperature ($r=0.45$) or relative humidity ($r=-0.45$). The critical effect of dead fuel moisture content on fire behaviour, mainly through its influence on ignitability (e.g. Wilson, 1985) and combustion rate (e.g. Rothermel, 1972; Catchpole et al., 1998b) has been widely recognized and modelled. Air temperature and relative humidity are major determinants of dead fuel moisture, and their correlation with this variable is very high in the data set (respectively, $p=0.0008$ and $p=0.0001$). However, dead fuel moisture is also affected by a number of other factors, such as aspect, slope, cloudiness, time of day and recent rainfall events. Therefore, it is reasonable to conclude that temperature and relative humidity are easily obtainable but are unsatisfactory surrogates for the effect of dead fuel moisture on fire propagation.

Table 2
Range of values for each fuel variable[a]

	cov. (%)	h (m)	W_f (t ha^{-1})	W_t (t ha^{-1})	% Fine	ρ_{pf} (kg m^{-3})	ρ_{pt} (kg m^{-3})
Average	84	0.7	14.6	19.8	82	2.7	2.3
Minimum	50	0.2	4.8	4.9	56	1.6	3.4
Maximum	95	1.9	36.6	64.9	99	3.5	5.0

[a] cov.: vegetation cover; h: vegetation height; W_f: elevated fine (<6 mm) fuel load; W_t: elevated total fuel load; ρ_{pf}: fine fuel bulk density; ρ_{pt}: total fuel bulk density.

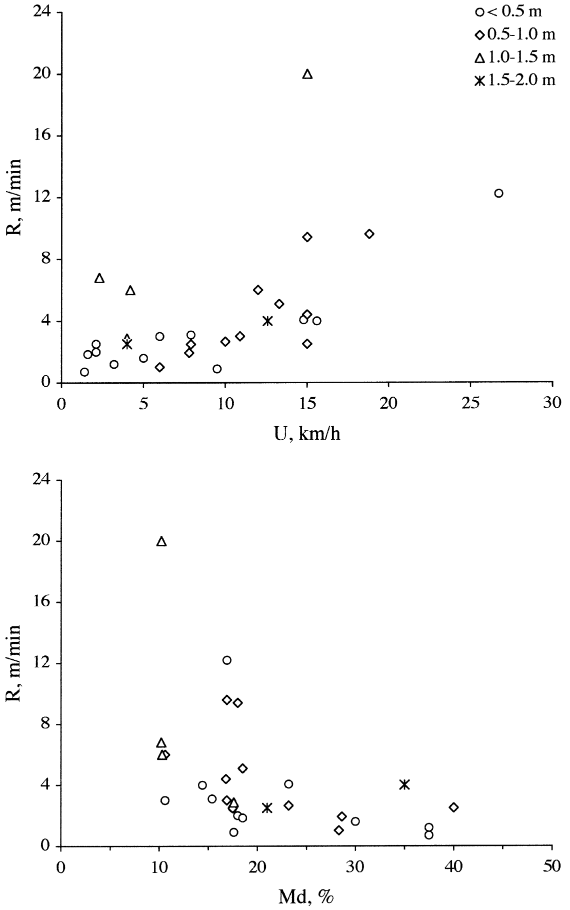

Fig. 1. Rate of fire spread (R) categorized by vegetation height classes vs. wind speed at 2 m (U) and elevated dead fuel moisture content (M_d).

Spread rate had an almost linear relationship with wind speed and was exponentially related to dead fuel moisture content (Fig. 1). The low degree of association between this two independent variables (Table 3) allowed building into a model their combined effect on rate of spread. The nature of the data recommended logarithmic transformations, a procedure that was attempted and subsequently abandoned because the resulting model underpredicted the fastest spreading fire by a factor of 2. Non-linear regression analysis was used instead to fit a model of the form

$$R = aU^b \exp(-cM_d) \qquad (1)$$

where R is the spread rate in m min^{-1}, U is the wind speed measured at 2 m in km h^{-1}, and M_d is the moisture content % of the elevated dead fuels. The estimates obtained for a, b and c were 3.258 (standard error (S.E.)=1.929), 0.958 (S.E.=0.216) and 0.111 (S.E.=0.026), respectively, and the model explained 65% of the variation in fire spread.

An influence of fuel structure on the rate of spread is visible in Fig. 1, suggesting improvements to Eq. (1). The other variables were plotted against the rate of spread residuals from Eq. (1), and added in turn to the model to examine their abilities to explain the remaining variation in fire spread (Table 4). The quantity or percentage of dead fuel presumably influences rate of spread, but because dead fuels were quantified only in a few burns, its effect will not be analyzed in this study.

Rate of spread tended to decrease with live fuel moisture content (M_l) and increase with ignition line length (L), but both variables were not significant (p>0.05) by themselves or when added to model (1). Except Lindenmuth and Davis (1973) in oak

Table 3
Correlation matrix between the variables with a significant effect on rate of fire spread[a,b]

	U	M_d	h	W_f	W_t	% Fine	ρ_{pf}
U	1	−0.12	−0.00	−0.09	0.00	−0.02	−0.03
M_d		1	−0.11	−0.07	−0.09	0.22	0.19
h			1	0.93^{***}	0.96^{***}	-0.90^{***}	-0.74^{***}
W_f				1	0.98^{***}	-0.86^{***}	-0.54^{**}
W_t					1	-0.90^{***}	-0.60^{***}
% Fine						1	0.71^{***}
ρ_{pf}							1

[a] Correlations significant at the 5, 1 and 0.1% levels are expressed by *, ** and ***, respectively.

[b] See Tables 1 and 2 for the explanation of the symbols for the variables.

Table 4
Significance of adding different variables to the model with wind speed and elevated dead fuel moisture content as rate of fire spread predictors[a,b]

Variable	p-value
L	0.3755
Vegetation cover	0.1053
h	0.0067^{**}
W_f	0.0227^{*}
W_t	0.0136^{*}
% Fine	0.0004^{***}
ρ_{pf}	0.0025^{**}
ρ_{pt}	0.7480
M_l	0.2623

[a] Significant effects on fire rate of spread at the 5, 1 and 0.1% levels are expressed by *, ** and ***, respectively.

[b] See Tables 1 and 2 for the explanation of the symbols for the variables.

chaparral, the effect of live moisture content on spread rate has never been identified experimentally as being significant, presumably because this parameter varies in a relatively narrow range when compared to other factors. The effect of ignition line length is obvious in grassland (Cheney and Gould, 1995) but has not been confirmed in shrub fuel types (Marsden-Smedley and Catchpole, 1995; Catchpole et al., 1998a). Mild burning conditions, like in this data set, can mask the effect of fire width on rate of spread (McAlpine and Wakimoto, 1991; Cheney and Gould, 1997).

Fine fuel % had an unexpected counter effect on the rate of fire spread, probably because shrub stands with higher proportions of >6 mm fuels tend to be more aged, and thus more flammable due to increased fuel availability and better conditions for heat transfer. In fact, highly significant ($p<0.001$) relationships were found between the % of fine fuel and the other fuel-complex descriptors (Table 3).

Vegetation height, fuel loadings and fine fuel bulk density were all capable of explaining part of the variation that remained on spread rate after fitting model (1) (Table 4), and were uncorrelated with wind speed ($p>0.633$) and elevated dead fuel moisture content ($p>0.318$) (Table 3). These fuel variables, however, were strongly correlated with each other ($p<0.002$) (Table 3) and this lack of independence means that their individual effects on fire behaviour are confounded. Preference for inclusion in the model was given to vegetation height, since it was the only fuel-complex characteristic that was measured in all the fires:

$$R = aU^b \exp(-cM_d)h^d \quad (R^2 = 0.86) \tag{2}$$

Estimated parameters are $a=1.764$ (S.E.=0.705), $b=1.034$ (S.E.=0.137), $c=0.062$ (S.E.=0.011) and $d=0.816$ (S.E.=0.131). The above model predicts no fire spread when wind speed is 0, which is of minor importance from the management viewpoint. Nevertheless, a model integrating an exponential function in wind speed was fitted

$$R = a\exp(bU)\exp(-cM_d)h^d \quad (R^2 = 0.91) \tag{3}$$

with $a=7.255$ (S.E.=1.262), $b=0.092$ (S.E.=0.008), $c=0.067$ (S.E.=0.009) and $d=0.932$ (S.E.=0.115). Eq. (3) is better adjusted to data than Eq. (2) and its predictions are plotted versus the observed spread rates in Fig. 2. The model was tested against Cruz and Viegas (1998) data, who conducted six experimental fires in no-slope conditions in the low shrubland of central Portugal, and the results are shown overlaid in Fig. 2; predictions are good, with a tendency to overpredict, but one of the burns was carried with zero wind speed, and in two other burns, live moisture content exceeded the maximum value in this data set.

The results are in agreement with the linear or near-linear dependence of fire spread on wind speed that is mentioned by other field studies in open fuel types (e.g. Cheney et al., 1993; Marsden-Smedley and Catchpole, 1995; Catchpole et al., 1998a). The moisture damping coefficients fall midway between the −0.02 value obtained by Marsden-Smedley and Catchpole (1995) for buttongrass moorland, where fire propagation can be sustained at extreme levels of dead fuel moisture, and the −0.11 coefficient reported by Cheney et al. (1998) for grassland and by McCaw (1998) for mallee-heath shrubland, where fuel discontinuity seems to exacerbate the effect of fuel moisture (McCaw, 1991). However, other workers did not succeed in relating the rate of spread to dead fuel moisture (Catchpole et al., 1998a; Vega et al., 1998). When live fuels are an important fraction of the total fuel load, dead fuel moisture content has a limited influence on the overall moisture content, and consequently, it is logical to expect also a limited effect on fire spread.

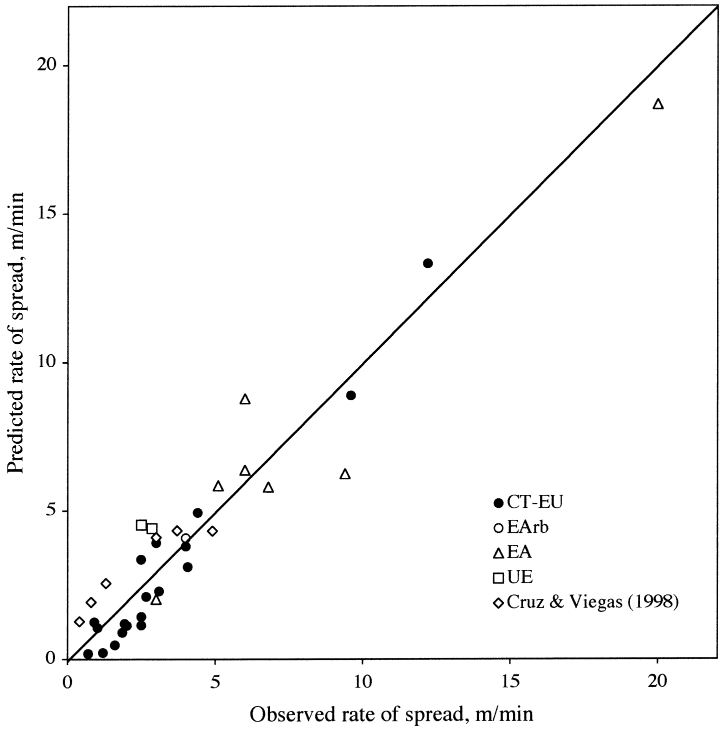

Fig. 2. Predicted vs. observed rates of fire spread from the model in wind speed, dead fuel moisture content and vegetation height (R=7.255 exp (0.092U) exp (−0.067M_d)$h^{0.932}$). Fuel types are individualized.

Existence of correlation between fuel parameters is a natural drawback of field-based fire spread modelling. Bulk density (Thomas, 1971), fuel loading (Noble et al., 1980), age (Marsden-Smedley and Catchpole, 1995) and a rating of disturbance (Cheney et al., 1998) all have been used to account for the fuel effect on fire propagation in aerated fuel beds. Vegetation height, however, is present in more models (Trabaud, 1979; Catchpole et al., 1998a; Vega et al., 1998) and is operationally appealing because it is easily assessed on-site. Fuel loading also has advantages since it can be readily linked to fuel accumulation models, fire hazard thresholds and prescribed burning prescriptions. However, there is ample experimental evidence from laboratory burns (e.g. Rothermel, 1972; Fourty, 1993; Catchpole et al., 1998b) that a porosity descriptor, such as bulk density, is the proper variable to express the fuel-complex effect on rate of spread.

Models (2) or (3) predict spread rates quite well, and the lack of correlation between the independent variables guarantees that the coefficients in the regression equations truly express the effect of the variables. Nevertheless, and given the scarce data availability for rates of spread above 6 m min^{-1}, it is not advisable to use the equations outside the low fire behaviour range. Also, even if this is not evident from Fig. 2, the equations may be biased towards the EU–CT communities, which provided more than two-thirds of the data for the modelling work.

4. Conclusions

The empirical models derived to predict rate of fire spread in Portuguese shrub stands seem robust enough to be used in prescribed burning conditions after some operational verification. The effects of wind speed, dead fuel moisture content and fuel-complex structure on the rate of fire spread were accounted for in a way similar to models derived elsewhere for other open vegetation types, but at this stage, it is not possible to point the fuel descriptor most suited to predict rate of spread. Since the selection of one or more fuel variable(s) as predictor(s) can be a troublesome task due to natural correlation between variables, practical considerations can and should be introduced in the decision process.

The effect of steep terrain has not been addressed by this study. Correction factors that were developed for forests (Noble et al., 1980, or Forestry Canada Fire Danger Group, 1992) can be used to adjust the predictions for slope, but some caution is required, since they are believed to overestimate rate of fire spread in shrubland (Catchpole et al., 1998a). A clarification of the influence of % dead fine fuel — not accounted by the equations — is also necessary, and could prove useful to discriminate between community types or the development stages of a community type.

Data analyzed in this study came from a relatively small number of fires, and it is acknowledged that the results may be biased. Considering the dangers of developing fire behaviour models for practical use without enough information and replication, more extensive experimentation is required to derive a solid predictive model for fire spread in shrubland. Future efforts should attempt to cover the broadest possible range in fuel and weather conditions in order to produce a model that responds equally well to prescribed burning and wildfire situations. Further work should also address the issues of backfire spread and critical environmental thresholds for propagation.

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