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Coupling fire behaviour modelling and stand characteristics to assess and mitigate fire hazard in a maritime pine landscape in Portugal

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Abstract Silvicultural models are often developed and applied without due consideration of fire modelling. Yet, this information is important for designing treatment options to lower fire hazard. We used the FlamMap software to assess potential fire behaviour under extreme fire weather conditions within a 10,881-ha maritime pine landscape in central Portugal, the Leiria National Forest. Models describing fire hazard and providing information to assess potential benefits of stand-level fuel treatments were developed based on fire behaviour simulation. These models use as predictors stand variables and may assist forest managers in identifying hazardous areas in pine forests. Models were built from a database comprising

94,207 unique combinations of variables to detect significant fire-landscape interactions between stand-level features and fire behaviour. A set of compatible models that express crown fire likelihood and tree mortality were fitted using logistic regression. Additionally, classification tree analysis was used to model the type of fire, fire suppression difficulty, and tree mortality. The results highlight the potential of this methodology to explain the influences of fuel- and stand-related variables on fire hazard. This approach allowed the identification of straightforward discrimination rules to implement fuel treatments that prevent crown fires, enhancing the effectiveness of fire suppression and thereby reducing fire damage in fire-prone forest stands. Results further allow developing specific hazard-reduction prescriptions based on common forest metrics without resorting to advanced simulation modelling.

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Introduction

Fuel-reduction options to decrease fire hazard are available for pine forests (e.g. Pollet and Omi 2002; Fernandes and Rigolot 2007), yet the quantitative methods available for assessing impacts of different silviculture treatments on potential fire behaviour require the use of advanced modelling tools (Scott and Reinhardt 2001; Cruz et al. 2008). Characterizing potential wildfire behaviour and its consequences as a function of current forest conditions is crucial for addressing wildfire hazard proactively, namely to enhance silvicultural practices through fuel treatments

effective at reducing fire-induced losses (Keyes and O'Hara 2002).

Maritime pine (*Pinus pinaster* Ait.) stands extend over 0.714 million hectares in Portugal, 23.4% of its forestland (ICNF 2013). The species is more fire-prone than other forest types in the country (Moreira et al. 2009), and 41.3% of its area burned between 1996 and 2012 (Mateus and Fernandes 2014). Most of the area is susceptible to high-severity wildfire, due to insufficient thinning and pruning and high fuel accumulation (Cruz et al. 2008; Fernandes 2009). Studies in Portugal have addressed the behaviour and effects of fire on maritime pine stands, especially in relation to prescribed burning (Fernandes et al. 2004; Fernandes and Rigolot 2007; Fernandes et al. 2009; Fernandes and Loureiro 2013). Fernandes (2009) combined forest structure data and fuel modelling to classify Portuguese forest types by fire hazard level and emphasized that stand structure was the main driver of fire vulnerability. In fact, stand structure affects fire hazard through its influence on surface, ladder and crown fuel structure and availability to burn (Cumming 2001; Fernandes 2009; Castro et al. 2003). Thus, modifying any of these fuel strata will affect fire behaviour and severity. This information is useful and may help develop silviculture guidelines to assist forest managers (Keyes and O'Hara 2002; Peterson et al. 2005). Interest in reducing pine forest susceptibility to crown fire through stand management is growing (Fernández-Alonso et al. 2013; Gómez-Vázquez et al. 2014). A few European studies considered density (basal area and number of trees) and stand height as potential predictors of fire type (Alvarez et al. 2012; Fernandes 2009; Fernández-Alonso et al. 2013). However, understanding of fire-resistant stand structures in Europe is still scarce, empirical, and in debate (Fernandes et al. 2010, 2015; Alvarez et al. 2012; Viedma et al. 2014).

Recent studies have developed wildfire risk and post-fire tree mortality models to assist long-term planning (González et al. 2005b; Garcia-Gonzalo et al. 2011; Botequim et al. 2013). These models include explanatory variables derived from forest inventories that are controllable by forest managers. These models provide further information to help develop both stand-level and landscape-level management scheduling optimization that may address wildfire risk (González et al. 2005a, b; Garcia-Gonzalo et al. 2014; Ferreira et al. 2012, 2014). However, these empirical models are independent of fire behaviour. With the exception of the density diagrams of Gómez-Vázquez et al. (2014) to mitigate crown fire hazard, no quantitative guidelines are available to assist forest managers in designing silviculture prescriptions where fire behaviour is integrated. This gap in knowledge hinders the development of quantitative forest management guidelines to mitigate

wildfire effects in maritime pine (*Pinus pinaster* Ait.) stands in Portugal and elsewhere.

Spatially explicit fire simulators such as FARSITE (Finney 2004) and FlamMap (Finney 2006) are used extensively both for research and for practical purposes (Alexander and Cruz 2013). While many issues are apparent, the main fire behaviour models used by practitioners continue to generate reasonable results for many applications (Cruz and Alexander 2010; Martín et al. 2016). These systems integrate site-specific vegetation, fuel, topographic and weather data to estimate fire behaviour characteristics such as fireline intensity and rate of spread (Finney and Andrews 1999). The use of fire behaviour simulators requires dynamic weather information and accurate spatially explicit estimation of fuel characteristics, which are difficult to predict over time and space (He and Mladenoff 1999). This constrains the use of fire simulators when developing medium and long-term forest management plans. Indirect approaches are desirable to overcome this shortcoming such that forest managers are able to design local stand- or compartment-level fuel treatments without actually using fire simulators.

In this study we simulated fire behaviour within an entire landscape to model the causal relationships between maritime pine stand structure and fire proneness. We then used our predictive variables, derived from standard forest inventory, in addition to fuel type and terrain data, to quantitatively support management decisions relating the type of fuel treatment with potential fire behaviour, fire damage, and fire suppression difficulty.

Data and methods

Study area

The case study area, Leiria National Forest (LNF), is a coastal public forest with historical and economic significance located in central western Portugal between latitude 39°42'45"N–39°53'N and longitude 8°03'30"W–9°03'W (Fig. 1). LNF extends over 10,881 hectares in predominantly flat terrain and sandy soil and comprises 8679 hectares of timber-productive pure maritime pine stands, plus a protection area along the coast managed to prevent dune erosion and to protect the production area stands (Garcia-Gonzalo et al. 2013). A Mediterranean climate with an oceanic influence, dry summers with rainfall concentrated in autumn and winter, and mean annual temperature and precipitation of 15 °C and 855 mm, respectively, characterize the region and contribute to the fragility of the local ecosystem exposing it to high levels of fire risk (Scarascia-Mugnozza et al. 2000). Between 1980 and 2007, 39.6% of LNF burned

Fig. 1 Leiria National Forest (LNF) location in Portugal, with its 542 plots across the forest management units (MU) (a) and topographic themes needed for fire behaviour simulation [elevation (b), slope (c),

aspect (d)]. The non-rectangular parts (a) correspond to a protection area along the coast managed to prevent the erosion of the dunes and to protect the stands located in the production area

(AFN 2010). As a consequence, younger stands are currently predominant. Periodic LNF forest inventories for management purposes have been carried out by the Portuguese Forest Service since 1970, whereby one permanent plot (500–1000 m²) per hectare is re-measured every 5 years. The total area is divided into 367 even-aged management units (MU), with a set of 342 units identified as timber stands (Fig. 1a). The typical LNF forest management consists of natural or artificial regeneration of approximately 2500 seedlings per hectare and mandatory pre-commercial thinning at 15 years of age to 1500 residual trees per hectare. The need for subsequent thinning is checked every 5 years, from ages 20–50 years, leaving the stand at an average density of 200–250 trees per hectare for final harvesting. Rotation age has been close to 80–90 years but there is a tendency to reduce it to 70–80 years (Ferreira et al. 2014; Garcia-Gonzalo et al. 2013).

Data

FlamMap 3.0.0 software (Finney 2004, 2006) was used to simulate fire behaviour characteristics from spatially explicit data. FlamMap was selected because it is the single available option to estimate maximum fire potential, i.e. the fire characteristics exhibited by the headfire section of the fire front when the directions of wind and slope are aligned. Fuel and stand management planning to reduce fire hazard should target maximum fire potential, which FlamMap computes for any given point of a landscape. Data used in the study pertain to three distinct groups: (1) weather, terrain, stand and fuel characteristics used as input data for fire behaviour simulation, (2) output data from fire behaviour simulation, namely fireline intensity (FLI), rate of fire spread (ROS), and crown fire activity (CFA), and (3) the stand descriptors stand density, basal area, and quadratic mean diameter.

Slope, aspect, and elevation of the study area (Fig. 1b–d, respectively) were mapped at 25 × 25-m resolution from the country's Digital Terrain Model (DTM) based on standard GIS procedures. Elevation and slope ranged between 4 and 142 m and from 0° to 35°, respectively, and the northwest aspect was prevalent.

LNF forest inventory data were used to characterise stands. Data from 546 plots covering about 342 MU were used to derive (1) the stand variables required to simulate fire behaviour, and (2) additional variables relevant for management planning purposes (Table 1). Thus, stand height (hdom, m), tree density (N, number of trees ha⁻¹), basal area (G, m² ha⁻¹), quadratic mean diameter (dg, m) and G/dg (a nonlinear density measure related to the number and sizes of trees per hectare) were collected or derived from the inventory data (Table 1). Crown base height (m) was estimated for each tree according to Torres et al. (2004, Eq. 1) by using tree size characteristics: tree height (HT, dm); basimetric area of the plot (lnSBA, m² ha⁻¹), a stand density measure; and the basal area of trees larger than the subject tree (BAL, m² ha⁻¹), a competition index. Then, crown base height was converted to its stand-level equivalent, canopy base height (CBH, m).

$$CBH = \frac{HT}{1 + e^{[2.4249 + (-0.0031 \times HT) + (-0.060 \times BAL) + (-0.7045 \times \ln SBA)]}} \quad (1)$$

Canopy cover (CC, %) was computed after summing the crown areas of the individual trees in each study plot (Torres et al. 2004). The maximum crown area (LCW, Eq. 2) of each tree was calculated using mean tree diameter at breast height (dbh, m), crown ratio (CR = crown length/HT), crown length (CL, dm), and stand height (HT, dm). A mean CC value was assigned to the plot and classified into intervals of 0–20, 21–50, 51–70, and 71–100% as required by FlamMap.

$$LCW = [8.9785 + (0.8181 \times dbh) + (0.0393 \times dbh^2)] \times [CR^{(0.00649 \cdot CL) + (0.6569 \cdot (\frac{dbh}{HT}))}] \quad (2)$$

Canopy bulk density (CBD, kg m⁻³) was obtained as recommended by Cruz et al. (2003). In this case, three main steps were considered: (1) a foliage biomass estimate as per Faias (2009, Eq. 3) was used to obtain the crown biomass of each tree (wl, kg), using information from the LNF inventory database (tree diameter at breast height, dbh, cm and stand height, HT, dm); (2) the canopy foliage loading per plot (wf, kg m⁻²) was calculated by dividing the sum of canopy foliage (wl, kg) by the plot area; (3) finally, canopy bulk density (CBD, kg m⁻³) is the mean canopy biomass for each plot (wf, kg m⁻²) divided by the average canopy length (CL, m), i.e. mean tree height minus CBH.

$$Wl = 0.065631 \times dbh^{1.612475} \times \left(\frac{HT}{dbh}\right)^{-0.547370} \quad (3)$$

Fuel models (Fm) for use in fire behaviour simulation were chosen from sets developed for maritime pine stands in Portugal (Cruz 2007; Cruz and Fernandes 2008; Fernandes et al. 2009). Each LNF plot was assigned a fuel model based on 20-year interval stand age classes (Table 2). Stand and fuel variables for the plots within each LNF compartment were averaged and mapped at the stand level (Fig. 2).

Fire behaviour simulation

Both geographic (elevation, slope, and aspect) (Fig. 1) and fuel-related data themes (fuel model, CC, hdom, CBH, CBD) (Figs. 2, 3) were processed by ArcGIS (version 9.3.) to develop the eight input layers required by FlamMap. Each layer (ASCII file) encompassed 169,789 cells (size 25 m).

Table 1 Descriptive statistics (2001 forest inventory) for plot-level stand characteristics (*n* = 546)

Type of variables	Stand variables	Data source	Mean	Range
Canopy fuel inputs for fire simulation	Canopy cover (CC, %)	Torres et al. (2004)	46	19–97
	Canopy base height (CBH, m)	Torres et al. (2004)	8	2–23
	Canopy bulk density (CBD, kg m ⁻³)	Faias (2009) (adapted)	0.114	0.037–0.315
	Stand height (hdom, m)	LNI	14	7–29
Stand structure	Basal area (G, m ² ha ⁻¹)	LNI	20	9–47
	Density (N, trees ha ⁻¹)	LNI	821	125–2110
	Quadratic mean diameter (dg, cm)	LNI	23	9–48
	G/dg ^a	LNI	1	0.37–3.53

^a Indirectly related to stand density

Table 2 Custom fuel models assigned to the LNF maritime pine stands ($n = 546$)

Fuel model	Age class (years)	Fuel complex	References
V-MAb	≤ 20	Dominated by understory vegetation, mainly <i>Ulex</i> and/or <i>Erica</i> species (<1-m tall)	Fernandes et al. (2009)
PPIN-05	20–40	Litter and understory	Cruz (2007)
M-PIN	40–60	Litter and understory	Cruz and Fernandes (2008)
F-PIN	≥ 60	Litter	Cruz and Fernandes (2008)

Fig. 2 Fuel-data layers required to simulate fire behaviour characteristics in FlamMap: fuel model (a), and canopy characteristics [canopy cover (b), stand height (c), canopy base height (d), canopy bulk density (e)]

Fig. 3 Methodology employed to develop models of potential crown fire occurrence and tree mortality to help support fuel treatment scheduling in maritime pine stands in Portugal

Fuel treatment prescriptions should be planned to withstand critical fire weather conditions. Daily weather records from the nearby (ca. 15 km) Monte Real weather station were used to characterize fire weather so as to define critical conditions to run the simulations, which we equated to the 97th percentiles of air temperature (40.1 °C) and relative humidity (17.2%) during the May–October period (1998–2008). The corresponding Fine Fuel Moisture Code of the Canadian FWI System (Van Wagner 1987) was 95.9, which corresponds to a fine (1-h size class) dead fuel moisture content of 4%. For the remaining simulation inputs, we assumed dead fuel moisture contents of 5% (10-h fuels) and 7% (100-h fuels); live fuel moisture contents of 75 and 120%, respectively, for shrubs and tree canopy foliage; and a 6-m wind speed of 40 km h⁻¹. Fire danger was rated very high (FWI = 38, corresponding to the 93th percentile of its distribution in the region) on the day of the largest fire recorded in the LNF (2578 ha in 2003, i.e. 23.38% of the total area corresponding to 97 MU burned). While the selected combination of weather-related inputs might reflect a seldom experienced worst-case scenario, it can, on the other hand, compensate for the under prediction bias that characterizes the fire behaviour models embedded in FlamMap (Cruz and Alexander 2010).

FlamMap produced maps of fire behaviour characteristics (ROS, FLI) and crown fire activity (CFA) classification—surface fire, passive crown fire, and active crown fire—over the whole landscape under constant wind speed and fuel moisture contents. Winds blowing uphill and aligned with slope direction were assumed, generating the maximum fire behaviour potential at any given cell. These maps were overlaid with dg, G, G/dg, N and fuel and terrain data layers (Fig. 3), resulting in 94,207 unique combinations (at the cell level) of variables. The corresponding file was used as a basis to model relationships of fire behaviour and effects with biometric and environmental variables.

Tree mortality estimation

Cell-level tree mortality (P_m) was generated with the continuous function ($0 \leq P_m \leq 1$) of Peterson and Ryan (1986), calculated from the fraction of crown kill (C_k), critical time for cambium kill (τ_c), and duration of lethal bole heating (τ_L); calculation details are described in online resource 1. This continuous function (varying between 0 and 1) responds realistically to changes in fire behaviour and stand structure and predicts mortality levels

that are in reasonable agreement with historic observation of fire-caused mortality. Ck ($0 \leq Ck \leq 1$) was determined from the height of crown kill (hk , m), tree height (ht , m), and crown length (CL , m). The latter variables were collected from the LNF inventory and hk determined as per Van Wagner (1973) from fireline intensity (Byram 1959), ambient air temperature (TA , °C) reached in the convection column above the fire, wind speed (U , $m\ s^{-1}$), and the lethal kill temperature threshold (TL , °C). Wind speed was adjusted for stand structure (Finney 2004). We assumed $TL = 70$ °C for maritime pine bud necrosis (Fernandes et al. 2008) and $TA = 40.1$ °C, i.e. the critical weather scenario. Bark thickness was computed for the observed tree diameters (Tapias et al. 2004) and used to estimate the critical time for cambial kill τ_c (min). The calculated duration of lethal heat (τ_L , min) and burning time (TB , min) were derived from the fuel model loading per size class (wi , $g\ cm^{-2}$) and fractional consumption in the fuel size class (fi) (Peterson and Ryan 1986). Peterson and Ryan (1986) model implies that a tree is completely dead when $\tau_c < 0.5\ \tau_L$. There is no cambial damage, and mortality is determined solely by crown kill when $\tau_c > 4.5\ \tau_L$. Intermediate values of τ_c/τ_L indicate a combination of cambial and crown damage.

Statistical methods

The objective of our statistical analysis was to obtain proxy equations and decision rules for the FlamMap outputs, akin to previous efforts (Noble et al. 1980; Beck 1995). Logistic regression was used to model the likelihoods of crown fire and tree mortality. The logistic function predicts the non-linear continuous probability (0–1) of an occurrence. The dependent variable is dichotomous (crown fire or surface fire; tree death or tree survival). A cut-off point may be defined to assign either “1” or “0” to the event of interest (Hosmer and Lemeshow 2000). The logistic regression model can be presented as (Eq. 4):

$$Y = \frac{1}{1 + e^{-(\beta_0 + \beta_1 X_1 + \dots + \beta_p X_p)}} \quad (4)$$

where Y is the dependent variable, x_1 to x_p are independent variables, and β_0 to β_p are parameters to be estimated.

The initial set of independent variables included landscape data, fire behaviour data, and stand characteristics data (e.g. dg , G , N). In total, 14 independent variables—12 continuous variables and two categorical variables for aspect (north, south, west, east) and fuel model (M-PIN, F-PIN, PPIN-05, V-MAB)—were analysed as potential predictor variables. All data were classified according to acquisition cost to support the development of models suited to end users ranging from typical forest practitioners with little access to data or lacking expertise (models II) to

experts with full access to data (models I). Thus, four models were developed to predict the potential for either crown fire or tree mortality in LNF maritime pine stands, *PfCrown I* and *PfCrown II*, and *PmI* and *PmII*, respectively.

The FlamMap-generated crown fire activity classification for each unique cell was coded “0” (surface fire, $n = 67,995$), and passive and active crown fire observations were merged ($n = 26,212$) and coded “1”. Fuel model (Fm) was categorized as a dummy variable. In the case of model *Pfcrown I*, a dummy pair was created for each fuel model resulting in the following assignments: M-PIN = $Fm1$ “0” + $Fm2$ “0”; F-PIN_PPIN-05 = $Fm1$ “0” + $Fm2$ “1” and V-MAB = $Fm1$ “1” + $Fm2$ “1”. For model *Pfcrown II*, to facilitate field assignment, the four fuel models were classified as litter-dominated (F-PIN combined with PPIN-05 “F-PIN_PPIN-05” to represent litter-dominated fuel complexes; and M-PIN with V-MAB “M-PIN_V-MAB” for shrub-dominated fuel complexes. *Pfcrown I* tested the prediction ability of site and fire behaviour descriptors (e.g. slope, FLI) and stand data (e.g. CBH, CC) (Table 3). *Pfcrown II* was fitted using site descriptors (e.g. Fm , slope) and available or readily obtainable forest inventory data (e.g. N , G , dg).

A number of variables defining site and stand conditions were used for estimating the probability of tree mortality (Table 4). Cell-level tree mortality was transformed into a dummy categorical variable, where $0 \leq \text{mortality} < 0.49$ ($n = 30,560$) was classified as “0” and $0.49 \leq \text{mortality} \leq 1$ ($n = 63,647$) as “1” as customarily assumed in tree mortality modelling, e.g. Ganio and Progar (2017). A subset of the input data to fire simulation was tested to fit model *PmI*. Biometric variables tested for inclusion in model *PmII* were restricted to easily measurable or predictable tree and stand characteristics such as dg , G , N , and G/dg .

Of all the available independent variables, only those with a statistically significant ($p < 0.05$) effect on the independent variable, as judged by the Wald χ^2 statistic, were retained as predictor variables for building a multivariate logistic model. Model assessment and selection considered the Akaike information criterion (AIC) (Burnham and Anderson 2003) and management relevance, i.e. the practical importance of the variable. Concordance analysis was used to support model outcomes interpretation (Hosmer and Lemeshow 2000). To convert a predicted probability to a dichotomous outcome, an optimal cut-off point was defined corresponding to the value where sensitivity and specificity are equal (Hosmer and Lemeshow 2000).

Model goodness-of-fit was assessed using Hosmer–Lemeshow goodness-of-fit statistics (Hosmer and Lemeshow 2000). Model performance was assessed through the

Table 3 Surface ($n = 67,995$) and crown fire ($n = 26,212$) observations, and statistics for the continuous variables considered to model crown fire likelihood

Variables	Description	Surface fire			Crown fire		
		Min	Mean	Max	Min	Mean	Max
<i>Input data to FlamMap</i>							
Slp (%)	Terrain slope	0	3	32	0	4	35
Elevation (m)	Terrain altitude	4	57	140	5	61	128
CC (%)	Canopy cover	31	51	97	19	42	55
CBD (kg m ⁻³)	Canopy bulk density	0.037	0.011	0.032	0.065	0.139	0.315
hdom (m)	Stand height	9	17	29	7	11	17
CBH (m)	Canopy base height	3	10	23	2	5	8
<i>Output data from FlamMap</i>							
FLI (kW m ⁻¹)	Fireline intensity	152	2002	5404	5577	22,455	30,876
ROS (m min ⁻¹)	Rate of spread	1	4.9	11.6	11.5	31.8	42.6
<i>Stand descriptors</i>							
N (no. trees ha ⁻¹)	Stand density	125	518	2110	338	1085	1900
G (m ² ha ⁻¹)	Basal area	11	24	47	9	18	39
dg (cm)	Quadratic mean diameter	10	27	48	9	14	27
G/dg ^a		0.37	0.97	3.01	0.68	1.24	3.53

^a Indirectly related to stand density

Table 4 Observations of maritime pine survival ($n = 30,560$ pixels) and death ($n = 63,647$ pixels), and statistics for the continuous variables considered to model tree mortality

Variables	Description	Survival			Death		
		Min	Mean	Max	Min	Mean	Max
<i>Input data to FlamMap</i>							
Slp (%)	Terrain slope	0	3	32	0	3	35.
Altitude (m)	Terrain altitude	5	61	140	4	56	128
CC (%)	Canopy cover	31	55	97	19	45	86
CBD (kg m ⁻³)	Canopy bulk density	0.037	0.094	0.193	0.065	0.132	0.315
hdom (m)	Stand height	10	20	29	19	13	22
CBH (m)	Canopy base height	3	12	23	2	6.5	17
<i>Output data from FlamMap</i>							
FLI (kW m ⁻¹)	Fireline intensity	152	427	1322	745	11,182	30,876
ROS (m min ⁻¹)	Rate of spread	1	2.1	6	3.4	17.3	42.6
<i>Stand descriptors</i>							
N (no. trees ha ⁻¹)	Stand density	125	312	828	258	850	2110
G (m ² ha ⁻¹)	Basal area	12	26	47	9	22	41
dg (cm)	Quadratic mean diameter	14	34	48	9	19	40
G/dg ^a		0.37	0.76	1.27	0.41	1.179	3.53

Survival is defined as an estimated probability of mortality <0.50 . See methods for details

^a Indirectly related to stand density

likelihood-ratio statistic and by calculating area under the receiver operating characteristics (ROC) curve. Collinearity was assessed by the variance inflation factor (VIF). The odds ratio was used to help interpret results. The JMP statistical software package, version 8 (SAS Institute Inc 2008), was used in all statistical procedures with significance set at $\alpha = 0.05$.

Classification tree analysis

Classification tree (CART) analysis divides a dataset into increasingly homogeneous subgroups and is adequate to model a categorical response variable from multiple variables, especially when data are nonparametric or unbalanced and relationships are nonlinear (De'ath and Fabricius

2000). CART can handle auto correlated data (Calbk et al. 2002) and can potentially reveal complex interactions between predictor variables and quantify their relative influences. Thus, regression trees complement or substitute traditional techniques such as multiple regression, logistic regression, log-linear models, linear discriminant analysis, and survival models (Breiman et al. 1984; De'ath and Fabricius 2000).

CART analysis was used to derive practical discrimination rules for specific forest management activities. We modelled the type of fire (surface, passive, or active crown fire), fire suppression difficulty, and tree mortality from site conditions (fuel model, slope, stand characteristics) ($n = 94,207$). The type of fire predicted by FlamMap (coded 1, 2, and 3, respectively, for surface fire, passive crown fire, and active crown fire) was employed to estimate thresholds for dramatic changes in fire behaviour in each unique set of cells. Suppression difficulty adopted the fireline intensity (kW m^{-1}) classes suggested by Alexander and Lanoville (1989) but merged the two upper classes: low ($<500 \text{ kW m}^{-1}$), moderate ($500\text{--}2000 \text{ kW m}^{-1}$), high ($2000\text{--}4000 \text{ kW m}^{-1}$), and very high to extreme ($>4000 \text{ kW m}^{-1}$); the upper class was assigned also when $\text{FLI} < 4000 \text{ kW m}^{-1}$, but active crown fire spread was predicted. Potential tree mortality in CART was treated as a continuous response variable (varying from 0 to 1). Model over fitting was prevented by basing the number of splits on a tenfold cross-validation.

Results

The FlamMap simulation maps showed that rate of fire spread (ROS) can be very high in LNF (maximum 42.6 m min^{-1}). This rate is associated with a maximum

fireline intensity of $30,876 \text{ kW m}^{-1}$, which is almost one order of magnitude higher than what defines the extreme danger class in terms of fire suppression difficulty (Fig. 4). Severe fires were associated to cells with elevation $>50 \text{ m}$, facing North, with a shrub-dominated understory, 30–40% CC, 7–9 m hdom, CBH ranging from 2 to 3 m, and CBD between 0.095 and 0.142 kg m^{-3} .

Probability of crown fire

The first logistic model (*PfCrown I*) describing crown fire probability in LNF pure and even-aged maritime pine stands included as predictive variables the canopy cover (CC), canopy base height (CBH), terrain slope (Slp), and the fuel models *Fm1* and *Fm2* as dummy pair variables (Table 5). Crowning likelihood increased with lower CBH and CC, with higher Slp, and with an increasingly important shrub layer.

CBH had the greatest impact on the probability of crown fire occurrence, as expected by FlamMap's adoption of Van Wagner (1977) model for crown fire initiation. For instance, in 40- to 60-year-old maritime pine stands characterized by the M-PIN fuel model, the crowning threshold was $\text{CBH} = 6.7 \text{ m}$ (S1a Fig.). A fuel model (Fm) change may increase the likelihood of crown fire. Indeed, FPIN_PPIN understories combined with low CBH facilitated canopy combustion (e.g. a CBH of 1.5 m) (S1b Fig.).

The more manager-friendly model (*PfCrown II*) to predict crown fire occurrence encompassed three alternative models (models 2, 3, and 4, Table 5). All models included Fm as a predictive variable, differing in the stand data needed as input (G, hdom). The regression coefficients of all three candidate models (model 2 to model 4) were significant at the 5% level. Collinearity among variables is nonexistent in the three models (Table 5).

Fig. 4 Fire control difficulty classification of the study area pixels as per Alexander and Lanoville (1989) based on simulated fireline intensity (FLI, kW m^{-1}) in LNF, plotted with rate of spread (m min^{-1}) and heat per unit area (kJ m^{-2}). All fire behaviour variables are FlamMap outputs

Table 5 Logistic regression parameter estimates and fit statistics for the crown fire probability models (model type I and model type II)

Model (ROC)	Parameter	Variables	Estimate	SE	Wald χ^2
Model 1	β_0	Intercept	−53.705	0.848	14,738
<i>PfCrownI</i>	β_1	<i>Fm1</i>	* ¹	849.757	13,211.24
(0.998)	β_2	<i>Fm2</i>	* ²	849.757	14,738.42
	β_3	CC	0.347	0.007	5188.35
	β_4	CBH	6.502	0.102	52,057.26
	β_5	Slp	−0.352	0.010	1377.96
Model 2	β_0	Intercept	−53.884	562.168	12,414.03
<i>PfCrownII</i>	β_1	<i>Fm</i>	* ³	562.168	12,412.03
(0.997)	β_2	hdom	3.881	0.0513	42,736.24
	β_3	G	1.206	0.0178	20,554.74
Model 3	β_0	Intercept	−9.490	501.541	79.35
<i>PfCrown II</i>	β_1	<i>Fm</i>	* ⁴	501.541	11,010
(0.998)	β_2	CBH	0.062	0.0064	36,565
	β_3	G	4.012	0.0492	97.04
Model 4	β_0	Intercept	−8.733	346.459	24.022
<i>PfCrown II</i>	β_1	<i>Fm</i>	* ⁵	346.459	3167.69
(0.979)	β_2	hdom	1.631	0.01327	54,561.33

*¹ $\beta_1 = 22.378$ if *Fmodel 1* = 0 and $\beta_1 = -22.378$ if *Fmodel 1* = 1;

*² $\beta_2 = -22.584$ if *Fmodel 2* = 0 and $\beta_2 = 22.584$ if *Fmodel 2* = 1

Fm, is Fuel model (Litter “0” or Shrub “1”);

*³ $\beta_1 = 19.881$ (*Fm* = litter) and $\beta_1 = -19.881$ (*Fm* = shrub)

*⁴ $\beta_1 = 16.190$ (*Fm* = litter) and $\beta_1 = -16.190$ (*Fm* = shrub);

*⁵ $\beta_1 = 11.243$ (*Fm* = litter) and $\beta_1 = -11.243$ (*Fm* = shrub); Wald > χ^2 , Wald Chi-square statistic; SE, standard error; CI, 95% lower and upper confidence limits

All variables are significant at $p < 0.001$

Probability of tree mortality

After analysing all possible variable combinations, two sets of compatible models to predict the fire-induced probability of mortality were selected (Table 6) to address the needs of end users ranging from researchers (*PmI*—models 5 and 6) to typical forest practitioners (*PmII*—models 7 and 8). All regression coefficients were significant at the 5% level. None of the three models presents collinearity among variables (Table 6).

FLI and hdom were the most important variables influencing the probability of mortality in most models (i.e. *PmI*—models 5 and 6 and *PmII*—model 8). In this case, higher fire intensity corresponded to higher tree mortality, while higher hdom corresponded to lower tree mortality. In two cases, dg^2 was also included in the model (*PmI*—model 5 and *PmII*—model 8) indicating that larger diameter trees suffer less mortality in case of fire. The fuel model was the most important variable in model *PmII* (models 7 and 8). The *PmII* model (models 7 and 8) showed that tree mortality is higher in the presence of a shrub understory layer.

Type of fire

The CART analysis explained 91.5% of the existing variation (after 7 splits), with areas under the ROC curve of 0.996, 0.993 and 0.997, respectively, for surface fire, passive crown fire, and active crown fire. The fire type associated to stands with CBH <7 m and CBD <0.101 kg m^{−3} (relatively open stands) and with a litter-dominated fuel complex was surface fire (100% of the observations) (Fig. 5). However, passive crown fire was generalized (95.7%) under the same stand conditions but in the presence of a shrub-dominated surface fuel complex. Maritime pine stands with surface fuels categorized as “Shrub”, CBH <6 m, and CBD equal or larger than 0.101 kg m^{−3} (relatively dense stands), will allow flames to propagate vertically and horizontally through the canopy resulting in an active crown fire (100% of the cases). On the other hand, when CBH equalled or exceeded 7 m, a CC threshold of 33% discriminated between surface fire and active crowning regardless of surface fuel conditions (Fig. 5).

Table 6 Logistic regression parameters and fit statistics for the post-fire tree mortality models (models 5 and 6 for type I; models 7 and 8 for type II)

Model (ROC)	Parameter	Variables	Estimate	SE	CI
Model 5	β_0	Intercept	18.386	0.0664	18.273/18.499
<i>PmI</i>	β_1	FLI	−0.046	0.0001	−0.047/−0.046
(0.998)	β_2	dg ²	0.032	0.0001	0.0320/0.0323
	β_3	hdom	0.498	0.0024	0.494/0.502
Model 6	β_0	Intercept	−23.274	0.862	−25.125/−21.545
<i>PmI</i>	β_1	FLI	−0.044	0.002	−0.047/−0.048
(0.986)	β_2	hdom	5.0724	0.184	4.703/5.467
Model 7	β_0	Intercept	−3.893	0.026	−3.945/3.844
<i>PmII</i>	β_1	<i>Fm</i>	−27.769	55.068	—
(0.994)	β_2	dg ²	0.0135	8.822	0.0133/0.0136
Model 8	β_0	Intercept	−4.774	0.0652	−4.906/−4.643
<i>PmII</i>	β_1	<i>Fm</i>	−16.206	27.164	—
(0.983)	β_2	hdom	0.538	0.005	0.527/0.549

PmI_x, probability of tree potential from fire behaviour input variables; *PmII_x*, probability of tree mortality from common stand variables. *Fm*, characterized the type of understory biomass present on the stands (“0” indicating that is litter-dominated and “1” that is commonly occupied by “shrubs”); SE, standard error; CI, 95% lower and upper confidence limits

Fig. 5 Classification tree for the type of fire at the cell level for LNF maritime pine stands as a function of fuel type and stand structure. Numbers at the ends of the terminal nodes are the percentage of

observations per type of fire (*SF* surface fire, *PCF* passive crown fire, *ACF* active crown fire)

Fire suppression difficulty

The CART analysis of fire control difficulty produced a discrimination based on *Fm*, *CBH*, *CBD*, and *CC* ($R^2 = 0.802$, 8 splits). Areas under the ROC curve were 0.974, 0.975, 0.973, 0.986 and 0.971, respectively, for low, medium, high, very high, and extreme fire suppression difficulty. The type of fuel (litter- or shrub-

dominated) determined the first partition of fire suppression difficulty, low to moderate or high to extreme, respectively (Fig. 6). Partitions on the left side of the classification tree were based on *CBH*, *CC*, and *CBD*, with increasingly difficult fire control associated to lower *CBH*. Fire suppression difficulty was rated low when either *CBH* >11 m and *CBD* <0.096 kg m^{−3}, or *CBH* <11 m and *CC* >66%, respectively, in 83.6 and

Fig. 6 Classification tree for fire suppression difficulty at the cell level. Numbers at the end of terminal nodes are the percentage of observations per class of fire suppression difficulty (*L* low, *M* moderate, *H* high, *VH* very high, *E* extreme)

Fig. 7 Classification tree for cell-level maritime pine post-fire mortality. Numbers at the ends of the terminal nodes are the percentage of mortality (*M*)

81.5% of the cases. Moderately difficult fire control prevailed when $CBH < 11$ m and $CC < 66\%$ and especially when $CBH < 15$ m and $CBD > 0.096 \text{ kg m}^{-3}$. On the right side of the tree, CBH again was the most important variable and the prospects of effective fire control were generally low. Fire suppression was particularly difficult when $CBH < 7$ m and $CBD > 0.101 \text{ kg m}^{-3}$ (extreme difficulty in 85% of the cases) (Fig. 6).

Tree mortality

The CART analysis achieved $R^2 = 0.997$ with just 3 splits. Maritime pine mortality was total for 63.9% of the observations ($n = 63,062$), all corresponding to shrub-dominated stands. Hence, *Fm* was the major determinant of the likelihood of tree death (Fig. 7). For 97.5% of litter-dominated understories, stands higher than 12 m with $CBH > 4$ m were very likely to survive wildfires (0.04% mortality) (Fig. 7).

Discussion and conclusions

Safe and effective fire management in coniferous forests depends of assessing crown fire potential with reliable predictive tools (Stocks et al. 2004; Cruz et al. 2006). Specifically, crown fire potential assessment should rely on accurate estimates of stand-level canopy fuel characteristics. Yet little guidance exists for its determination, even if quantitative data on tree crown and canopy characteristics are generally available (Scott and Reinhardt 2001). Models relating stand characteristics with fire vulnerability should include variables controllable through management. This is instrumental to schedule treatments to minimize expected losses. Fuel-related metrics such as surface fuel characteristics, stand density, vertical continuity, and tree size are controllable and can potentially be used as predictors in forest planning systems (González et al. 2006; Garcia-Gonzalo et al. 2011; Ferreira et al. 2012, 2014).

The models differ in their predictive variables in order to address needs of different end users with different access to data (from researchers to forest managers). The *pfCrownI* (model 1) is based on FlamMap input data and can be used when Fm, slp, CBH, and CC are known. Vertical discontinuity in the form of the CBH outperformed the other variables in explaining crown fire likelihood, which is consistent with empirical studies in conifer forests (Cruz et al. 2004; Fernandes et al. 2015). Results for the alternative set of models driven by commonly available inventory data indicate crown fire likelihood to be a combined function of surface fuel (Fm, litter or shrub-dominated) and stand structure (hdom and G). The *PfCrownII* (model 2) had the best fit, indicating lower crown fire susceptibility of taller stands with basal area (G) concentrated in fewer trees. Because crown fire resistance is expected to increase with lower G (e.g. Garcia-Gonzalo et al. 2011; Fernandes et al. 2015), this indicates that older stands with a lower number of trees are less prone to crown fire. Model 4 is recommended when G is unknown. In this case, the model is based on data easy to obtain from forest inventories (e.g. Fm and hdom). Our results are consistent with the determinant role, even if indirect, played by stand structure in determining the type of fire as reported recently for several pine forests in the Mediterranean basin (Alvarez et al. 2012; Fernández-Alonso et al. 2013; Gómez-Vázquez et al. 2014; Fernandes et al. 2015). In addition, G and hdom are biometric variables commonly related with crown fire model inputs CBH and CBD (e.g. Fernandes et al. 2015) that are not measurable in the field (Fernández-Alonso et al. 2013).

Two compatible models (*PmI* and *PmII*) were developed to predict tree mortality. The *PmI* model does not use fire injury indicators (e.g. crown kill, bole kill) as predictors

but is driven by FLI, which is the major influence on crown scorch height (Van Wagner 1977) and the major determinant of stem/bole char heights (Alexander and Cruz 2012). The remaining biometric variables (dg^2 and hdom) in *PmI* confirmed the findings of previous national studies (Garcia-Gonzalo et al. 2011; Marques et al. 2011). FLI is replaced by Fm in the tree mortality model *PmII* that includes variables similar to an approach presented by Garcia-Gonzalo et al. (2011) for Portuguese maritime stands, i.e. related to tree size. Previous studies showed that mature even-aged stands are usually more resistant to fire damage (Agee et al. 2000; Fernandes and Rigolot 2007; González et al. 2007; Omi and Martinson, 2004; Pollet and Omi 2002) and are less likely to be affected by fire (González et al. 2006) than multi-storied or young stands. Nonetheless, tree mortality likelihood for litter-dominated situations seems underestimated by comparison with mortalities observed after wildfire, e.g. Burrows et al. (2000). Various reasons may have contributed to this, namely assumptions regarding the sub-canopy wind profile and the temperature threshold for bud kill; overestimation of the relative role of crown kill on tree mortality in Peterson and Ryan (1986) model; and the fact that simulations do not account for post-frontal combustion and underestimate burning time, hence underestimating both the heat output affecting the canopy and stem girdling due to non-flaming combustion of woody and duff fuels.

Usage of the previous models allows developing site-specific prescriptions to treat surface and crown fuels, either emphasizing tree survival or fire control, or achieving a compromise between these two objectives. The CART approach is more straightforward and identified thresholds for sudden changes in fire behaviour and further provided quantitative evidence for implementing the hierarchy of fuel-reduction treatment principles (Agee and Skinner 2005), i.e. reducing surface fuels, increasing CBH and decreasing canopy density (expressed through CBD and CC in the analysis) through thinning. A CBH of 7 m emerged as the most relevant threshold for dramatic changes in the type of fire (Fig. 5). This threshold is consistent with empirical observations, e.g. Fernandes et al. (2004, 2015) recommended a 6-m CBH as the minimum requirement for pruning height, based on experimental fire and wildfire data. Crown fires in maritime pine stands are more common in low (young) stands, as found by Jiménez et al. (2013). CART analysis also identified a 0.1-kg m^{-3} CBD threshold which, following an empirical deduction by Agee (1996), is often mentioned as the approximate threshold for active crowning. The highest fire intensity is attained (100% active crowning, extreme fire control difficulty) whenever $\text{CBH} < 7\text{ m}$ combines with $\text{CBD} > 0.1\text{ kg m}^{-3}$ and the understory is shrub-dominated

(Fig. 5). Stands with these characteristics should be prioritized for treatment. Opening the canopy has implications to surface fuels and the physical environment within stands. It reduces dead fuel moisture content, increases in-stand wind exposure, and enhances understory vegetation development (Fernandes and Rigolot 2007; Jactel et al. 2009; Fernandes et al. 2010; Castedo-Dorado et al. 2012). Thus, the effectiveness of thinning treatments (Scott and Reinhardt 2001; Whitehead et al. 2006) depends on a thoughtful combination with the scheduling of surface fuel treatments. The same stand conditions with a “litter-dominated” understory produce a surface fire (Fig. 5), indicating the crucial importance of surface fuel reduction.

This study is the first attempt to predict fire type and tree mortality using statistical models by matching information from fire simulations with a reduced set of fuel models and stand characteristics data easily obtainable from forest inventories. The simulation approach relies on linkages between surface and crown fire behaviour models that suffer from some inconsistencies and tend to under predict crown fire behaviour (Cruz and Alexander 2010). While an alternative modelling approach was not available, usage in this study of fuel models calibrated to reproduce observed fire behaviour characteristics (Cruz and Fernandes 2008) contributed to minimize the potential under prediction bias (Cruz and Alexander 2010) and served as a partial proxy for validation. Likewise, empirical models for fire-induced mortality of maritime pine were available, but were either developed for small trees subjected to prescribed burning (Fernandes and Rigolot 2007) or could not be directly linked with fire behaviour (Vega et al. 2011), hence our adoption of Peterson and Ryan (1986) model.

Results demonstrate the potential of the methodology to understand the influence of stand and fuel variables on fire behaviour and effects and to identify hazardous fuel situations in maritime pine stands and select mitigation treatments. Our models may be used to help integrate wildfire considerations in long-term forest planning, albeit with the limitations inherent to the fire behaviour models implemented in FlamMap. Thus, optimistic expectations of fuel treatments performance when challenged by wildfire are likely to ensue from the models developed in this study. This is not a critical limitation, because it does not affect the identification of priorities for fuel treatment; fire behaviour is highly variable in space and time and along the wildfire perimeter, which implies that only part of a given area will experience extreme fire behaviour under extreme fire weather conditions, and we have purposely selected a worst-case, very low probability fire weather scenario.

This research provides benchmark values to support the design of canopy and surface fuel treatments in maritime pine stands to diminish the likelihood of high-severity and uncontrollable fire, including prescribed burning, pruning,

and thinning. Although the general findings of the study are expected to hold in maritime pine stands elsewhere, model coefficients and variable thresholds are specific of the ranges and combinations of fuel, stand, and slope conditions found in the study area. Hence, development of robust equations to guide fuel treatments in maritime pine forest in general would require a near-complete dataset covering the input variables full variability. Alternatively, regional model variants could be built to address other representative maritime pine landscapes, namely those dominated by steep terrain. Future work should employ robust fire modelling tools (Plucinski et al. 2017) at the stand scale to examine how natural and management-induced fuel and stand structure dynamics interact with the entire fire weather range to determine fire behaviour. This would tackle the uncertainty implied by variable fire weather, contributing also to assess to what extent and under which conditions fuel management is effective at mitigating fire hazard.

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References

- AFN (2010) Inventário Florestal Nacional. Portugal Continental. IFN5, 2005–2006. Autoridade Florestal Nacional. Lisboa, Portugal (in Portuguese)
- Agee J (1996) The influence of forest structure on fire behaviour. In: Proceedings of the 17th annual forest vegetation management conference, Redding, CA, USA, 16–18 Jan, pp 52–68
- Agee JK, Skinner CN (2005) Basic principles of forest fuel reduction treatments. For Ecol Manag 211(1–2):83–96
- Agee JK, Bahro B, Finney MA, Omi PN, Sapsis DB, Skinner CN, Wagtendonk JW, Weatherspoon CP (2000) The use of shaded fuelbreaks in landscape fire management. For Ecol Manag 127:55–66
- Alexander ME, Cruz MG (2012) Graphical aids for visualizing Byram’s fireline intensity in relation to flame length and crown scorch height. For Chron 88:185–190

- Alexander ME, Cruz MG (2013) Are the applications of wildland fire behaviour models getting ahead of their evaluation again? *Environ Model Softw* 41:65–71
- Alexander ME, Lanoville RA (1989) Predicting fire behaviour in the black spruce-lichen woodland fuel type of western and northern Canada. For. Can., North. For. Cent., Edmonton, Alberta, and Gov. Northwest Territ., Dep. Renewable Resour., Territ. For. Fire Cent., Fort Smith, Northwest Territories
- Alvarez A, Gracia M, Vayreda J, Retana J (2012) Patterns of fuel types and crown fire potential in *Pinus halepensis* forests in the Western Mediterranean Basin. *For Ecol Manag* 270:282–290
- Beck JA (1995) Equations for the forest fire behaviour tables. *CALMScience* 1(3):325–348
- Botequim B, Garcia-Gonzalo J, Marques S, Ricardo A, Borges JG, Tomé M, Oliveira MM (2013) Developing wildfire risk probability models for *Eucalyptus globulus* stands in Portugal. *ifor-Biogeoosciences For* 6:217–227. doi:[10.3832/for0821-006](https://doi.org/10.3832/for0821-006)
- Breiman L, Friedman JH, Olshen RA, Stone CJ (1984) Classification and regression trees. Chapman & Hall, New York
- Burrows N, Ward B, Robinson A (2000) Behaviour and some impacts of a large wildfire in the Gnangara maritime pine (*Pinus pinaster*) plantation, Western Australia. *CALM Sci* 3:251–260
- Burnham KP, Anderson DR (2003) Model selection and multi model inference: a practical information-theoretic approach. Springer, New York
- Byram GM (1959) Combustion of forest fuels. In: Davis KP (ed) 'Forest fire: control and use'. pp 61–89
- Calbk ME, White D, Kiester AR (2002) Assessment of spatial autocorrelation in empirical models of ecology. In: Scott JM, Heglund PJ, Morrison ML, Haufler JB, Raphael MG, Wall WA, Samson FB (eds) Predicting species occurrences: issues of scale and accuracy. Island Press, Washington, pp 429–440
- Castedo-Dorado F, Gómez-Vázquez I, Fernandes PM, Crecente-Campo F (2012) Shrub fuel characteristics estimated from overstory variables in NW Spain pine stands. *For Ecol Manag* 275:130–141
- Castro FX, Tudela A, Sebastià MT (2003) Modeling moisture content in shrubs to predict fire risk in Catalonia (Spain). *Agric For Meteorol* 116:49–59
- Cruz MG (2007) Guia Fotográfico para identificação de combustíveis florestais - Região Centro, Centro de Estudos sobre Incêndios Florestais, associação para o desenvolvimento da Aerodinâmica Industrial versão 2, Junho, Coimbra. ADAI (in Portuguese)
- Cruz MG, Alexander ME (2010) Assessing crown fire potential in coniferous forests of western North America: a critique of current approaches and recent simulation studies. *Int J Wildland Fire* 19:377–398
- Cruz MG, Fernandes PM (2008) Development of fuel models for fire behaviour prediction in maritime pine (*P. pinaster* Ait) stands. *Int J Wildland Fire* 17:194–204
- Cruz MG, Alexander ME, Wakimoto HR (2003) Assessing canopy fuel stratum characteristics in crown fire prone fuel types of western North America. *Int J Wildland Fire* 12(1):39
- Cruz MG, Alexander ME, Wakimoto RH (2004) Modeling the likelihood of crown fire occurrence in conifer forest stands. *For Sci* 50(5):640–658
- Cruz MG, Butler BW, Alexander ME (2006) Predicting the ignition of crown fuels above a spreading surface fire. Part II: model evaluation. *Int J Wildland Fire* 15:61–72
- Cruz MG, Alexander ME, Fernandes PM (2008) Development of a model system to predict wildfire behaviour in pine plantations. *Aust For* 71:113–121. doi:[10.1080/00049158.2008.10676278](https://doi.org/10.1080/00049158.2008.10676278)
- Cumming SG (2001) Forest type and wildfire in the Alberta boreal mixedwood: what do fires burn? *Ecol Appl* 11:97–110
- De'ath G, Fabricius E (2000) Classification and regression trees: a powerful yet simple technique for ecological data analysis. *Ecology* 81:3178–3192
- Faia MP (2009) Analysis of Biomass Expansion Factors for the most important tree species in Portugal. Dissertação de Mestrado de Engenharia Florestal e dos Recursos Naturais. ISA, Lisboa (in Portuguese)
- Fernandes PM (2009) Combining forest structure data and fuel modelling to classify fire hazard in Portugal. *Ann For Sci* 66:415
- Fernandes PM, Loureiro C (2013) Fine fuels consumption and CO₂ emissions from surface fire experiments in maritime pine stands in northern Portugal. *For Ecol Manag* 291:344–356
- Fernandes PM, Rigolot E (2007) The fire ecology and management of maritime pine (*Pinus pinaster* Ait.). *For Ecol Manag* 241:1–13
- Fernandes PM, Loureiro C, Botelho HS (2004) Fire behaviour and severity in a maritime pine stand under differing fuel conditions. *Ann For Sci* 61:537–544
- Fernandes PM, Vega JA, Jimenez E, Rigolot E (2008) Fire resistance of European pines. *For Ecol Manag* 256:246–255
- Fernandes P, Gonçalves H, Loureiro C, Fernandes M, Costa T, Cruz M, Botelho HS (2009) Modelos de combustível florestal para Portugal. In: Proceedings Congresso Florestal Nacional, Açores (in Portuguese)
- Fernandes P, Luz A, Loureiro C (2010) Changes in wildfire severity from maritime pine woodland to contiguous forest types in the mountains of northwestern Portugal. *For Ecol Manag* 260:883–892
- Fernandes PM, Fernandes M, Loureiro C (2015) Post-fire live residuals of maritime pine plantations in Portugal: structure, burn severity, and fire recurrence. *For Ecol Manag* 347:170–179
- Fernández-Alonso JM, Alberdi I, Álvarez-González JG, Vega JA, Cañellas I, Ruiz-González AD (2013) Canopy fuel characteristics in relation to crown fire potential in pine stands: analysis, modelling and classification. *Eur J For Res* 132:363–377
- Ferreira L, Constantino M, Borges J, Garcia-Gonzalo J (2012) A stochastic dynamic programming approach to optimize short-rotation coppice systems management scheduling: an application to eucalypt plantations under wildfire risk in Portugal. *For Sci* 58(4):353–365. doi:[10.5849/forsci.10-084](https://doi.org/10.5849/forsci.10-084)
- Ferreira L, Constantino M, Borges JG (2014) A stochastic approach to optimize Maritime pine (*Pinus pinaster* Ait.) stand management scheduling under fire risk: an application in Portugal. *Ann Oper Res* 219(1):359–377. doi:[10.1007/s10479-011-0845z](https://doi.org/10.1007/s10479-011-0845z)
- Finney MA (2004) FARSITE: fire area simulator-model development and evaluation. Research Paper RMRS-RP-4 Revised. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT
- Finney MA (2006) An overview of FlamMap fire modeling capabilities. In: Fuel management—how to measure success: conference proceedings RMRS-P-41. 28–30 March, Portland, Oregon, pp 213–220
- Finney MA, Andrews PL (1999) FARSITE—a program for fire growth simulation. *Fire Manag Notes* 59(2):13–15
- Ganio LM, Progar RA (2017) Mortality predictions of fire-injured large Douglas-fir and ponderosa pine in Oregon and Washington, USA. *For Ecol Manag* 390:47–67
- Garcia-Gonzalo J, Marques S, Borges JG, Botequim B, Oliveira MM, Tomé J, Tomé M (2011) A three-step approach to post-fire mortality modelling in Maritime pine (*Pinus pinaster* Ait) stands for enhanced forest planning in Portugal. *Forestry* 84(2):197–206. doi:[10.1093/forestry/cpr006](https://doi.org/10.1093/forestry/cpr006)
- Garcia-Gonzalo J, Palma JHN, Freire JPA, Tome M, Mateus R, Rodriguez LCE, Bushenkov V, Borges JG (2013) A decision support system for a multi stakeholder's decision process in a Portuguese National Forest. *For Syst* 22(2):359–373

- García-Gonzalo J, Pukkala T, Borges JG (2014) Integrating fire risk in stand management scheduling. An application to Maritime pine stands in Portugal. *Ann Oper Res* 219:379–395. doi:10.1007/s10479-011-0908-1
- Gómez-Vázquez I, Fernandes PM, Arias-Rodil M, Barrio-Anta M, Castedo-Dorado F (2014) Using density management diagrams to assess crown fire potential in *Pinus pinaster* Ait. stands. *Ann For Sci* 71:473–484. doi:10.1007/s13595-013-0350-4
- González JR, Pukkala T, Palahí M (2005a) Optimising the management of *Pinus sylvestris* L. stand under risk of fire in Catalonia (northeast of Spain). *Ann For Sci* 62:493–501
- González JR, Palahí M, Pukkala T (2005b) Integrating fire risk considerations in forest management planning in Spain—a landscape level perspective. *Landsc Ecol* 20:957–970
- González JR, Palahí M, Trasobares A, Pukkala T (2006) A fire probability model for forest stands in Catalonia (north-east Spain). *Ann For Sci* 63:169–176
- González JR, Trasobares A, Palahí M, Pukkala T (2007) Predicting stand damage and tree survival in burned forests in Catalonia (North-East Spain). *Ann For Sci* 64:733–742
- He HS, Mladenoff DJ (1999) spatially explicit and stochastic simulation of forest landscape fire disturbance and succession. *Ecology* 80:81–99
- Hosmer DW, Lemeshow S (2000) Applied logistic regression. Wiley series in probability and mathematical statistics, 2nd edn. Wiley, New York
- ICNF (2013) Áreas dos usos do solo e das espécies florestais de Portugal continental. Resultados preliminares. Instituto da Conservação da Natureza e das Florestas, Lisboa, Portugal, p 34 (in Portuguese)
- Jactel H, Nicoll BC, Branco M, González-Olbarria JR, Grodzki W, Langstrom B, Moreira F, Netherer S (2009) The influences of forest stand management on biotic and abiotic risks of damage. *Ann For Sci* 66(701):1–18. doi:10.1051/forest/2009054
- Jiménez E, Vega JA, Ruiz-González AD, Guijarro M, Álvarez-González JG, Madrigal J, Cuiñas P, Hernando C, Fernández-Alonso JM (2013) Carbon emissions and vertical pattern of canopy fuel consumption in three *Pinus pinaster* Ait. active crown fires in Galicia (NW Spain). *Ecol Eng* 54:202–209
- Keyes CR, O'Hara KL (2002) Quantifying stand targets for silvicultural prevention of crown fires. *West J Appl For* 17(2):101–109
- Marques S, García-Gonzalo J, Borges JG, Botequim B, Oliveira MM, Tomé J, Tomé M (2011) Developing post-fire *Eucalyptus globulus* stand damage and tree mortality models for enhanced forest planning in Portugal. *Silva Fenn* 45(1):69–83
- Martín A, Botequim B, Oliveira TM, Ager A, Pirotti F (2016) Temporal optimization of fuel treatment design in blue gum (*Eucalyptus globulus*) plantations. *For Syst* 25(2):eRC09
- Mateus P, Fernandes PM (2014) Forest fires in Portugal: dynamics, causes and policies. In: Reboredo F (ed) Forest context and policies in Portugal, present and future challenges. World forests, vol 19. Springer, Berlin, pp 219–236
- Moreira F, Vaz P, Catry FX, Silva JS (2009) Regional variations in wildfire susceptibility of land-cover types in Portugal: implications for landscape management to minimize fire hazard. *Int J Wildland Fire* 18:563–574
- Noble IR, Gill AM, Bary GAV (1980) McArthur's fire-danger meters expressed as equations. *Aust J Ecol* 5(2):201–203
- Omi PN, Martinson EJ (2004) Effectiveness of thinning and prescribed fire in reducing wildfire severity. In: Murphy DD, Stine PA (eds) Proceedings of the Sierra Nevada science symposium: science for management and conservation. General technical report PSW-193. Albany, California, USDA Forest Service, pp 87–92
- Peterson DL, Ryan KC (1986) Modeling postfire conifer mortality for long-range planning. *Environ Manag* 10:797–808
- Peterson DL, Johnson MC, Agee JK, Jain TB, McKenzie D, Reinhardt ED (2005) Forest structure and fire hazard in dry forests of the Western United States. Gen. Tech. Rep. PNW-GTR-628. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR
- Plucinski MP, Sullivan AL, Rucinski CJ, Prakash M (2017) Improving the reliability and utility of operational bushfire behaviour predictions in Australian vegetation. *Environ Model Softw* 91:1–12
- Pollet J, Omi PN (2002) Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. *Int J Wildland Fire* 11(1):1–10
- SAS Institute Inc (2008) SAS/STAT user's guide, version, 8th edn. SAS Institute Inc., Cary
- Scarascia-Mugnozza G, Oswald H, Piussi P, Radoglou K (2000) Forests of Mediterranean region: gaps in knowledge and research needs. *For Ecol Manag* 132:97–109
- Scott JH, Reinhardt ED (2001) Assessing crown fire potential by linking models of surface and crown fire behaviour. Research Paper RMRS-29. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, USA
- Stocks BJ, Alexander ME, Wotton BM, Steffner CN, Flannigan MD, Taylor SW, Lavoie N, Mason JA, Hartley GR, Maffe ME, Dalrymple GN, Blake TW, Cruz MG, Lanoville RA (2004) Crown fire behaviour in a northern jack pine-black spruce forest. *Can J For Res* 34:1548–1560
- Tapias R, Climent J, Pardos JA, Gil L (2004) Life histories of Mediterranean pines. *Plant Ecol* 171:53–68
- Torres CL, Ordóñez-Alonso C, Bravo Oviedo F (2004) Desarrollo de ecuaciones de copas para *Pinus pinaster* Ait. en el Sistema Ibérico Meridional. Actas de la reunión de Modelización Forestal. Sociedad Española de Ciencias Forestales, UE, Forest fire in southern europe. Report I. Cuad. Soc. Esp. Cien. 18:173–177, ISSN 1575-2410
- Van Wagner CE (1973) height of crown scorch in forest fire. *Can J For Res* 3:373–378
- Van Wagner CE (1977) Conditions for the start and spread of crown fire. *Can J For Res* 7:23–34
- Van Wagner CE (1987) Development and structure of the Canadian forest fire weather index system. In: Forestry technical report, vol 35. Canadian Forestry Service, Ottawa, p 37
- Vega J, Jimenez E, Vega D, Ortiz L, Pérez JR (2011) *Pinus pinaster* Ait. tree mortality following wildfire in Spain. *For Ecol Manag* 261(12):2232–2242
- Viedma O, Quesada J, Torres I, Santis AD, Moreno JM (2014) Fire severity in a large fire in a *Pinus pinaster* forest is highly predictable from burning conditions, stand structure, and topography. *Ecosystems* 1–14
- Whitehead RJ, Russo GL, Hawkes BC, Taylor SW, Brown BN, Barclay HJ, Benton RA (2006) Effect of a spaced thinning in mature lodgepole pine on within-stand microclimate and fine fuel moisture content. In: Andrews PL, Butler BW (eds) Fuels management—how to measure success: conference proceedings. USDA For. Serv., Proc. RMRS-P-41, Fort Collins, CO, pp 523–536