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# Fire-severity mitigation by prescribed burning assessed from fire-treatment encounters in maritime pine stands

Juncal Espinosa, Pedro Palheiro, Carlos Loureiro, Davide Ascoli, Assunta Esposito, and Paulo M. Fernandes



**Abstract:** Maritime pine (*Pinus pinaster* Ait.) stands are prone to high-intensity fire. Fuel treatments lessen potential fire behaviour and severity, but evidence of their effectiveness when tested by wildfire is extremely scarce in Europe. We assess the longevity of prescribed burning in maritime pine plantations in decreasing fire severity. Heights of crown scorch and stem-bark char were measured in treated and untreated adjacent areas after fire-treatment encounters in Portugal, Italy, and Australia. Treatment effect was quantified as the log-transformed ratio between prescribed-burned and untreated fire-severity data. Linear mixed modelling indicated that for typical wildfire conditions, the effect of prescribed burning in crown scorch height lasts 2–6 years. The persistence of prescribed burning benefits is higher for fire control operations than for fire-severity mitigation. Regression tree analysis of data from one wildfire highlighted the roles of wind direction, topography, and stand height in explaining variability in fire severity. A 4-year interval between prescribed burning treatments in maritime pine stands is recommended in general, depending on site quality and stand age and structure. Improved fuel-consumption prescriptions and monitoring procedures are advisable to foster prescribed-burning effectiveness and its evaluation.

*Key words:* fuel treatment effectiveness, fire behaviour, fire management.

**Résumé :** Les peuplements de pin maritime (*Pinus pinastri* Ait.) sont sujets à des feux de forte intensité. Les traitements des combustibles atténuent le comportement et la sévérité potentiels du feu mais la preuve de leur efficacité à la suite de feux de forêt est extrêmement mince en Europe. Nous évaluons la durée de l'effet du brûlage dirigé pour réduire la sévérité du feu dans des plantations de pin maritime. La hauteur du roussissement dans les cimes et de la carbonisation de l'écorce sur le tronc a été mesurée dans des zones traitées et non traitées adjacentes après le passage d'incendies dans des zones traitées au Portugal, en Italie et en Australie. L'effet du traitement a été quantifié au moyen du logarithme du rapport entre les données de sévérité du feu avec et sans brûlage dirigé. Un modèle linéaire mixte a indiqué que dans des conditions typiques de feu de forêt, l'effet d'un brûlage dirigé caractérisé par la hauteur du roussissement dans les cimes dure 2 à 6 ans. La persistance des bénéfices d'un brûlage dirigé est plus longue lorsqu'on considère les opérations de lutte contre le feu plutôt que l'atténuation de la sévérité du feu. L'analyse des données provenant d'un feu de forêt au moyen d'un arbre de régression a fait ressortir les rôles de la direction du vent, de la topographie et de la hauteur du peuplement pour expliquer la variabilité de la sévérité du feu. En général, on recommande un intervalle de 4 ans entre les brûlages dirigés dans les peuplements de pin maritime dépendemment de la qualité de la station ainsi que de la structure et de l'âge du peuplement. L'amélioration des prescriptions de consommation des combustibles et l'adoption de procédures de suivi sont souhaitables pour favoriser l'efficacité du brûlage dirigé et son évaluation. [Traduit par la Rédaction]

*Mots-clés :* efficacité du traitement des combustibles, comportement du feu, gestion du feu.

## 1. Introduction

Maritime pine (*Pinus pinaster* Ait.) is a major western Mediterranean Basin conifer, and its plantations are flammable and prone to high-intensity fire owing to the nature, quantity, and structural arrangement of fuels (Burrows et al. 2000; Fernandes and Rigolot 2007; Jiménez et al. 2016). In fact, conifer plantations often result in rapid fuel buildup and homogeneous fuel structures requiring fire-hazard reduction treatments (Keyes and O'Hara 2002; Cruz et al. 2017; Zald and Dunn 2018). Changing the structure and reducing the amount of forest fuels through treatments such as prescribed underburning and mechanical thinning is expected to moderate subsequent wildfire behaviour and mitigate its impacts (Graham et al. 2004; Fernandes 2015; Cruz et al. 2017). Whether or not a fuel treatment is effective when challenged by wildfire is a function of several factors, both treatment-related (type, intensity,

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**J. Espinosa.** INIA, Forest Research Centre, Department of Silviculture and Forest Management, Forest Fire Laboratory, Ctra. Coruña Km 7.5, 28040 Madrid, Spain.
**P. Palheiro.*** Gestão Integrada e Fomento Florestal Lda. Rua D. João Ribeiro Gaio, 9B – 1E, 4480-811 Vila do Conde, Portugal.
**C. Loureiro and P.M. Fernandes.** Centre for the Research and Technology of Agro-Environmental and Biological Sciences, University of Trás-os-Montes e Alto Douro, Apartado 1013, 5001-801 Vila Real, Portugal.
**D. Ascoli.** Dipartimento of Agricultural Sciencies, Università di Napoli Federico II, via Università 100, 80055 Portici, Italy.
**A. Esposito.** Department of Environmental Biological and Pharmaceutical Sciences and Technologies, University of Campania "Luigi Vanvitelli", Via Vivaldi 43, 81100 Caserta, Italy.
**Corresponding author:** Paulo M. Fernandes (email: pfern@utad.pt).
*Present address: Parks and Wildlife Service, Department of Biodiversity, Conservation and Attractions, P.O. Box 835, Karratha, Western Australia 6714, Australia.



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spatial patterns, time since application) and contextual (vegetation type, fire weather, terrain conditions, and fire-suppression capability) (Cochrane et al. 2012).

Prescribed burning (PB) removes fuels beneath the forest canopy and thus reduces potential wildfire intensity and severity (Agee and Skinner 2005). The interaction between fuel and weather conditions determines to what extent and for how long PB is effective in reducing fire growth and fire severity or assisting with fire-suppression operations (Fernandes 2015). The hazard reduction effectiveness of PB is then dependent on its initial impact and on fuel recovery rate, which define the longevity of the effect (e.g., McCaw et al. 2012).

PB to reduce fire hazard has been practiced in southern European pine forests since the 1980s and is employed under environmental conditions reconciling satisfactory removal of litter and understory fuels with minimum tree damage and maintenance of site quality (Fernandes and Rigolot 2007). Fuel consumption and posttreatment fuel dynamics and their modelled effects on fire behaviour have been reasonably studied (Fernandes 2018). Yet, observational evidence of PB effectiveness is limited to the analysis of experimental fire behaviour in maritime pine stands in relation to fuel age, i.e., time since PB (Fernandes et al. 2004; Fernandes 2009). Additional empirical-based quantification of modified fire behaviour and severity in prescribed-burned stands is needed to improve treatment guidelines and prescriptions (Fernandes 2018), namely because of the shortcomings of fire modelling systems in this regard (Cruz et al. 2014). Unforeseen encounters between wildfires and treated areas offer opportunities to acquire valuable data, especially if fire behaviour or severity is documented in treated and untreated contiguous areas; paired observations control for the influences of dissimilar weather and terrain conditions, enabling objective assessment of PB effectiveness (Martinson and Omi 2008).

We examine the extent to which PB mitigates fire severity in maritime pine stands based on crown scorch and stem-bark char data primarily collected after wildfires in Portugal, Italy, and Australia. Specifically, we expect the PB effect to (*i*) decrease with time since treatment, (*ii*) decrease with increasingly extreme fire weather conditions, (*iii*) be affected by interactions between fire spread and topography, and (*iv*) increase with stand height.

## 2. Methods

### 2.1. Study sites and data

We used data from maritime pine stands where adjacent untreated and treated (prescribed burned) areas had been exposed to the same wildfire, presumably under very similar weather and fuel moisture content conditions, and supplementary data from experimental fires (Fernandes et al. 2004; Fernandes 2009). Eligibility criteria of wildfire sites for sampling comprised knowledge of burn date; time (months) since treatment, from forest service records; undifferentiated stand characteristics and topography within each untreated–treated pair; and the absence of potentially confounding effects, e.g., fire-suppression activity (Pollet and Omi 2002). Overall, we acquired 30 observations in the north and centre of Portugal, distributed among 10 locations involving 12 wildfires and seven experimental fires (Fig. 1). Given the limited extent of PB in pine forests in Portugal and Italy, data collection spanned from 1992 to 2017 and included all fire-treatment encounters known to the authors, either directly or communicated by forest managers. Also, PB units in pine forests in Portugal are typically small and do not form large patches, which restricts fire-treatment overlaps and the number of potential sample locations within a given fire. Each observation was defined by a fire × location within fire × time since PB combination. Additionally, we collected data in the Vesuvio National Park, Italy, using the same criteria and used data from the Gnangara plantation in Western Australia (Burrows et al. 2000), structurally similar to Portuguese coastal stands.

Data collection was plot-based, with some variation in plot size (100–600 $m^2$) and shape (circular, quadrangular, rectangular) and equal sampling effort ($n$ = 1–4) among pairs of treated and untreated areas at each observation site. Fire severity in the PB area would often decrease with increasing distance from the treatment edge, as found by others (Safford et al. 2012). The PB plots were thus established immediately after crown scorch height stabilized and the edge effect was no longer discernible. Nonetheless, plots were usually located within 100 m of either side of the untreated–treated boundary.

The Cepões wildfire near Viseu burned 3074 ha under the most extreme weather conditions in our sample. Four fuel ages, respectively, 2, 3, 4, and 5 years since PB, were available at two distinct locations within the wildfire perimeter. This provided an opportunity to further examine variability in fire severity through a different sampling scheme. Plots ($n$ = 30, each comprising a group of five trees) were located as a function of combinations between fuel age, slope position (lower or upper half), fire spread direction (upslope or downslope), and whether the location was burned by the heading, flanking, or backing sections of the fire.

As fire-severity metrics, we measured crown scorch height ($h_s$) and maximum (lee-side) stem-bark char height ($h_c$) to the nearest 0.1 m on each individual tree within a plot. We did not distinguish between crown scorch and crown combustion, hence burned trees were equated to fully scorched trees.

Fire weather conditions for the day that the study sites burned were generically described through the Fire Weather Index (FWI) of the Canadian Forest Fire Weather Index System (Van Wagner 1987), the fire danger rating system adopted in Portugal, using data from the nearest (usually within 50 km) weather station. The FWI for the Western Australia wildfire was obtained in Gellie (2005). The FWI is a relative numerical rating of fire-line intensity, which in turn is a major determinant of $h_s$ (Van Wagner 1973).

### 2.2. Data analysis

Tree fire-severity metrics $h_s$ and $h_c$ were averaged by plot, and the former was divided by stand height to obtain the scorch height ratio (SHR). Inclusion of completely scorched and fully green trees can underestimate mean $h_s$ (Martinson and Omi 2008). Hence, fully scorched dominated trees did not contribute to the plot average; we estimated the potential $h_s$ of green trees as $3.83 \times h_c$, after regressing the two variables, and used the resulting values to calculate mean $h_s$. The treated and untreated values for each observation resulted from averaging the respective plot values; the 30 plots sampled within the Cepões wildfire provided six observations.

Analysis of the effect of PB on fire severity was based on the dimensionless extent of the mean difference between neighbouring untreated and treated plots. Following Martinson and Omi (2013), we adopted the log response ratio as the log-transformed ratio between the treatment mean and the control mean (Hedges et al. 1999), calculated for both $h_s$ and $h_c$. Absolute log response ratios < 0.20 indicate insignificant treatment effect (Cohen 1988). We examined whether the sizes of PB effects were related to the fire-severity descriptors. A linear mixed model was fitted to each log response ratio, with fire as the random effect. The candidate-independent models for inclusion in the model were the log-transformed time since PB (in years), to approach the levelling-off of fuel accumulation with time since fire, the FWI, and stand height, plus their interactions.

We used the Cepões individual plot data to examine PB effectiveness as affected by variations in tree size and in fire characteristics along its perimeter by applying regression tree analysis. We took $h_c$ as a fire-intensity proxy, but because crown damage depends on the relative amount of scorched crown (Peterson and Ryan 1986), we preferred SHR to $h_s$ to describe fire severity. Time since PB, slope position, fire spread direction, location on the fire

**Fig. 1.** Study sites location in Portugal and respective number of observations (map data courtesy of ©2018 Google). Numbers in parentheses indicate the number of fires, whenever it is >1. Shaded dots correspond to wildfire locations; the black dot corresponds to experimental fires (plus one wildfire observation). [Colour version available online.]




perimeter, and tree height were used as putative independent variables. Untreated plots were assigned a fuel age of 25 years, the approximate age of the stand. The splitting process inherent to regression tree analysis was carried out until the Akaiki's information criterion corrected for small samples (AICc) was minimized. The influence of each variable on SHR and $h_c$ was evaluated by its relative contribution (%) to the total amount of variability explained by the model.

## 3. Results

The available PB–untreated pairs covered a substantial range in time since PB, from 4 months to 13 years (Table 1), but 66% of the observations pertained to fuel ages < 6 years (Fig. 2). Likewise, variation in fire weather severity as represented by the FWI was wide, ranging from low (FWI < 8.4) to extreme (FWI > 38.2) as per Palheiro et al. (2006). The FWI was fairly regularly distributed but with evident gaps (Fig. 2). Stand height was normally distributed (Shapiro–Wilk $W$ test, $p > 0.05$) and <15 m for half of the observations. Variation in fire-severity metrics (both in PB and in untreated plots) was wide, but data distribution patterns varied: normal for $h_s$, left-skewed for SHR, right-skewed for $h_c$ in PB plots, and fairly homogeneous for $h_c$ in untreated plots. Full-canopy scorch occurred in 56.3% of the untreated observations but only in 9.4% of the PB observations. On average, treatments $h_s$ and $h_c$ were 81% and 44%, respectively, of the corresponding measurements in the untreated neighbouring area. This difference between fire-severity metrics translated into a PB effect size that was larger by a factor of three for $h_c$ in relation to $h_s$.

Regression analysis indicated that the mitigating effect of PB on $h_s$ decreased ($p < 0.0001$) with increasingly higher log-transformed time since PB (Ln $T$) and increased nonsignificantly ($p = 0.0936$) with higher FWI. We used FWI ≤ 23 and FWI ≥ 37, boundaries of the first important discontinuity in the FWI distribution (Fig. 2) that correspond approximately to low-to-high and to extreme fire danger (Palheiro et al. 2006), to define two FWI classes, qualified respectively, as lower and upper FWI ranges. This new variable was significant ($p = 0.0107$) in the linear mixed model when added to Ln $T$; there was a trend for the log response ratio of $h_s$ to decrease with stand height, but its inclusion in the model was not supported ($p = 0.2565$). Interactions between the independent variables were not significant. Treatment $h_c$ increased signifi-

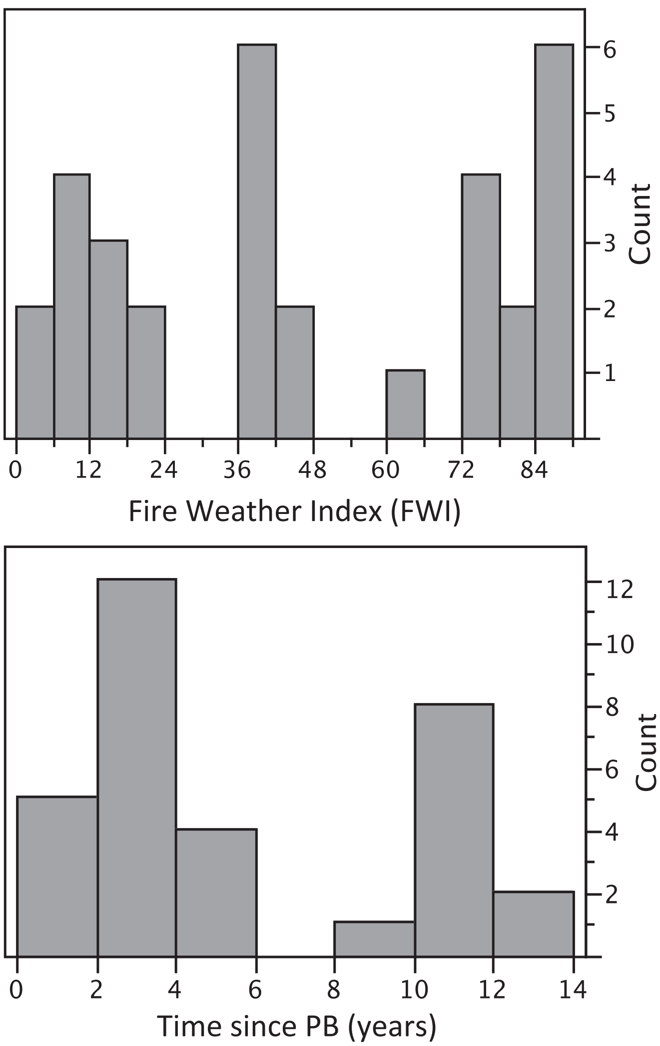
**Table 1.** Mean (range) for the (putative) determinants and descriptors of fire severity ($n$ = 32, except stem-bark char metrics, $n$ = 23).

| Variable | Units | PB treatment | Untreated |
|---|---|---|---|
| Time since PB | years | 5.4 (0.3–13) | — |
| Stand height | m | 13.3 (7.5–22.9) | |
| Fire Weather Index (FWI) | adimensional | 47 (5–87) | |
| Crown scorch height ($h_s$) | m | 10.2 (4.4–21.5) | 12.6 (5.5–21.5) |
| Stem-bark char height ($h_c$) | m | 2.9 (0.9–9.3) | 6.6 (1.2–13.6) |
| Scorch height ratio (SHR) | adimensional | 0.77 (0.26–1) | 0.93 (0.71–1) |
| PB effect, $h_s$ | adimensional | −0.23 (−1.36–0) | — |
| PB effect, $h_c$ | adimensional | −0.77 (−2.43–0) | — |

**Note:** Prescribed-burning (PB) effect is the log response ratio, i.e., the PB mean to untreated mean ratio after log transformation.



**Fig. 2.** Fire Weather Index and time since prescribed burn (PB) histograms ($n$ = 32). Count is the number of observations.




cantly with Ln $T$ ($p$ = 0.0252) but did not respond to FWI class or to stand height.

Table 2 displays the coefficients of the resulting models for the effect sizes of PB on $h_s$ and $h_c$. Predictions and confidence intervals for the models indicate that the PB effect on $h_s$ persists for 3 (2–6) and 9 (5–15) years after treatment for the upper and lower FWI ranges, respectively (Fig. 3). PB longevity in terms of $h_c$ is greater, 14 years as predicted by the fitted equation and 6 years for the worst-case (lower confidence interval boundary) scenario.

Within the Cepões wildfire, mean SHR in PB plots was lower than in the untreated plots by 9.4%. Regression tree analysis of fire severity indicated that SHR was primarily determined by fire-spread direction, averaging 0.72 and 0.87 for downslope and upslope spread, respectively (Table 3). Within the downslope partition, SHR averaged 0.66 for fuel age ≤ 5 years, i.e., in PB plots, while in untreated plots, it reached 0.82. Two major partitions were distinguished for upslope spread: fuel age < 5 years (SHR = 0.82) and fuel age ≥ 5 years (SHR = 0.91). Within the later, SHR was higher for stands lower than 14.6 m (0.96 versus 0.76).

Mean $h_c$ in the Cepões wildfire PB plots was two-thirds of the corresponding value in the untreated areas. The first splitting level was decided by fuel age, with an average $h_c$ of 3.3 m for fuel age < 5 years, and 6.8 m for fuel age ≥ 5 years. Subsequent partitions indicated lower $h_c$ in the backing and flanking sections of the fire, as well as in the lower half of the hillsides burned by the headfire, for fuel age < 5 years and lower $h_c$ for downslope fire spread for fuel age ≥ 5 years.

## 4. Discussion

### 4.1. Prescribed-burning effects on wildfire severity and treatment longevity

We found that PB decreases the impact of a subsequent fire on maritime pine overstory and that the effect declines with time since treatment. Under typical wildfire conditions, i.e., for the upper fire danger range used in the $h_s$ effect-size model, $h_s$ is reduced up to 2–6 years after PB. Fuel treatments may need to be frequent (intervals of 2–10 years) in productive ecosystems, especially if understory regeneration is fast (Stephens et al. 2012). Such is the case in this study's plantations, which are grown under a Mediterranean-type humid climate. Data from northern Florida similarly indicates that PB in pine forest avoids the impacts of high-severity wildfires for up to 5 years after treatment (Malone et al. 2011). Sackett (1975) recommended a 3-year burn interval in southeastern USA pine flatwoods.

As in other studies (Lydersen et al. 2014, 2017; Storey et al. 2016), fire-induced canopy injury increased with fire weather severity; however, fuel treatments in conifer forests can be effective even when tested by extreme fire weather (Finney et al. 2005; Safford et al. 2012; Prichard and Kennedy 2014). In our case, recent (<4 years) PB does not always warrant significant fire-severity modification in relation to the contiguous untreated stand, as 58.3% of the observations in the upper fire danger range had a log response ratio for $h_s$ higher than −0.20.

The longevity of the PB effect on potential fire behaviour and severity is dependent not only on fuel consumption but also on fuel dynamics (Fernandes 2015), which are a function of site productivity, stand density and age, decomposition rate, and understory species response to fire. In particular, posttreatment needle accretion can be a significant influence, depending on $h_s$ and canopy base height, but the effects of PB on litterfall have seldom been examined (Espinosa et al. 2018). Tools to assist in the evaluation of the immediate impacts of PB on fuels are available (Fernandes et al. 2012), but the characterization of fuel dynamics and persistence of

**Table 2.** Coefficients (standard errors) for the linear mixed models for the effects of prescribed-burning (PB) treatment on fire-severity descriptors.

| Effect variable | Intercept | Ln *T* | FWI class | $R^2$ |
|---|---|---|---|---|
| Crown scorch height ($h_s$) | −0.5783 (0.0739) | 0.2358 (0.0441) | −0.1047 (0.0406) | 0.397 |
| Stem-bark char height ($h_c$) | −1.1856 (0.2634) | 0.3620 (0.1503) | — | 0.655 |

**Note:** Ln *T* is the log-transformed time since PB.

**Fig. 3.** Predicted effects of prescribed burning (PB, years) on crown scorch height, $h_s$, as a function of time since treatment and fire weather as per Table 2. Increasingly higher PB effect (the log response ratio) implies decreased effectiveness. The dotted and dashed lines bound the 95% confidence intervals for the lower and upper fire weather index (FWI) ranges, respectively.

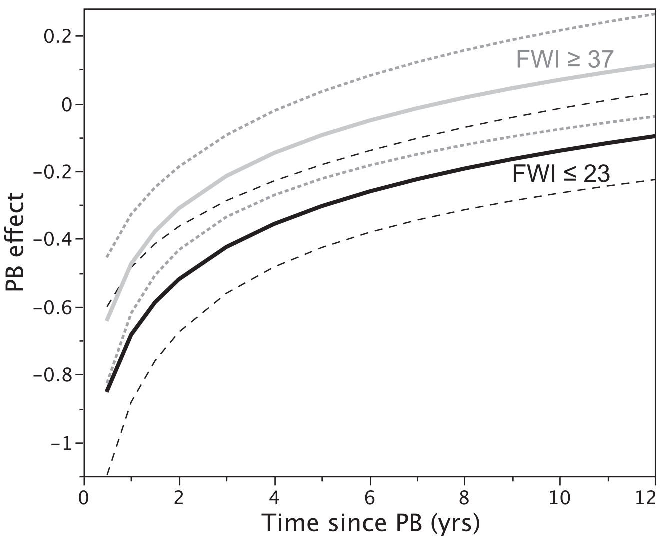



**Table 3.** Relative influences (percentage; from regression tree analysis) on fire-severity metrics for the Cepões wildfire ($n$ = 30).

| Independent variables | $h_s$ ($R^2$ = 0.431), % | $h_c$ ($R^2$ = 0.385), % |
|---|---|---|
| Time since PB | 20.1 | 49.2 |
| Fire spread direction | 42.9 | 43.6 |
| Topographic position | 5.7 | 0.4 |
| Location on the fire perimeter | — | 6.9 |
| Stand height | 31.3 | — |

**Note:** $h_s$, crown scorch height; $h_c$, stem-bark char height; PB, prescribed burn.

the hazard-reduction effect would benefit from more complete and detailed monitoring procedures (Fernandes 2018).

### 4.2. Drivers of fire severity in the Cepões wildfire

Fuel age was a minor contributor to the explanation of variation in SHR within the Cepões wildfire. Instead, fire spread pattern and stand height were the major determinants, with lower crown injury resulting from downslope spread or taller stands, as found by others (Oliveras et al. 2009; Fernandes et al. 2010; Viedma et al. 2015), and showcasing spatial variation in treatment benefits. The limited influence of fuel age variation on $h_s$, as well as the small SHR differences between downslope and upslope fire spread, may be an outcome of the particularly extreme fire weather under which the wildfire developed. Fuel age, however, was as important in determining $h_c$ as the combined influences of fire spread pattern, location on the fire perimeter, and topographic position.

Decreased fire intensity along the flanks and rear of a wildfire (Catchpole et al. 1992) is expected to reduce fire impacts. Unequal sampling did not favour detection of such effect, i.e., most of the plots (25 out of 30) were burned by the head fire. Still, $h_c$ did decrease in the backing and flanking sections of the fire.

### 4.3. Fire-severity mitigation and fire-suppression difficulty

While $h_s$ and SHR are of major interest to postfire tree survival and growth, $h_c$ is more relevant from the fire-suppression perspective. The treatment effect size was substantially higher for $h_c$ in comparison with $h_s$. As an example, $h_s$ reached 9.5 m in a 10.1 m tall stand 3 years after PB, signifying negligible treatment effect (−0.13), even though it changed a crown fire into a surface fire. The separate analysis of the Cepões fire data also supported higher PB effectiveness regarding $h_c$. Nonetheless, our findings that the effect of PB on $h_c$ persists for 14 years are likely to be inflated, because changes in fuel accumulation and structure in maritime pine stands in Portugal are usually minor beyond ~10 years after PB (Fernandes and Rigolot 2007). Small sample size, confounded effects with fire weather that the analysis could not resolve, and influences of tree diameter and wind speed on the $h_c$ – flame size relationship (Gutsell and Johnson 1996) might be implicated in the result.

Treatment benefits are thus higher and extend longer in time for fire control operations than for fire-severity mitigation. We see three motives for this difference: crown scorch extent is dependent on stand and canopy base heights; $h_s$ is mainly a function of fire intensity, but wind speed and air temperature also play a role (Van Wagner 1973); and postfrontal combustion of duff and downed woody fuels may result in additional crown damage (Alexander and Cruz 2012). Current burn prescriptions are conservative regarding duff consumption (Fernandes and Rigolot 2007), facilitating postfrontal combustion in a subsequent wildfire.

Detection of a significant PB treatment effect does not imply success in avoiding substantial pine mortality and (or) bringing fire behaviour to within control capacity. Maritime pine endures low- to moderate-intensity fire, but the expression of fire adaptation traits is variable, with prevalence of either thick bark or cone serotiny (Fernandes and Rigolot 2007). Studies of maritime pine mortality after wildfire show that the probability of mortality is >90% when crown damage exceeds two-thirds of its volume (Catry et al. 2010; Vega et al. 2011). However, those studies are with respect to wildfires in non-treated areas. Maritime pine stands thinned by consecutive short-return (<4 years) wildfire should be a better analogue of the mitigating effect of PB on tree survival (Fernandes et al. 2015). One year after the experimental summer fire used in our analysis, with crown scorch ratios of 0.94 and 0.88, tree mortality was 55% and 41%, respectively, where PB had been applied 3 and 2 years before the summer fire (Fernandes et al. 2004). Avoidance of trunk basal girdling due to the shallow forest floor in recently treated stands would explain this lower than expected pine mortality level (Burrows et al. 2000).

Objective insight on the ability of recent (2–3 years) treatments to assist with effective head fire suppression in maritime pine stands is provided by the fire behaviour data in Burrows et al. (2000) and Fernandes et al. (2004). In the former, flame heights were in the range of 1–2 m in 4 t·ha$^{-1}$ fuels in comparison with 3–10 m in heavier fuels (9–23 t·ha$^{-1}$). In the latter, a crown fire changed to a surface fire with 1.2–2.5 m flame lengths when fuel load decreased from 36–45 t·ha$^{-1}$ to 11–12 t·ha$^{-1}$. In both cases, the observed decreases are consistent with effective fire control by direct attack (Hirsch and Martell 1996). It can be argued that more severe fire weather conditions would override such effect. However, the head fire accounts for approximately one-third of the fire perimeter length at most and for 10%–50% of the area burned, and fire-line intensity varies 10-fold around the fire's perimeter

(Catchpole et al. 1992). This variation in fire-line intensity enhances the chances of containing a wildfire through direct or indirect attack along its flanks; decreased fuel loads in treated stands further expand fire control strategies and tactics, hence the opportunities for safe, fast, and effective fire suppression.

### 4.4. Limitations

This study sample included a wide range in fire weather conditions and covered a representative range in fuel load and structure in the short term to midterm after PB (Fernandes and Rigolot 2007). However, limitations are readily apparent and are inherent to the opportunistic and retrospective nature of the study. Wildfire-treatment encounters cannot be anticipated, precluding collection of data prior to and during the event. Crown scorch ratio (length of crown scorch in relation to crown length) expresses actual foliar damage and is a better indicator of tree mortality likelihood than $h_s$ and SHR (Peterson 1985), but in most cases, it could not be calculated due to lack of crown base height data. Sample size was small, as was the number of fire-severity variables and putative independent variables common to all observations.

Data analyses accounted for modest fractions of the observed variability in treatment effect size and fire-severity metrics. To some degree, this reflects the equalizing effect imposed by the severe weather conditions experienced during wildfires, exacerbated by the young age and correspondingly relatively low height of the stands (Zald and Dunn 2018). The moderate amount of explained variability is also a natural outcome of the crude metrics used to evaluate fire behaviour potential, namely time since treatment in lieu of local fuel characteristics and the FWI from a fire weather station instead of the local wind speed and fuel moisture content.

## 5. Conclusion

Fuel dynamics in flammable well-stocked conifer forests grown for timber production challenges fire-severity mitigation through surface fuel treatments. Despite the uncertainty in fuel and burning conditions inherent to its opportunistic nature, this study offers empirical insight into the effectiveness of PB areas tested by wildfire in Europe. The results highlight both the strengths and limitations of PB: respectively, maintenance of fire-intensity levels below the pretreatment situation for at least 10 years and mitigation of fire-induced canopy injury restricted to a relatively narrow period after treatment. While the former is consistent with the dynamics of fuel load and fuel structure recovery in maritime pine stands, the latter is a natural outcome of (young) stand age and (small) tree size. Consequently, PB effectiveness expectations depend on the perspective, either forest management or fire suppression.

To comply with both fire-severity mitigation and effective fire control operations, a generic interval of 4 years between consecutive treatments in maritime pine stands emerges from this study, although benefits to suppression via facilitated containment of the flanks are expected to last longer. This recommendation is adjustable depending on site productivity and stand age and structure. This also implies that lower crown-scorch levels are more likely in taller and older stands, as well as in wind-protected and moister topographic positions. Finally, avoiding marginal PB conditions that decrease fuel consumption and adopting less conservative prescriptions in relation to duff retention can increase treatment longevity. Further work would benefit from improved documentation in the frame of the PB planning and monitoring process.

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## References

Agee, J.K., and Skinner, C.N. 2005. Basic principles of forest fuel reduction treatments. For. Ecol. Manage. **211**: 83–96. doi:10.1016/j.foreco.2005.01.034.

Alexander, M.E., and Cruz, M.G. 2012. Interdependencies between flame length and fireline intensity in predicting crown fire initiation and crown scorch height. Int. J. Wildland Fire, **21**: 95–113. doi:10.1071/WF11001.

Burrows, N., Ward, B., and Robinson, A. 2000. Behaviour and some impacts of a large wildfire in the Gnangara maritime pine (*Pinus pinaster*) plantation, Western Australia. CALMScience, **3**: 251–260.

Catchpole, E.A., Alexander, M.E., and Gill, A.M. 1992. Elliptical-fire perimeter- and area-intensity distributions. Can. J. For. Res. **22**(7): 968–972. doi:10.1139/x92-129.

Catry, F.X., Rego, F., Moreira, F., Fernandes, P.M., and Pausas, J.G. 2010. Post-fire tree mortality in mixed forests of central Portugal. For. Ecol. Manage. **260**: 1184–1192. doi:10.1016/j.foreco.2010.07.010.

Cochrane, M.A., Moran, C.J., Wimberly, M.C., Baer, A.D., Finney, M.A., Beckendorf, K.L., Eidenshink, J., and Zhu, Z. 2012. Estimation of wildfire size and risk changes due to fuels treatments. Int. J. Wildland Fire, **21**: 357–367. doi:10.1071/WF11079.

Cohen, J. 1988. Statistical power analysis for the behavioral sciences. 2nd ed. Erlbaum, Hillsdale, N.J.

Cruz, M.G., Alexander, M.E., and Dam, J.E. 2014. Using modeled surface and crown fire behavior characteristics to evaluate fuel treatment effectiveness: a caution. For. Sci. **60**: 1000–1004. doi:10.5849/forsci.13-719.

Cruz, M.G., Alexander, M.E., and Plucinski, M.P. 2017. The effect of silvicultural treatments on fire behaviour potential in radiata pine plantations of South Australia. For. Ecol. Manage. **397**: 27–38. doi:10.1016/j.foreco.2017.04.028.

Espinosa, J., Madrigal, J., De La Cruz, A.C., Guijarro, M., Jimenez, E., and Hernando, C. 2018. Short-term effects of prescribed burning on litterfall biomass in mixed stands of *Pinus nigra* and *Pinus pinaster* and pure stands of *Pinus nigra* in the Cuenca Mountains (Central-Eastern Spain). Sci. Total Environ. **618**: 941–951. doi:10.1016/j.scitotenv.2017.08.291. PMID:29146076.

Fernandes, P.M. 2009. Examining fuel treatment longevity through experimental and simulated surface fire behaviour: a maritime pine case study. Can. J. For. Res. **39**(12): 2529–2535. doi:10.1139/X09-145.

Fernandes, P.M. 2015. Empirical support for the use of prescribed burning as a fuel treatment. Curr. For. Rep. **1**: 118–127. doi:10.1007/s40725-015-0010-z.

Fernandes, P.M. 2018. Scientific support to prescribed underburning in southern Europe: what do we know? Sci. Total Environ. **630**: 340–348. doi:10.1016/j.scitotenv.2018.02.214. PMID:29482142.

Fernandes, P.M., and Rigolot, E. 2007. The fire ecology and management of maritime pine (*Pinus pinaster* Ait.). For. Ecol. Manage. **241**: 1–13. doi:10.1016/j.foreco.2007.01.010.

Fernandes, P.M., Loureiro, C., and Botelho, H. 2004. Fire behaviour and severity in a maritime pine stand under differing fuel conditions. Ann. For. Sci. **61**: 537–544. doi:10.1051/forest:2004048.

Fernandes, P.M., Luz, A., and Loureiro, C. 2010. Changes in wildfire severity from maritime pine woodland to contiguous forest types in the mountains of northwestern Portugal. For. Ecol. Manage. **260**: 883–892. doi:10.1016/j.foreco.2010.06.008.

Fernandes, P.M., Loureiro, C., and Botelho, H. 2012. PiroPinus: a spreadsheet application to guide prescribed burning operations in maritime pine forest. Comput. Electron. Agric. **81**: 58–61. doi:10.1016/j.compag.2011.11.005.

Fernandes, P.M., Fernandes, M., and Loureiro, C. 2015. Post-fire live residuals of maritime pine plantations in Portugal: structure, burn severity, and fire recurrence. For. Ecol. Manage. **347**: 170–179. doi:10.1016/j.foreco.2015.03.023.

Finney, M.A., McHugh, C.W., and Grenfell, I.C. 2005. Stand- and landscape-level effects of prescribed burning on two Arizona wildfires. Can. J. For. Res. **35**(7): 1714–1722. doi:10.1139/x05-090.

Gellie, N. 2005. Effectiveness of fire management measures in pine plantations. Report for the ACT Department of Urban Services, Canberra, Australia.

Graham, R.T., McCaffrey, S., and Jain, T.B. 2004. Science basis for changing forest structure to modify wildfire behavior and severity. USDA Forest Service, Gen. Tech. Rep. RMRS-GTR-120. doi:10.2737/RMRS-GTR-120.

Gutsell, S.L., and Johnson, E.A. 1996. How fire scars are formed: coupling a disturbance process to its ecological effect. Can. J. For. Res. **26**(2): 166–174. doi:10.1139/x26-020.

Hedges, L.V., Gurevitch, J., and Curtis, P.S. 1999. The meta-analysis of response ratios in experimental ecology. Ecology, **80**: 1150–1156. doi:10.1890/0012-9658(1999)080[1150:TMAORR]2.0.CO;2.

Hirsch, K.G., and Martell, D.L. 1996. A review of initial attack fire crew productivity and effectiveness. Int. J. Wildland Fire, **6**: 199–215. doi:10.1071/WF9960199.

Jiménez, E., Vega-Nieva, D., Rey, E., Fernández, C., and Vega, J.A. 2016. Midterm fuel structure recovery and potential fire behaviour in a *Pinus pinaster* Ait. forest in northern central Spain after thinning and mastication. Eur. J. For. Res. **135**: 675–686. doi:10.1007/s10342-016-0963-x.

Keyes, C.R., and O'Hara, K.L. 2002. Quantifying stand targets for silvicultural prevention of crown fires. West. J. Appl. For. **17**: 101–109.

Lydersen, J.M., North, M.P., and Collins, B.M. 2014. Severity of an uncharacteristically large wildfire, the Rim Fire, in forests with relatively restored frequent fire regimes. For. Ecol. Manage. **328**: 326–334. doi:10.1016/j.foreco.2014.06.005.

Lydersen, J.M., Collins, B.M., Brooks, M.L., Matchett, J.R., Shive, K.L., Povak, N.A., Kane, V.R., and Smith, D.F. 2017. Evidence of fuels management and fire weather influencing fire severity in an extreme fire event. Ecol. Appl. **27**: 2013–2030. doi:10.1002/eap.1586. PMID:28644577.

Malone, S.L., Kobziar, L.N., Staudhammer, C.L., and Abd-Elrahman, A. 2011. Modeling relationships among 217 fires using remote sensing of burn severity in southern pine forests. Remote Sens. **3**: 2005–2028. doi:10.3390/rs3092005.

Martinson, E.J., and Omi, P.N. 2008. Assessing mitigation of wildfire severity by fuel treatments — an example from the Coastal Plain of Mississippi. Int. J. Wildland Fire, **17**: 415–420. doi:10.1071/WF06067.

Martinson, E.J., and Omi, P.N. 2013. Fuel treatments and fire severity: a meta-analysis. USDA Forest Service Res. Pap. RMRS-RP-103WWW.

McCaw, W.L., Gould, J.S., Cheney, N.P., Ellis, P.F.M., and Anderson, W.R. 2012. Changes in behaviour of fire in dry eucalypt forest as fuel increases with age. For. Ecol. Manage. **271**: 170–181. doi:10.1016/j.foreco.2012.02.003.

Oliveras, I., Gracia, M., Moré, G., and Retana, J. 2009. Factors influencing the pattern of fire severities in a large wildfire under extreme meteorological conditions in the Mediterranean basin. Int. J. Wildland Fire, **18**: 755–764. doi:10.1071/WF08070.

Palheiro, P.M., Fernandes, P., and Cruz, M.G. 2006. A fire behaviour-based fire danger classification for maritime pine stands: comparison of two approaches. For. Ecol. Manage. **234**(Suppl.): S54. doi:10.1016/j.foreco.2006.08.075.

Peterson, D.L. 1985. Crown scorch volume and scorch height: estimates of postfire tree condition. Can. J. For. Res. **15**(3): 596–598. doi:10.1139/x85-097.

Peterson, D.L., and Ryan, K.C. 1986. Modeling postfire conifer mortality for long-range planning. Environ. Manage. **10**: 797–808. doi:10.1007/BF01867732.

Pollet, J., and Omi, P.N. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. Int. J. Wildland Fire, **11**: 1–10. doi:10.1071/WF01045.

Prichard, S.J., and Kennedy, M.C. 2014. Fuel treatments and landform modify landscape patterns of burn severity in an extreme fire event. Ecol. Appl. **24**: 571–590. doi:10.1890/13-0343.1. PMID:24834742.

Sackett, S.S. 1975. Scheduling prescribed burns for hazard reduction in the southeast. J. For. **73**: 143–147.

Safford, H.D., Stevens, J.T., Merriam, K., Meyer, M.D., and Latimer, A.M. 2012. Fuel treatment effectiveness in California yellow pine and mixed conifer forests. For. Ecol. Manage. **274**: 17–28. doi:10.1016/j.foreco.2012.02.013.

Stephens, S.L., Collins, B.M., and Roller, G. 2012. Fuel treatment longevity in a Sierra Nevada mixed conifer forest. For. Ecol. Manage. **285**: 204–212. doi:10.1016/j.foreco.2012.08.030.

Storey, M., Price, O., and Tasker, E. 2016. The role of weather, past fire and topography in crown fire occurrence in eastern Australia. Int. J. Wildland Fire, **25**: 1048–1060. doi:10.1071/WF15171.

Van Wagner, C.E. 1973. Height of crown scorch in forest fires. Can. J. For. Res. **3**(3): 373–378. doi:10.1139/x73-055.

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Can. For. Serv. For. Tech. Rep. 35.

Vega, J., Jimenez, E., Vega, D., Ortiz, L., and Pérez, J.R. 2011. *Pinus pinaster* Ait. tree mortality following wildfire in Spain. For. Ecol. Manage. **261**: 2232–2242. doi:10.1016/j.foreco.2010.10.019.

Viedma, O., Quesada, J., Torres, I., De Santis, A., and Moreno, J.M. 2015. Fire severity in a large fire in a *Pinus pinaster* forest is highly predictable from burning conditions, stand structure, and topography. Ecosystems, **18**: 237–250. doi:10.1007/s10021-014-9824-y.

Zald, H.S.J., and Dunn, C.J. 2018. Severe fire weather and intensive forest management increase fire severity in a multi-ownership landscape. Ecol. Appl. **28**: 1068–1080. doi:10.1002/eap.1710. PMID:29698575.