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Modeling *Pinus pinaster* Tree Damage Induced by Up-slope Wind driven Prescribed Fires in Northern Portugal

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Abstract. Prediction of prescribed fire injury to trees was the aim of an European cooperative research project. Two headfire experimental burns were conducted, corresponding to different dead fuel moisture content levels. Preburn fuel characterization, fire behaviour and overstory fire effects were quantified at the individual tree level. It was not possible to objectively relate fire injury to fire behaviour, regardless of a large range in fire behaviour parameters variation. The results obtained show clearly a relationship between damage and tree size and mortality was limited to 13% of the trees. Logistic regression models to predict postfire mortality were developed as a function of foliar injury variables and diameter at the breast height. Precribed burning prescriptions can be expanded to include fires up-slope and with the wind.

Keywords: Prescribed fire; fire effects; mortality modeling; Portugal.

Introduction

The potential of precribed burning under tree stands to accomplish management objective such as fuel reduction, forage improvement and habitat manipulation is increasingly being recognized in Southern Europe. When planning prescribed fire, sound prescriptions are required to constrain tree damage and mortality to acceptable levels, which demands the development of predictive models based on easily assessed parameters.

Pinus pinaster Ait. stands are economically valuable and occupy large areas in Portugal with an important wildfire incidence, which makes this species an obvious subject of prescribed fire research. The links between preburn conditions, fire behaviour and tree damage, to establish application thresholds in these stands, are being studied for backfiring, the current ignition technique (Botelho et al. 1996). However, the hypothesis of prescribing headfires should also be considered.

The objective of this paper, in the frame of an European cooperative research project, is to examine the possibility of attaining acceptable tree injury levels when doing prescribed burns up-slope and with the wind. Tree mortality fire caused involves crown, cambium and root damage. Bark thickness specially, but also degree of bud shielding from heat and rooting habit are important factors that determine the resistance to injury differences between tree species (Reinhardt & Ryan 1989). Because *Pinus pinaster* has thick bark and deep root habit, mortality due to these types of damage is not likely in prescribed fire conditions, and the study focused on crown injury.

Methods

This work was carried out in two even-aged stands of *Pinus pinaster* trees, of 20 and 18 years, respectively, at the locations of Sevivas and Tinhela in Serra da Padrela, Northern Portugal. All the variables (fuel, wind, fire behaviour and overstory fire effects) were measured at the individual tree level (n=30 for each plot). Preburn fine (< 6 mm diameter) fuel loads on each observation unit were estimated non-destructively from understory age, height and cover and litter depth (Botelho et al. 1995). The two experimental fires were conducted as wind-driven up-slope fires and executed at different fuel moisture content levels. Measurement of fire behaviour followed the classical procedures (Alexander 1982) and the fires were also registered on video tape. Fuel reduction was estimated from litter depth reduction and residual diameter of the shrubs terminal twigs (Botelho et al. 1995).

Tree dimension parameters were measured before the burns. Injury descriptors used by other authors in tree mortality modeling were measured two weeks after the fires, when foliar damage becomes apparent: scorch height (Hs) (Van Wagner 1973), ratio of crown scorched (RCs) (Wyant et al. 1986), fraction of scorched crown volume (Ck) (Peterson & Ryan 1986) and scorched crown volume by visual estimation (Csv) (Ryan & Reinhardt 1988).

Following data collection, tree mortality was modeled using multivariate logistic regression, which estimates a non linear continuous probability of an event. A nominal dichotomous dependent variable was assigned to the trees, according to their live (0) or dead (1) condition. Discriminat analysis with SAS LOGISTIC (SAS Inst. 1990) was used to determine the independent variables that best explain postfire mortality.

Results and Discussion

Preburn conditions and fire behaviour on each burned plot are displayed on Table 1. The fuel-complex was composed of pine litter and a discontinuous low understory of *Erica umbelatta* and *Chamaespartium tridentatum*. It was impossible to measure fire behaviour in all tree plots, due to lack of visibility and relatively high intensity of the burns. Up-slope fire conduction induced higher fire severity than in previous experiments (Botelho et al. 1994), which conformed to the study objectives. Despite faster spread and longer flames in Tinhela, calculated fireline intensity is higher for Sevivas; preburn litter load was much superior in Sevivas, which inflated frontal fuel consumption estimates. Spatial variability of fuels and temporal variability of wind induced relatively large ranges of variation in fire behaviour within a single burn. Therefore a whole range in damages to the overstory are to be expected.

Only 13% of the trees died (17% in Sevivas and 10% in Tinhela). Dead trees have significantly smaller sizes and bark thicknesses than the surviving ones (Table 2). They also display higher amounts of fire injury (Table 3), with the exception of scorch height (Hs). Dbh is negatively correlated with mortality as other authors found (Wyant et al 1986, Harrington 1987, Ryan 1993, Ryan et al. 1994a), which indicates fire thins from below and removes essentially the smaller trees. Dbh reflects the resistance to cambium injury (larger stems have thicker barks), but once is correlated with tree height can simultaneously be a measure of crown damage resistance. Dbh was also positively correlated with crown base height (Bh), which contributes to explain why small trees are scorched to a higher extent.

Table 1. Preburn conditions and fire behaviour by plot: means and ranges.

Parameter	Sevivas*		Tinhela**	
	average	range	average	range
Fuels				
h, m	0.51	0.38-0.65	0.41	0.25-0.70
Wf, kg m^{-2}	1.00	0.61-1.53	0.60	0.35-1.05
1hr Mc, %	30.0	26.3-32.8	13.2	-
Live Mc, %	103.7	99.9-105.1	76.3	65.7-82.9
Slope, %	10	-	22	-
Weather				
T, °C	16	-	12	-
RH, %	49	-	51	-
U, km h^{-1}	2.7	0.6-7.1	5.9	4.1-9.4
Fuel reduction				
Wf, kg m^{-2}	0.61	0.05-1.30	0.48	1.18
Wt, kg m^{-2}	1.61	0.05-3.60	0.21-0.85	0.34-2.08
Fire behaviour				
R, m min^{-1}	2.63	0.29-5.83	4.49	0.77-6.84
L, m	1.02	0.15-1.69	1.22	0.36-2.45
I_h, kW m^{-1}	706	44-2369	635	94-1489

h - vegetation height; Wf - litter and understory fine fuel (< 6 mm) loads; Mc - moisture contents, % ovendry weight; T - air temperature; RH - air relative humidity; U - midflame windspeed; Wt - duff + Wf load; R - rate of spread; L - flame length; I_h - fireline intensity calculated from H Wf R (Byram 1959), where H is the low heat of combustion, assumed to be 18700 J g^{-1} (Albini 1976).

* R and I_h - n=13; L and I_L - n=30.

** R and I_h - n=24; L and I_L - n=29.

Table 2. Tree characteristics by live and dead condition, averages and ranges.

Condition	Nº trees	dbh, cm	btdbh, cm	Bh, m	ht, m
Live	52				
average		9.90a	1.17a	2.70a	5.99a
range		4.8-17.2	0.4-2.05	0.7-5.5	4.0-9.2
Dead	8				
average		3.61b	0.475b	1.75b	3.87b
range		2.7-5.9	0.30-0.65	0.80-3.3	2.9-5.5

dbh- diameter at breast height; btdbh- bark thickness at dbh; Bah- crown base height; ht - tree height.
Means followed by the same letter in a column are not significantly different (P<0.05).

Preburn and postburn fuel conditions as well fire behaviour aren't significantly different (P>0.05) between live and dead trees. The correlations between scorch height and fire behaviour descriptors (R, L and I_h) and between visually evaluated crown scorch volume and flame length are significant (P<0.05), but explain only 5 to 17% of the observed variation. Size thresholds of the dead trees are ht <5.5 m and dbh <5.9 mm, corresponding to R>2.3 m min^{-1} and I_h>360 kW m^{-1}. Measured scorch height can not be related to fireline intensity, windspeed and air temperature using Van Wagner (1973) approach, and the best fitted equation is the following:

$$Hs = 1.55 + 0.197U + 0.525Bh \quad (R^2=0.69,\ s_{yx}=0.64)$$

Table 3. Tree damage parameters by live and dead condition, averages and ranges.

Condition	Hs, m	RCs, %	Ck, %	Csv, %
Live				
average	3.86a	37.0a	57.5a	60.6a
range	0.0-6.5	0-100	0-100	0-100
Dead				
average	3.24a	80.1b	93.0b	96.2b
range	2.1-4.2	50-100	75-100	90-100

Hs - height of crown scorch; RCs - ratio of crown scorch; Csv - percentage of crown volume scorch visually estimated; Ck - % of crown kill. Means followed by the same letter in a column are not significantly different (P<0.05).

Data indicates that crown scorch damage expressed as volume or length of scorch is a better predictor of tree mortality than scorch height. Several studies reached the same conclusion, which means that probability of mortality is accounted more by effective foliage injury than by fire behavior (Peterson 1985, Wyant et al. 1986, Ryan & Reinhardt 1988, Ryan et al. 1988). Some trees with 100% of crown scorch survived because most of the buds remained alive; Sucoff & Allison (1968) and Duhoux (1994) found the same phenomena. The logistic probability of mortality equations are on Table 4, and Fig. 1 for Ck and Dbh and Fig. 2 for Rcs and Dbh.

Table 4. Logistic models for predicting probability of tree mortality.

x_i	a	b_1	b_2	x^2	P
dbh	-10.173	2.017	-	30.04	0.0000
Ck 13.771	-15.345	-	26.95	0.0000	
dbh, Ck	-1.628	1.478	-7.070	33.31	0.0000
RCs	6.882	-9.083	-	23.46	0.0000
dbh, RCs	-5.703	1.607	-3.806	32.29	0.0000
Csv	29.923	-0.318	-	27.26	0.0000
dbh, Hs	-9.337	2.644	-1,212	31.44	0.0000

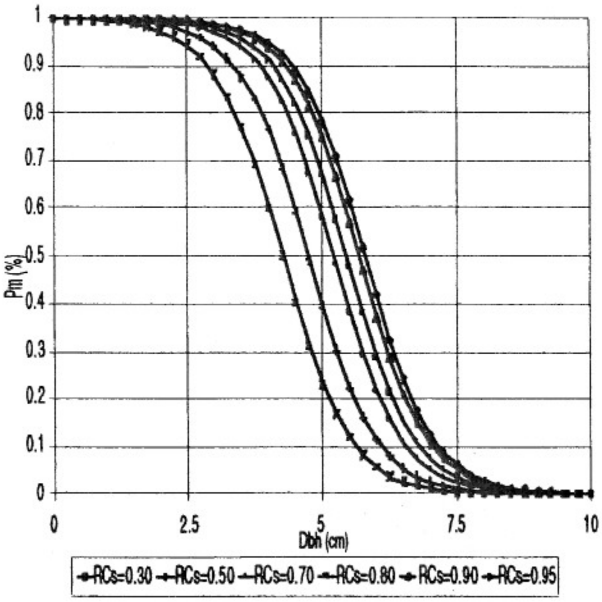

Figure 2. Mortality prediction by RCs and Dbh Y=1/(1+exp(-5.703+1.607*Dbh-3.806*RCs))

Conclusions

In previous works *Pinus pinaster* was considered a species highly resistant to heat (Duhoux 1994, Ryan et al. 1994a,b). Descriptors of tree injury and fire behaviour were relatively independent in this study, but the results show that this pine can withstand relatively high levels of fire behaviour with mortality restricted to small and dominated trees. An obvious conclusion is that prescribed burning can be conducted up-slope with the wind without detrimental effects on the trees, being a viable alternative when dead fuel moisture contents are too high to support backfire propagation. However, considering that growth rate can be reduced by the loss of significant amounts of photosynthetic foliage, the conditions for prescribed headfires execution must be carefully examined. Moderate fuel accumulations, low windspeeds and crown base heights higher than in this study are therefore advisable.

The predictive quality of the models is only suitable for identical situations. Solid knowledge on this issue requires more experiments covering the normal range of stand, fuel and weather conditions.

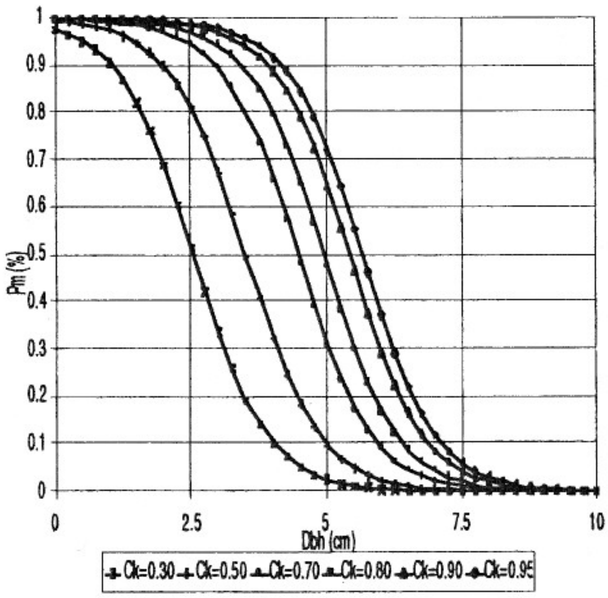

Figure 1. Mortality prediction by Ck and Dbh Y=1/(1+exp(-1.20+1.156*Dbh-5.671*Ck))

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