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Original article

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

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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.

fire behaviour / fire severity / experimental fire / fuel management / *Pinus pinaster*

Résumé – Comportement et sévérité d'un feu dans un peuplement de pin maritime pour des conditions de végétation variées. Un feu expérimental a été réalisé pendant l'été dans une plantation de pin maritime (*Pinus pinaster*) âgé de 28 ans, situé au Nord-Est du Portugal. Les conditions du combustible dans le peuplement étaient dépendantes de la période d'accumulation, avec quatre situations; trois traitées avec brûlage dirigé en différents moments, respectivement 2, 3, et 13 ans avant l'étude, et une jamais traitée, où le temps d'accumulation de combustible était égal à l'âge du peuplement. Malgré la diversité des caractéristiques du combustible, la vitesse de propagation du feu n'a été influencée que par la vitesse du vent. La partie du peuplement traitée 13 ans auparavant et celle non traitée ont connu un feu d'une intensité élevée, qui a touché partiellement ou totalement le couvert arboré et tué tous les arbres, mais les effets bénéfiques du traitement furent encore décelables dans la partie brûlée antérieurement. En revanche, l'intensité du feu de surface, le potentiel à engendrer un feu de cime et la sévérité du feu (y compris la mortalité des arbres) ont été fortement réduits dans les zones où un brûlage dirigé avait été conduit récemment. Les conséquences en terme de gestion du combustible et du feu sont discutées.

comportement du feu / sévérité du feu / feu experimental / gestion du combustible / *Pinus pinaster*

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-document 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].

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Fuel management is expected to diminish the extent of wildfires 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 experimental 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 influences, thus offering potential insights into the issue of fuel management 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 annual 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 accumulation 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 operations 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 characteristics. 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 fermentation horizon (F layer). Shrubs *Erica umbellata* Loefl. and *Chamaespartium tridentatum* (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 line-interception method [19] by locating three 15-m transects on each plot. Canopies intercepted by the transects were measured in height, which was defined as the vertical distance (cm) between litter surface and the general vegetation top. A representative height was calculated for each plot as the weighted (by cover) average of the individual height measurements.

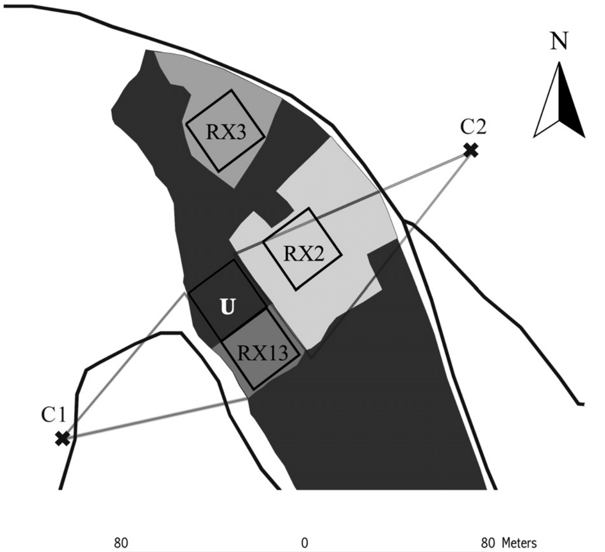

Figure 1. Fuel condition map in the study stand, plot layout and location of the video cameras.

Mean plot estimates of fuel load, i.e. fuel weight by unit area ($t \cdot ha^{-1}$), were generated for the fine fuels (diameter < 6 mm) that control fire propagation [50]. Total and upper (L-layer) litter depths were translated into weight by the use of bulk density relationships, respectively of $3.13\ t \cdot ha^{-1} \cdot cm^{-1}$ [32] and $1.84\ t \cdot ha^{-1} \cdot cm^{-1}$ [29]. For the shrub stratum we have applied site-specific bulk density values of 1.85 and $1.67\ kg \cdot m^{-3}$ [29], respectively in the RX plots and the U plot, after calculating vegetation volume ($m^3 \cdot ha^{-1}$) as the product of covered area ($m^2 \cdot ha^{-1}$) and shrub height.

Canopy base height, canopy fuel (foliage) load, and canopy bulk density are the structural properties that describe the tree layer as a fuel complex [56]. Tree-level foliage weight was estimated according to [32], using the crown length and crown width measurements taken on each tree. A fuel load figure for the plot was obtained by summing the individual trees and expressing the result on an area basis. Canopy bulk density (CBD) was calculated by dividing canopy fuel load (CFL) by the average crown length of the trees in the plot [6].

An automatic portable weather station was set up on-site, approximately 50 m up-wind the stand, so as not to be endangered or influenced by the fire, and in open terrain, given the absence of tree cover in the vicinity. Records of ambient temperature, relative humidity, and wind speed and direction were taken continuously at a 2-m height for the duration of the burn.

Fine fuel samples for moisture content determination (on a dry weight basis) were collected throughout the stand immediately before ignition, sealed, and later oven-dried at 65 °C for 48 h. Individual plots were not sampled independently because heterogeneity in the exposure to solar radiation was higher within plots than between plots. Three dead fuel categories were considered, respectively L-layer litter ($n = 5$), F-layer litter ($n = 3$), and standing dead shrub biomass ($n = 5$). One sample was taken of each of the following live fuel components: very fine (foliage and woody biomass of diameter < 3 mm) *Chamaespartium*

Table I. Descriptors of stand and fuel characteristics (mean ± standard error) by fuel condition in the study site.

Characteristics	Plot			
	U	RX13	RX3	RX2
Density (trees·ha^{-1})	2192	1480	1856	1760
DBH (cm)	12.4 ± 0.3 a	12.4 ± 0.4 a	13.4 ± 0.3 a	12.3 ± 0.4 a
H (m)	9.1 ± 0.1 a	8.5 ± 0.2 a	10.1 ± 0.2 b	9.1 ± 0.1 a
CBH (m)	4.7 ± 0.1 a	4.0 ± 0.1 b	5.4 ± 0.1 c	5.2 ± 0.1 c
CFL, t·ha^{-1}	10.56	8.45	10.85	8.57
CBD, kg·m^{-3}	0.24	0.19	0.23	0.22
Shrub cover (%)	84.9 ± 4.6 a	84.6 ± 5.5 a	21.4 ± 6.7 b	17.3 ± 1.6 b
Shrub height (m)	0.52 ± 0.03 a	0.50 ± 0.03 a	0.31 ± 0.05 b	0.30 ± 0.07 b
Litter depth (cm)	12.1 ± 0.5 a	9.1 ± 0.4 b	5.9 ± 0.2 c	5.6 ± 0.3 c
SFL (t·ha^{-1})	45.46	36.41	12.07	11.23

U = untreated; RX = prescribed burned, respectively 13, 3 and 2 years before the experimental burn. DBH = tree diameter at 1.3 m. H = tree height. CBH = crown base height. CFL = canopy fuel load. CBD = canopy bulk density. SFL = surface (shrubs and litter) fine fuel load. Means followed by the same letter within a row are not different at the 5% significance level, according to the Tukey-Kramer HSD test.

tridentatum, very fine *Erica umbellata*, shrub fuel of diameter 3–6 mm, and *Pinus pinaster* needles. The differences in sampling intensity are justified by the major role dead fuels have on fire propagation; nevertheless, each sample is made up of plant material gathered from various locations, which should compensate the minimum sampling effort that was devoted to live fuels.

Two drip-torch operators ignited a fire line along 40 m of the windward edge of the stand, which propagated freely with the wind down the length of the stand. Plot location in relation to the fire path followed the sequence RX13-U-RX2-RX3. Fire behaviour was monitored by a pair of observers on each side of the fire and walking parallel to its main direction of propagation. The observers timed (with stopwatches) the flame base arrival to reference points in order to estimate the rate of fire spread, and made visual estimates of flame height and flame tilt angle [5]. Flame height was estimated in 0.2-m and 0.5-m classes, respectively for flames shorter and taller than 2 m, and tilt angle was estimated to the nearest 5°, assigning 0° to vertical flames. Flame length was determined from these two variables by trigonometry.

We were especially interested in acquiring detailed fire behaviour data for plots RX13 and U, because of the utility of such information to assess the temporal effectiveness of fuel management. This goal was reached by using one stationary video camera on each side of the fire, placed at the centre of a field of view encompassing plots RX13 and U (see Fig. 1). Subsequent analysis of the resulting imagery, crossed with the visual observations taken near the fire, allowed spread rate measurements and mean flame characteristics estimates at 1-min. intervals. The duration of surface fire and crown fire propagation for each period was also measured, and expressed as a percentage of the observation interval.

Fire severity, the overall immediate effect of fire on the ecosystem [54], was evaluated by several descriptors. Depth of burn, the vertical extent of forest floor combustion, is a broadly used and important indicator of the downward heat pulse. The random placement of 20-cm metallic pins on each plot just before ignition allowed the subsequent assessment of burn depth. Each pin was pressed into the forest floor until its flat extremity was level with the litter top [41].

Depth of burn was measured (mm) at each pin, averaged for the plot, and converted to forest floor mass consumption with the bulk density figures previously mentioned. The reduction in shrub loading was inferred from the measurement (n = 15 on each plot) of the minimum tip diameter of the remaining branches and stems with a calliper [43]. Rate of fire spread, the estimated fuel consumption, and a standard low heat of combustion value of 18 000 kJ·kg^{-1} [34] were multiplied to yield, for each plot, the mean fire intensity, defined by Byram [18] as the rate of heat release per unit length of fire edge (kW·m^{-1}).

The fire impact on the overstorey vegetation was appraised by inspecting the plots two weeks and twelve months after the burn, respectively to measure crown scorch height, i.e. the maximum average height to which foliage is lethally damaged by fire, and to classify individual trees regarding their live or dead condition. Crown scorch ratio was calculated as the scorched proportion of total crown length, thus providing a more meaningful indication of physical damage than scorch height alone.

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.

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

Weather	
Temperature (°C)	29 (29–30)
Relative humidity (%)	25 (24–27)
Open 2-m wind speed (km·h^{-1})	
1-min. mean values	12 (1–19)
1-min. max. values	17 (10–27)
Fine fuel moisture (%)	
L-layer litter	3.4
F-layer litter	7.3
Shrubs, dead fuel	4.8
Shrubs, < 3 mm live fuel	
Chamaespartium tridentatum	104.4
Erica umbellata	90.8
Shrubs, 3–6 mm live fuel	64.5
Pinus pinaster live needles	116.5

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

Parameter	Plot			
	U (n = 7)	RX13 (n = 9)	RX3	RX2
R (m·min^{-1})	3.6 ± 0.6 a (2.4–6.7)	1.9 ± 0.5 b (0.8–5.2)	2.6	1.2
L_S (m)	5.4 ± 0.4 a (4.0–6.9)	3.8 ± 0.2 b (3.0–4.8)	2.5	1.2
I_S (kW·m^{-1})	4925	1520	931	399
L_C (m)	13.6 ± 1.8 a (9.1–23.3)	9.4 ± 0.3 b (8.0–10.2)	–	–
Crown fire %	100 ± 0 a	35 ± 7 b	0	0

R = rate of fire spread; L_S = surface fire flame length; I_S = surface fire intensity; L_C = 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.

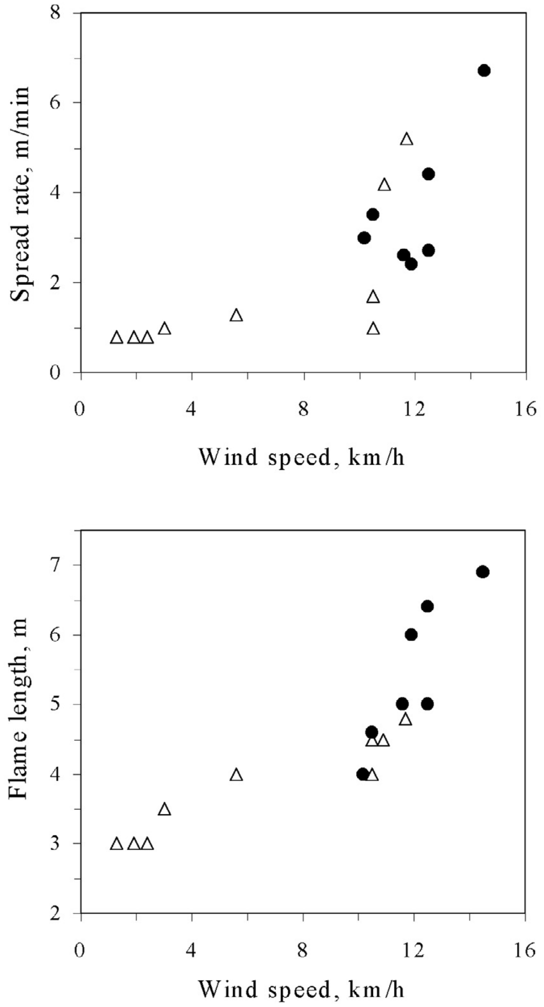

Figure 2. 2-m open wind speed versus rate of fire spread and surface flame length in plots RX13 (triangles) and U (dots).

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).

	R	L_s	L_c	Crown fire %	Wind speed
R	1	0.79***	0.68**	0.60*	0.76**
L_s		1	0.80***	0.76***	0.86***
L_c			1	0.56*	0.55*
Crown fire %				1	0.79***
Wind speed					1

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

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). Flame length and fire rate of spread increased from RX13 plot to U plot (Tab. III), but the same is true for wind speed, with significantly different mean values of 6.4 ± 1.5 km·h^{-1} and 12.0 ± 0.5 km·h^{-1}, according to the Tukey-Kramer HSD test. Overall, the best fit (r^2 = 0.71) to the observed overall variation in the spread rate as a function of wind speed is granted by a power function of the form $y = a + bx^c$ (with c = 3.8), while 74% of the variation in flame length is explained by a linear regression in wind speed. The residual variances after the wind speed effect had been accounted for cannot be explained by the plot (i.e., the fuel) effect (p = 0.6711 for spread rate and p = 0.2913 for flame length), even if on average the flame length residual variance after accounting for the plot effect is 0.4 m higher on plot U. Objectively, surface fire behaviour differences between plots U and RX13 are not recognizable as the result of distinct fuel conditions or, in other words, if a fuel effect exists it is confounded with the wind effect.

The scatterplot in Figure 2 and the coefficient c = 3.8 fitted by non-linear least squares suggests a far more pronounced wind effect on spread fire rate than what would be predicted by surface fire behaviour models [15, 21, 22, 28, 50]. Actually, this dramatic fire response to a modest increase in wind speed is the expected trend in the region of transition between surface and crown fire in conifer stands, especially in plantations with a well-defined gap between the two fuel layers. A fire is expected to alternate in a short time span between the surface fuel and the tree canopy within a certain range of the possible wind fluctuation [53]. Once a fire crowns the propagation regime is modified, with the crown phase exerting some degree of control over fire spread [34, 64]. Surface to crown transition in fire propagation should be associated, as a minimum, to a double increase in spread rate [7]. The fire front is vertically extended to the highly porous tree canopy, which hasten ignition and enhances combustion, involves more fuel thus increasing pre-heating of the adjacent unburned fuels, and indirectly modifies the wind profile.

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 $y = a\,x^b$ (with b = 0.30, r^2 = 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

Table V. Fire severity description in the study plots.

Plot	Depth of burn (cm)	Shrub terminal diameter (mm)	Crown scorch ratio	Tree mortality (%)
U	13.9	12	1.00	100
RX13	7.8	8	1.00	100
RX3	5.9	4	0.94	55
RX2	5.5	3	0.88	41

of the reduced number of observations. Vega et al. [66] have observed in a controlled combustion environment that the decomposing litter of *Pinus pinas*ter, 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 *Erica umbellata – Chamaespartium tridentatum* communities increase in porosity as they age and are richer in dead components and lower in live moisture content [33].

The function $y = a\,x^b$ (with $b = 0.31$) also applies to the relationship between rate of fire spread and crown fire 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 (β) 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 *Erica umbellata* 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 schlerophylous 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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