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Outcomes of a high-intensity experimental fire in a maritime pine stand

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Abstract

This study describes the behaviour and severity of a summer experimental fire conducted in a 28-years old maritime pine (*Pinus pinaster*) stand in northeastern Portugal where fuel conditions were diverse, and discusses the results' implications for fuel management. No evidences were found of a spread fire rate response to factors other than wind speed, i.e. to the variation in fuel structure and load. Flame dimensions, crown fire potential and tree damage were greatly reduced by prescribed fires that took place 2 and 3 years before the experiment, compared to a plot burned 13 years before and the untreated part of the stand, but fuel management benefits were still detectable in the former.

Introduction

Fuel management is expected to decrease the extent and damage caused by wildfires, mainly by decreasing fire intensity and increasing the efficacy of fire suppression. This assumption is soundly supported by theory, common sense and informal observation, which might explain the surprising scarcity of studies examining the subject in a scientific context with field data, by looking at fire behaviour and severity differences between treated and untreated forest stands (Pollet and Omi 2002, Fernandes and Botelho 2003). The role of fuel characteristics in fire behaviour, especially in a severe weather environment, is still viewed by Australian researchers (e.g., Gould et al. 2001) as unclear, in spite of an impressive body of knowledge accumulated after more than 40 years of real world fire experiments.

The E.U. Project 'FIRE STAR: a decision support system for fuel management and fire hazard reduction in Mediterranean wildland-urban interfaces' includes field burning activities whose main objective is the validation of the multiphase approach (Larini et al. 1997) to fire behaviour modelling. A summer experimental fire conducted in the frame of FIRE STAR in a maritime pine (*Pinus pinaster*) stand provided a unique opportunity to compare the characteristics and effects of a fire propagating under varying fuel conditions, thus offering potential insights into the issue of fuel management effectiveness.

Methods

This study took place in a residual maritime pine stand, an unburned 2 ha patch that escaped a 3000 ha wildfire in the Padrela upland of northeastern Portugal. Design of the experiment took advantage of four distinct fuel situations that existed in the studied stand, respectively undisturbed (U) areas, without prior fuel management actions, and where the time of fuel accumulation equalled stand age, i.e. 28 years, and areas burned 13, 3 and 2 years before by low-intensity experimental fires in the frame of prescribed burning studies (Rx plots).
A combination of line transect sampling, quadrant sampling, visual estimates and tree measurement methods were used to characterize stand and fuel structure in the plots (25 x 25 m, one per fuel condition).A grid layout was defined on each plot by means of poles placed at 5 m intervals, which were used as visual references for fire behaviour measurement. Samples for fuel moisture content determination (on an oven dry weight basis) were collected immediately before ignition.
Line ignition (50 m length) by two drip-torch operators was employed to initiate the fire. Fire observation was carried independently by two pairs of experienced observers with hand-held instruments that walked parallel to the fire front direction of propagation, measuring for each in-between poles distance the average wind speed (at an height of 2 m) and the fire travelling time, and making estimates of flame height and flame angle with the vertical.
The fire was also surveyed by two stationary video cameras. Subsequent image analysis allowed the estimation of mean fire behaviour characteristics for each minute of fire duration, including the duration of surface and crown fire propagation periods; the correspondent means for wind speed (2 m) and direction were obtained from data collected by a weather station located in open terrain approximately 50 m up-wind.
The plots were inspected immediately after the burn, two weeks later, and six months after, with the objective of assessing fire severity descriptors, respectively depth of burn in the forest floor and residual terminal diameter of the shrubs, crown scorch height, and tree mortality.

Results and Discussion

Stand and fuel structure descriptors for each plot are given in Table 1. Stand structure differences between plots are not relevant. However, tree density in plot U is higher (consequently, crown fuel bulk density CBD is also higher), and the canopy bottom is more distant from the ground in the recently prescribed burnt areas (due to crown defoliation). CBH and CBD are the two key fuel variables that respectively determine crown fire initiation and spread, according to the widely used theory of Van Wagner (1977).
Fuel-complex characteristics were considerably variable over the experimental area. The situations without previous surface fuel management (U) and where prescribed fire had been carried 13 years ago (Rx13) exhibited a low and aerated, relatively continuous shrub stratum with a high percentage of dead fuel, and significant litter accumulation. Shrubs were sparse and greener, and total litter depth was 2/3 to 1/2 lower in the recently burnt areas. Plots U and Rx13 were statistically differentiated ($p<0.05$) by the thickness of the decomposing litter layer.
Fire danger for the day of the experimental fire (16 July, 2002) rated Very High (FWI=40), naturally requiring attendance by fire fighters. Wildfire area in Portugal

during the week of the fire was ca. 17.000 ha, approximately 15% of the year's total. Table 2 displays average values of weather descriptors during the fire.

Table 1. Structural and fuel descriptors (mean ± s.e.) for the maritime pine stand by fuel condition.

Characteristic	Plot			
	U	Rx13	Rx3	Rx2
Tree density, n 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
G, m^2 ha^{-1}	27.8	19.5	28.0	22.8
CFL, t ha^{-1}	11.874	8.997	12.027	8.091
CBD, kg m^{-3}	0.270	0.200	0.256	0.207
Shrubs				
Cover, %	84.9±4.6 a	84.6±5.5 a	21.4±6.7 b	17.3±1.6 b
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				
Upper (L layer)	2.9±0.1 a	2.8±0.1 a	2.8±0.1 a	2.1±0.1 b
Lower (F layer)	9.2±0.4 a	6.3±0.3 b	3.1±0.2 c	3.4±0.2 c
SFL, t ha^{-1}	23.3	19.7	8.9	8.2

U=untreated; Rx=prescribed burnt, respectively 13, 3 and 2 years before the experimental burn. DBH = tree diameter at 1.3 m. H = tree height. CBH = crown base height. G = basal area. CFL = crown fuel (needles) load. CBD = crown fuel (needles) bulk density. SFL = surface (shrubs and litter) fine fuel load.

Within a row, means followed by the same letter are not different at the 5% significance level, according to the Tukey-Kramer HSD test.

Table 2. Mean values for the fire weather descriptors and fuel moisture contents.

Weather	
Temperature, °C	29.4
Relative humidity, %	24.8
Wind speed at 2 m, km h^{-1}	12.1
Dead fuel moisture, %	
Surface dead fuels <25 mm	4
Lower litter	7
Humus	26
Live fuel moisture, %	
Shrubs <3 mm	101
Shrubs 3-6 mm	65
Pinus pinaster needles	117

Dead fuels were quite dry, but mean wind speed inside the stand can be considered low (around 4 km hr^{-1}, i.e. one third of the value measured by the weather station). Elevated and surface dead fuels were homogeneous in moisture content (4%), regardless of their position or size class. Drought conditions were just moderate (a rainfall of 19 mm was recorded 6 days before, with a total amount of 69 mm during the month that preceded

the fire), but live fuel moisture contents were already lower than the values usually measured in spring.
The fire was conducted approximately between 16:00 and 16:30, within the period of the day previously determined to have the highest wind speeds (15:30 and 17:30) and matched the minimum relative humidity value for the day.
Table 3 quantifies fire behaviour in the different plots. Ground slope in the direction of fire propagation was 0-5% throughout the stand. So, the observed fire behaviour range was controlled by wind and fuel variation. The most apparent differences between plots were related to flame size and type of fire, i.e., surface or crown fire. Three fire behaviour levels were observed; respectively i) surface fire of low to moderate intensity (Rx2, Rx3), with flames never exceeding 3 m in height, ii) intense surface fire with crowning periods (Rx13), and iii) a solid wall of flames (up to 15 m height) involving both the surface and the tree layer in plot U, i.e. a passive crown fire (Van Wagner 1977) where the crown phase of the fire never leaned ahead of the surface phase and had a tendency to lag behind it. Short-distance (5-15 m) spotting occurred with frequency in plots Rx13 and U requiring suppression efforts in the shrubland bordering the stand.

Table 3. Fire behaviour description in the study plots.

Plot	Spread rate, m/min	Surface fire flame length, m	Crown fire flame length, m	Crown fire %	Spotting
U	3.6	5.4	13.6	100	yes
Rx13	1.9	3.8	8.7	35	yes
Rx3	5.4	2.5	-	0	no
Rx2	1.2	1.2	-	0	no

There's no doubt that fire behaviour moderation in plots Rx2 and Rx3 is a direct consequence of the recent fuel treatment. However, what is the temporal persistence of such effect? This question was addressed by a comparative fire behaviour analysis between plots U and Rx13. The one minute interval data (n=16) shows that flame length and fire rate of spread are significantly ($p<0.05$) different between plots U and Rx13, but also that these fire behaviour descriptors are positively correlated with wind speed, which explains 74% and 71% of their variation, respectively and by fitting a linear regression and an exponential function. The residual variance after the wind speed effect had been accounted for could not be explained by the plot (i.e., the fuel) effect, which means the surface fire behaviour difference between plots U and Rx 13 cannot be attributed to differing fuel conditions. If a fuel effect exists, it is confounded with the wind effect.
Fire spread rate and surface flame length are heavily correlated ($R=0.79$, $p<0.001$). However, after adjusting to flame length a function in rate of spread, the mean residual flame length is 0.5 m higher in plot U than in plot Rx13, suggesting the existence of an actual fuel effect on that variable, albeit not statistically significant ($p>0.05$) because of the reduced number of observations. This slight difference could prevent the transition to a crown fire in stands with a higher canopy base. The same procedure, applied to crown fire flame length ($R=0.70$, $p=0.0025$), reveals also a non-significant plot effect, flames being 1.7 m longer in plot U, where CBD and CFL were higher.
In plot Rx13 the fire was mainly plume-driven, since the horizontal wind strength was unable to overcome the fire's buoyancy; the fire front advance was apparently restrained

by indrafts, an inference drawn from the upright position of the flames that prevailed most of the time. Tree torching always happened after the passage of the surface fire and usually during periods of higher wind velocity. In fact, 63% of the variation observed in crown fire % in plots Rx13 and U is explained by wind speed, but the plot adds a significant explanation of 25%. Since surface fuel structure descriptors are not distinguishable between these plots, total litter load and other fuel variables (not assessed by the study) might be involved: it's reasonable to anticipate a higher load of downed dead woody fuels in the untreated stand, and its aged shrubs are expected to be more aerated, lower in moisture content and richer in dead components (Fernandes and Rego 1998).

Table 4 displays the indicators of fire severity. Surface fine fuels were completely consumed and total fuel removal was very high. Differences between plots in the post-burn fuel-complex are a reflection of initial fuel presence, i.e. depth of burn is dependent of pre-burn forest floor depth, and diameter of the residual stems is a consequence of pre-burn shrub development. Differences between plots concerning the indicators of fire severity on the overstory vegetation were determined by fire behaviour, but differential fire damage and survival within a plot was important in plot Rx2 only, because the magnitude of fire behaviour was sufficiently low to allow selective and size-determined tree mortality.

Table 4. Fire severity description in the study plots.

Plot	Depth of burn, cm	Shrub terminal diameter, mm	Scorch height / tree height	Tree mortality, %
U	13.9	12	1	100
Rx13	7.8	8	1	> 95
Rx3	5.9	4	0.94	90
Rx2	5.6	3	0.88	30

Conclusion

This study concerned an experimental fire conducted in the wildfire season in a forest stand where fuel conditions were diverse, and consequently a remarkable fire behaviour range was exhibited. It is the first attempt of this type in Europe, or at least the first fully documented and reported to an international audience.

The critical importance of wind speed in fire behaviour is well known, but when dead fuels are very dry, like in this experiment, the fire response to wind variation will be even more dramatic. Consequently, wind speed will condition to a great extent the impact of fuel management on a propagating wildfire. In this fuel-complex – litter from a long-needled pine combined with schlerophylous and flammable shrubs – fuel accumulation and structure did not affect the rate of fire spread. Flame dimensions (an expression of fire intensity) were obviously different between the recently treated plots and the old-treated and untreated plots. The benefits of a prescribed fire – a decrease of crown fire likelihood, and a slight decrease of surface fire intensity – were still visible after surface fine fuels in plot Rx13 had regained the pre-treatment level (i.e., the plot U level), possibly reflecting a longer lasting treatment effect on the overall fuel structure and moisture.If fuel conditions are very dry but wind speeds are in the low to moderate range (and slope is absent), a long-needled pine stand recently (say, up to 3 years)

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prescribed burnt will not support a crown fire and will partially survive a surface fire. Fuel treatments that eliminate the shrub layer and decrease litter depth in pine stands should provide an adequate level of protection to structures and people in the wildland-urban interface, facilitating fire suppression and greatly increasing its cost-effectiveness.

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