Fire behaviour and severity in a maritime pine stand under differing fuel conditions

Paulo A.M. FERNANDES*, Carlos A. LOUREIRO, Hermínio S. BOTELHO

Centro de Estudos de Gestão de Ecossistemas / UTAD, Departamento Florestal, Univ. Trás-os-Montes e Alto Douro, Quinta de Prados, 5000-911 Vila Real, Portugal

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Abstract – An experimental fire was conducted in the summer in a 28-year old maritime pine (Pinus pinaster) plantation in northeastern Portugal. Fuel conditions within the stand were age-dependent and comprised four situations: treated with prescribed fire at differing times, respectively 2, 3, and 13 years before the study, and undisturbed, where fuel accumulation time equalled stand age. The rate of fire spread did not respond to factors other than wind speed, in spite of the fuel-complex diversity. A high-intensity fire involving partially or totally the tree canopy and killing all trees was experienced in the older treatment area and in the untreated part of the stand, but the benefits of fuel management were still detectable in the former. Surface fire intensity, crown fire potential and fire severity (including tree mortality) were drastically reduced where prescribed fire had been carried recently. Fuel and fire management implications are discussed.

1. INTRODUCTION

Maritime pine (Pinus pinaster Ait.) is one of the major forest species in the southwest of Europe, both geographically and economically. As with most pine plantations [7], stands of maritime pine are unfortunately also known for their flammability and susceptibility to wildfire, in Portugal [10], Spain [38] and France [26], even if the species has traits allowing a fast reestablishment [47, 48].

Fire behaviour models offer an objective basis to evaluate, select and plan stand and fuel management practices aimed at safeguarding forest resources from high-intensity and stand-replacement wildfires. Regardless of the adopted modelling approach, field-burning trials are essential to the overall process, providing the necessary real world data to develop, validate and calibrate the models. Several studies have explicitly addressed the behaviour of low to moderate-intensity fires in maritime pine stands [12, 25, 30, 65], frequently in the frame of prescribed burning research. However, quantitative documentation on the characteristics of high-intensity wild or experimental fires in maritime pine is absent from the European literature, and is limited to Australasian sources [9, 16, 17, 40, 44, 57]. Furthermore, well-documented cases of conifer crown fire behaviour are scarce in the USA [56], and high-quality crown fire data is almost restricted to Canadian boreal forest types [8, 58, 59, 61].

* Corresponding author: pfern@utad.pt
Fuel management is expected to diminish the extent of wild- 
fires and their damage, mainly by lessening fire intensity and 
increasing the efficiency of fire suppression, even if the exact 
role of fuel characteristics in fire behaviour remains unclear, 
especially in a severe weather environment, e.g. [36]. This 
assumption is soundly supported by theory, common sense and 
informal observation, which might explain the surprising paucity 
of studies examining the subject in a scientific context with 
field data, by looking at fire behaviour and severity differences 
between adjacent treated and untreated forest stands [31, 45].

This paper describes the behaviour and severity of an exper- 
imental summer fire conducted in the frame of a cooperative 
European Union project in a maritime pine (Pinus pinaster) 
stand in northern Portugal comprising various fuel conditions. 
A study of this type is a unique opportunity that serves the dual 
purpose of obtaining high-intensity fire data in an experimental 
setting for validation purposes, and comparing the characteristics 
and effects of a fire propagating under dissimilar fuel influ- 
ences, thus offering potential insights into the issue of fuel man-
agement effectiveness.

2. MATERIALS AND METHODS

Most of the maritime pine (Pinus pinaster Ait.) plantations in the 
Padrela upland of northeastern Portugal experienced a 3000 ha stand-
replacement wildfire in the summer of 1998. Within the wildfire 
perimeter, one unburned 1-ha patch (roughly 200 × 50 m) in communal 
land under Forestry Service management was the elected experimental 
burning site, at 41° 27’ N, 07° 30’ W and an elevation of 970 m. Mean 
national rainfall and air temperature in the Padrela region are 1000 mm 
and 12 °C, respectively [3].

Selection of the experimental site was primarily motivated by the 
existence of four distinct and contiguous fuel situations, but also by 
its relatively level ground (thus removing the effect of terrain slope 
on fire behaviour), easy access to fire crews, and isolation from other 
forest stands. Prior fuel management actions had not been undertaken 
in the undisturbed (U) portion of the stand, where the time of fuel accu-
ulation equalled stand age, i.e. 28 years. The remaining area could 
be divided in three different zones (RX13, RX3, RX2) which had been 
subjected, respectively 13, 3 and 2 years before, to low-intensity 
experimental fires [11, 30] that mimicked prescribed burning opera-
tions for fuel hazard reduction: part of the RX2 and RX3 area was 
burned twice, since it also had prescribed fire 13 years before this 
study.

One 25 × 25 m plot was located per fuel condition (Fig. 1). Plots 
RX13 and U were contiguous and their demarcation was guided by 
physical evidence of the previous fire boundaries, i.e. the presence of 
charred tree boles, thus minimizing the edge effect on fire character-
istics. Visual references to assist the quantification of fire behaviour 
were provided by 2-m height poles with 0.5-m increments, placed on 
each plot at 5-m intervals along the longitudinal axis of the stand, the 
anticipated direction of fire propagation. All trees within each plot 
boundaries were measured in diameter at breast height (1.3 m), height, 
live crown base height (CBH), and crown diameter.

Quantitative description of the fuel-complex resorted to non-
destructive procedures. Litter depth (to the nearest mm) was measured 
at 40 random points per plot, separating the loose, freshly cast needles 
(L layer) from the underlying and more compact fertilization horizon 
(F layer). Shrubs Erica umbellata Loefl. and Chamaespartium triden-
tatum (L.) P. Gibbs, typical of Mediterranean-type heathland of the 
Ericion umbellatae Loefl. alliance [49], dominated the understorey 
vegetation. Ground coverage of this shrub layer was assessed with the 

Figure 1. Fuel condition map in the study stand, plot layout and loca-
tion of the video cameras.
3. RESULTS AND DISCUSSION

3.1. Fire environment

Differences in tree morphology between plots are not relevant (Tab. I), but a wider gap between tree canopy and the ground is apparent in plots RX2 and RX3, due to the defoliation imposed by the recent fire treatments on the lower branches. Canopy fuel load and bulk density are higher where tree density is higher, but the differences between plots are sufficiently small to be irrelevant as a source of crown fire hazard variation [62]. All CBD values are well above the tentative threshold of 0.10 kg·m⁻³ required to sustain the spread of an active crown fire [1, 23].

The characteristics of the surface fuel complex were highly variable over the experimental area. The plots without previous surface fuel management (U) and where prescribed fire had been carried 13 years before (RX13) exhibited a low and aerated, relatively continuous shrub stratum and notorious litter accumulation. In contrast, plots RX2 and RX3 had sparse shrubs and a litter layer that was thinner by 2/3 to 1/2. Plots U and RX13 were statistically different (p < 0.05) from RX2 and RX3 regarding all the examined fuel descriptors, whereas U and RX13 were significantly different from each other in litter thickness but not in shrub height and cover.
The experimental burn took place on the 16th July of 2002 under a Fire Weather Index [63] value of 40, i.e. fire danger rated Very High [67], and on-site attendance by fire fighting crews was naturally required. The average and extreme observations collected by the weather station during the period (16:08–16:35) of fire propagation inside the study plots are reported in Table II, which also includes fuel moisture contents. Air temperature and relative humidity (the minimum daily value was attained during the burn) were reasonably constant, contrarily to wind speed. Dead fuels were very dry, but the live fuel moisture status was just slightly below the spring maximums indicated by a previous study [27] conducted in the region.

### 3.2. Fire behaviour and severity

Table III quantifies fire behaviour in the different plots. Ground slope along the fire propagation axis was 0–5% throughout the stand, thus implying a wind and fuel-driven variation in fire behaviour. The fire was generally slow moving, undoubtedly because of the prevailing weak winds. It must be noted that 2-m wind speeds inside the stand, as measured by the fire observers, were three to five times lower than the concurrent winds measured by the weather station.

The most striking discrepancies in fire characteristics between plots are related to flame size and type of fire, i.e., surface or crown fire. Flame length and fire intensity increased with surface fuel accumulation. Three fire behaviour levels can be distinguished, respectively: (i) a surface fire of low (RX2) to moderate (RX3) intensity, with flames never exceeding 3 m in height; (ii) an intense surface fire with crowning periods (RX13); and (iii), a relatively continuous wall of flames involving both the surface and the tree canopy layers in plot U. Short-distance (5–15 m) spotting was observed in RX13 and U, demanding suppression efforts to be taken in the shrubland that bordered the stand.

According to the crown fire classification of Van Wagner [62], the observed fire behaviour level (ii) is readily qualified as a passive crown fire. The horizontal wind strength was unable to overcome the fire’s buoyancy in the RX13 plot, and the fire front advance was apparently restrained by indrafts, an inference drawn from the upright flame position that prevailed most of the time. Tree torching always succeeded the surface fire and usually occurred during periods of higher wind velocity, when fire intensity and flame depth increased. Because of wind, convective heat transfer to the canopy attains its peak before radiative heat transfer does [24]. Convection from a surface fire might be insufficient to initiate crowning, but the ignition temperature required for vertical fire development can still be attained if the radiative heat flux that follows the passage of the main flame front is strong enough.

Fire behaviour level (iii) does not fully concern to the definition of an active crown fire, because the surface and crown components of the fire rarely moved together as a linked unit and the crown fire phase lagged behind the surface fire in most instances; this is why a distinction is made in Table III between surface and crown flame lengths. Active crown fires typically display flame extensions above the canopy in the order of half

### Table II. Mean and range in fire weather descriptors and mean fuel moisture contents.

<table>
<thead>
<tr>
<th>Weather</th>
<th>Mean (Range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>29 (29–30)</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>25 (24–27)</td>
</tr>
<tr>
<td>Open 2-m wind speed (km·h⁻¹)</td>
<td>12 (1–19)</td>
</tr>
<tr>
<td>1-min. max. values</td>
<td>17 (10–27)</td>
</tr>
</tbody>
</table>

| Fine fuel moisture (%)         |                      |
| L-layer litter                 | 3.4                   |
| F-layer litter                 | 7.3                   |
| Shrubs, dead fuel              | 4.8                   |
| Shrubs, < 3 mm live fuel       | 90.8                  |
| Chamaespartium tridentatum     | 104.4                 |
| Erica umbellata                | 90.8                  |
| Shrubs, 3–6 mm live fuel       | 64.5                  |
| Pinus pinaster live needles    | 116.5                 |

### Table III. Fire behaviour description in the study plots (mean ± standard error, range in brackets).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Plot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>U (n = 7)</td>
</tr>
<tr>
<td>R (m·min⁻¹)</td>
<td>3.6 ± 0.6 a</td>
</tr>
<tr>
<td></td>
<td>(2.4–6.7)</td>
</tr>
<tr>
<td>Lₕ (m)</td>
<td>5.4 ± 0.4 a</td>
</tr>
<tr>
<td></td>
<td>(4.0–6.9)</td>
</tr>
<tr>
<td>Iₕ (kW·m⁻¹)</td>
<td>4925</td>
</tr>
<tr>
<td>Lₐ (m)</td>
<td>13.6 ± 1.8 a</td>
</tr>
<tr>
<td></td>
<td>(9.1–23.3)</td>
</tr>
<tr>
<td>Crown fire %</td>
<td>100 ± 0 a</td>
</tr>
</tbody>
</table>

R = rate of fire spread; Lₕ = surface fire flame length; Iₕ = surface fire intensity; Lₐ = crown fire flame length. Mean, standard error and observed range are provided for plots U and RX13. Within a row, U and RX13 means followed by the same letter are not different at the 5% significance level, according to the Tukey-Kramer HSD test.
An experimental fire in a maritime pine stand

An experimental fire in a maritime pine stand to twice the stand height [7, 53], but such magnitudes were never observed, further adding to the impression that the fire did not develop to its full crowning potential anywhere in the stand. Assuming the consumption of 90% of the canopy needle mass, total fire intensity in plot U averages 5.955 kW·m⁻¹ and peaks at 11.040 kW·m⁻¹, values in the low range of the possible intensity of a crown fire [53]. Had windier conditions prevailed during the experiment and the combination of abundant and very dry fuel would presumably lead to extreme fire behaviour in plots U and RX13.

There is no doubt that fire behaviour moderation in plots RX2 and RX3 is a direct consequence of the recent fuel treatment, but to what extent is the hazard-reduction effect persistent in time? This question was addressed by a comparative fire behaviour analysis between plots U and RX13.

The one-minute interval data available for plots RX13 and U shows significant (p < 0.05) correlations between all fire behaviour descriptors, and a consistently strong and positive association between wind speed and fire characteristics (Tab. IV and Fig. 2).

Table IV. Correlation matrix between fire behaviour variables and 2-m open windspeed for the 1-min observation periods in plots U and RX13 (n = 16).

<table>
<thead>
<tr>
<th></th>
<th>R</th>
<th>Ls</th>
<th>Lc</th>
<th>Crown fire %</th>
<th>Wind speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>1</td>
<td>0.79***</td>
<td>0.68**</td>
<td>0.60*</td>
<td>0.76**</td>
</tr>
<tr>
<td>Ls</td>
<td>1</td>
<td>0.80***</td>
<td>0.76***</td>
<td>0.86***</td>
<td>0.55*</td>
</tr>
<tr>
<td>Lc</td>
<td>1</td>
<td>0.56*</td>
<td>0.55*</td>
<td>0.79***</td>
<td></td>
</tr>
<tr>
<td>Crown fire %</td>
<td>1</td>
<td>0.79***</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind speed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

Correlations significant at the 5, 1 and 0.1% levels are denoted by *, ** and *** respectively. Symbols for the variables are explained in Table III.

![Figure 2. 2-m open wind speed versus rate of fire spread and surface flame length in plots RX13 (triangles) and U (dots).](image)

Fire spread rate and surface flame length are highly correlated (Tab. IV). After describing flame length in terms of spread rate by an equation of the form y = axᵇ (with b = 0.30, r² = 0.71), the non-explained variance can be ascribed to a fuel influence, because flame length depicts fire intensity and therefore varies proportionally to rate of spread and fuel availability [18]. The mean of flame length residuals in plot U is 0.5 m higher than in plot RX13, again suggesting the existence of an actual fuel effect, albeit not statistically significant (p = 0.1367) because of the 2-m open windspeed for the 1-min observation periods in plots U and RX13 (n = 16).
of the reduced number of observations. Vega et al. [66] have observed in a controlled combustion environment that the decomposing litter of Pinus pinaster, if dry enough, burns actively in the fire front and adds to flame size. Surface fuel descriptors other than total litter depth and load are not distinguishable between plots RX13 and U, but other fuel characteristics not assessed in this study (coarse fuel loading, porosity, dead fuel percentage) are presumably different and favourable to more extreme fire behaviour in the untreated portion of the stand. The difference in fuel accumulation time is expected to generate a higher load of downed dead woody fuels in plot U, and a more flammable shrub layer, because *Erythroxylum coca*—*Chamaespartium tridentatum* communities increase in porosity as they age and are richer in dead components and lower in live moisture content [33].

The function $y = ax^b$ (with $b = 0.31$) also applies to the relationship between rate of fire spread and crown flame length, even if their association is noticeably weaker ($r^2 = 0.37$). Again, a non-significant plot effect ($p = 0.3134$) arises after accounting for the effect of spread rate, with the mean residuals of flame length being 1.6 m longer in plot U. Canopy fuel load and bulk density increase respectively by 25% and 26% in the U plot in relation to the RX13 plot (see Tab. I). Whether the increase in crown flame length in the U plot is caused by the more vigorous surface fire phase or by the denser canopy is a matter of speculation, but both factors are probably involved.

The role of fuel in fire behaviour is significant only when crown fire % is the analysis variable. A stepwise regression selects the plot ($p = 0.0002$) and wind speed ($p = 0.0107$) as the two sole determinants of crown fire % ($R^2 = 0.88$). The plot effect is dominant, since it is associated with a standardised regression coefficient ($\beta$) of 0.65, while for wind speed $\beta = 0.37$. If these two variables are removed from the analysis, the stepwise regression prefers surface flame height ($p = 0.0002$, $R^2 = 0.63$) and surface flame length ($p = 0.0007$, $R^2 = 0.57$) to rate of spread ($p = 0.0148$, $R^2 = 0.35$), which is suggestive of a fuel load effect. A probabilistic model for crown fire initiation based on a sound data basis has identified surface fuel consumption as a meaningful variable [23]. Fuel consumption was indeed different between plots RX13 and U (Tab. V) and, as mentioned before, this might have been true for fuel properties not examined in this study. Such differentiation naturally led to a distinct history of heat release rate [4] with potential implications in the development of crown fire. However, and similarly to crown flame length, the plot effect should also comprise a crown fuel component, and the results are consistent with the theory of Van Wagner [62] which relates persistent fire propagation in the canopy to higher values of foliar bulk density.

Table V displays indicators of fire severity for the four study plots. Surface fine fuels were completely consumed and total fuel removal was very high. Post-burn fuel differences between plots and the apparent higher fire severity in RX13 and U are reflections of the initial fuel presence, i.e. depth of burn is dependent on pre-burn forest floor thickness, and diameter of the residual stems is a consequence of pre-burn shrub development.

Depth of burn has been correlated or associated with soil heating by several authors [13, 14, 35, 53, 55, 60], thus making it a good indicator of belowground biological impact, with effects in the density and composition of the vegetation regenerating after the fire [42]. In view of the opposing reproductive strategies of the two dominant shrub species in the study site, *Chamaespartium tridentatum* being a vigorous sprouter and *Erythroxylum coca* an obligate seeder [46], the respective response to variations in the degree of organic soil removal can be different; which would affect their relative importance in the post-burn community. In addition, the establishment success of *Pinus pinaster* seedlings should decrease with burn depth [20].

Tree mortality in RX13 and U was total, the expected result after full crown scorch in this species or in any other pine lacking resprouting traits [39]. Approximately half of the trees were killed in the recently treated areas, but this figure should rise during the second post-fire year, as indicated by a model for fire-induced mortality in *Pinus pinaster* [11] that uses crown scorch ratio as the independent variable and predicts mortality levels of 65% and 80% for RX2 and RX3, respectively.

Variability in the fire and in tree morphology are key factors that determine the degree of tree mortality [51, 52]. Tree injury differences between plots were determined by fire behaviour, but differential damage and survival within a plot were only observed in RX2 and RX3, where fire intensity was sufficiently low to allow selective, size-determined tree mortality processes to come into play. In contrast, fire behaviour in plots RX13 and U was always above some critical threshold for tree mortality.

Fires that burn deeper into the forest floor imply not just the consumption of more fuel but also longer residence times that increase the amount of energy delivered to the soil and the resulting effects on its physical, chemical and biological properties [37]. So, and even though plots U and RX13 have both experienced a stand-replacement fire, a comparison of fire severity can still be made on the basis of the observed differences in fuel consumption in the ground, surface and tree canopy. Such distinction is relevant to the direct impact of the fire, but also to its secondary consequences on nutrient cycling and erosion potential.

### 4. CONCLUSION

A dramatic contrast was observed in fire behaviour and severity between plots that had received recent fuel management
(RX2, RX3) and plots that did not (RX13, U). However, where within plot variability was quantified (RX13 and U), wind speed had the chief role in determining the fire behaviour range, to the point of masking the possible existence of a plot effect caused by fuel complex differences. Minor wind speed increases were critical to the transition of a surface fire to a crown fire or greatly enhanced the propagation and intensity of the crown fire phase.

In the studied fuel complex – litter from a long-needled pine combined with sclerophyllous and flammable low shrubs – the fire spread rate was apparently independent of fuel characteristics. On the contrary, the difference between fire intensity in the recently treated plots and in the old-treated and unmanaged plots was obvious. The statistical analysis suggested that prescribed burning benefits in reducing fire intensity had not entirely vanished 13 years after the treatment and after understorey vegetation had regained its former importance: litter quantity was still below the undisturbed fuel situation level and the overall flammability was probably lower.

If fuel conditions are very dry but wind speeds are in the low to moderate range, like in the present study, a pruned long-needled pine stand recently prescribed burnt will not support a crown fire and will partially survive a surface fire. The resulting stand structure is hardly interesting from the strict viewpoint of forest production, but is considerably more fire-resistant, and can be managed as a shaded fuel break [2]. Fuel treatments that eliminate the shrub layer and decrease litter depth in pine stands should therefore provide an adequate level of protection to structures and people in the wildland-urban interface, facilitating fire suppression and greatly increasing its cost-effectiveness. Even though fuel management has effectiveness limitations, the ecological severity of a wildfire and the feasibility of fire fighting are undoubtedly dictated by fuel accumulation.

We have examined the characteristics and consequences of an experimental fire conducted in the wildfire season in a forest stand. It is the first attempt of this type in southern Europe, or at least the first one that it is fully documented and reported to an international audience. Although limited in the conclusions that can be drawn, this study case provides useful and objective information about the efficiency of fuel management, and can be used as a source of data to develop, test and validate fire behaviour models.

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REFERENCES


