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Predicting potential cambium damage and fire resistance in *Pinus nigra* Arn. ssp. *salzmannii*

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ABSTRACT

Fire management can play a key role in ensuring stand maintenance in future scenarios of global change, particularly in *Pinus nigra* stands, which are known to be adapted to low-intensity surface fires through characteristics such as thick bark. In this study, laboratory tests were carried out to quantify cambium damage and fire resistance in *P. nigra*, by using a mass loss colorimeter device in a vertical configuration for the first time. In addition, low-intensity prescribed burning treatments were conducted in the field, and the field and laboratory data were compared. The following variables were used as proxy measures to assess cambium damage: time that temperature remained above 60 °C, heating rate and maximum absolute temperature in the inner bark area. The data were analysed using a Bayesian hierarchical approach (generalized linear mixed model). A threshold heat flux (25 kW m^{-2}) for the time to ignition of bark was identified. A critical temperature of 60 °C was reached in the cambium during the combustion phase, after the flame was extinguished. The laboratory experiments showed, for the first time, the influence of flame residence time on the potential cambium damage. A bark thickness of 17 mm can be considered the threshold level for preventing critical temperatures being reached in *Pinus nigra* stands. The influence of bark thickness on protection against fire was confirmed, as was the importance of the coefficient of variation of bark thickness. The field results showed that flame characteristics (maximum temperature and residence time) were the most significant predictors of cambium damage. The combination of fire intensity and exposure time at low heat fluxes is more important than bark in determining cambium damage and may have important implications in the field of forest fuel management and in the ecology of pine forests.

1. Introduction

Future scenarios of climate change project a longer period of fire season (Westerling et al., 2006) and an increase in burnt areas (Mann et al., 2016). Prescribed burning (PB) may be a tool to buffer the impact of wildfires on forest ecosystems properties (Plaza-Álvarez et al., 2017), mainly diminishing fuel loads. However, the way in which species display strategies to respond to perturbations is an important uncertainty in predicting the reaction of ecosystems (Pellegrini et al., 2017). Hence, forest managers require knowledge about the damage that fires cause in trees to enable the effective implementation of prescribed burning and for planning post-fire management.

Bark thickness is regarded as vital in stem resistance to fire (e.g. Harmon, 1984; Lawes et al., 2011a; Pausas, 2017), even in juvenile trees and saplings (Jackson et al., 1999; Midgley and Lawes, 2016). Furthermore, species that live in fire prone habitats, particularly those maintained by frequent low intensity surface fires, generally have thicker bark (Rosell and Olson, 2014). Mostly, it protects underlying tissues from temperatures above 60 °C that is commonly accepted to cause necrosis of the cambium (e.g. Hare, 1965; Dickinson and Johnson 2004; Bauer et al., 2010). High intensity fires may cause the death of the cambium around the entire bole circumference of stem, disturbing water and nutrient supply to the leaves and translocation of photosynthates to the roots (Rozas et al., 2011), which may cause death of the tree. If the fire does not cause the tree death, it may stress enough to the tree to show a systemic reaction which is reflected in a depletion of annual ring widths of the stem (Seifert et al., 2017). Other properties also influence fire resistance: specific gravity, moisture content, bark flammability and physical structure (Vines, 1968; Hengst and Dawson, 1993; Gignoux et al., 1997), although to a much lesser extent than bark thickness (VanderWeide and Hartnett, 2011; Odhiambo et al., 2014).

The area of distribution of *Pinus nigra* Arn. ssp. *salzmannii* (Spanish black pine) in the Mediterranean region has been reduced in the last decade, partly due to the incidence of more intense wildfires (López-Serrano et al., 2009). In addition, montane communities of Spanish black pine do not produce serotinous cones (Tapias et al., 2001), and the fact that they do not maintain a canopy or soil seed bank (Ordóñez et al., 2005) exacerbates the problem. Nonetheless, *Pinus nigra* is adapted to surface fire regimes by its thick bark and high crown base height (Pausas et al., 2008), as indicated by the presence of a relict, multi-aged forest in eastern Spain (Fulé et al., 2008). It is also a long-lived tree species with a relatively open structure (Fulé et al., 2008), in

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which post-surface fire growth remains unaffected (Valor et al., 2015). Fuel reduction treatments with low intensity prescribed burning may, therefore, be a good option for this species.

Several studies have been carried out to assess the insulating capacity of bark by monitoring cambial and surface temperatures, by experimental burning conducted in the field (Hengst and Dawson, 1993; Pinard and Huffman, 1997; Lawes et al., 2011a); in laboratory tests (Bauer et al. 2010; Odhiambo et al. 2014); or in both, field and laboratory, determining the distribution of temperature inside a tree under fire conditions (Costa et al., 1991). Other studies have assessed forest fuel flammability in forest species (Madrigal et al., 2009) or the relationship between flammability properties and the chances of survival after a fire (Frejaville et al., 2013). However, very few studies have considered together as predictor variables: bark traits, fire intensity and flammability (sustainability, ignitability and consumability) (Anderson, 1970; Martin et al., 1993; Pausas, 2017). In addition, most of the current studies have been conducted in non-Mediterranean ecosystems (Rosell, 2016) with different approaches and non-standardized methods, making it difficult to compare the results (Dehane et al., 2015). The established protocols by Della Rocca et al. (2018) and Madrigal et al. (2019) with the mass loss calorimeter (MLC), in a horizontal configuration, were used to characterize the resistance of bark to fire. Nevertheless, a vertical configuration (Dehane et al., 2015) seemed more suitable for simulating heating conditions and bark position in the field (Molina et al., 2018). The heat fluxes selected in the laboratory test covered a wide temperature range, simulating conditions observed in prescribed burning or in a wildfire and the bark thickness range sampled allowed tested the resistance threshold of *Pinus nigra* bark. However, because laboratory assessment of bark fire resistance is limited by the scale of the experiment, data from prescribed burning trials were required for comparison with data obtained in laboratory (Molina et al. 2018). Known the effectiveness of *Pinus nigra* bark against cambium damage due to overheating after the passage of fire, this study addressed the influence of additional variables that had not been sufficiently clarified to date. In this context, we explored the potential influence of coefficient of variation of bark thickness as there was not sufficient data to support its role in stem protection (Graves et al., 2014).

Because of live tissue in the inner bark is particularly sensitive to fire (Frejaville et al., 2013), and the degree to which the trunk resists fire depends on the flammability and thermal conductivity of the bark (Dehane et al., 2015), variables such as time of exposure to a critical temperature (60 °C), heating rate and temperature in inner bark were used as a good proxy measures for determining the potential damage to the cambium (Madrigal et al. 2019). Similarly, variables related to heat exposure, bark flammability – and the interactions between these – can potentially affect the resistance of bark to fire, although the available information is scarce (Frejaville et al., 2013; Varner et al., 2015), especially regarding thin barks. Thus, determining the most suitable variables for predicting tree damage caused by thermal injury may be key to understanding and making management decisions prior to fire (e.g. adjustment of fire prescriptions) and after fire for guiding the procedures adopted by land managers.

The novelty of this study is to address, for the first time, the influence of these variables both in the laboratory and in the field, being a first step to expand the results to other conifers. The aims of the present study were as follows: (i) to analyze some properties of *Pinus nigra* bark, such as thickness and the coefficient of variation of bark thickness, to determine the fire-induced cambium damage; (ii) to relate external variables of fire behaviour (temperature and heat exposure) and variables associated with bark flammability (sustainability, ignitability and consumability) to the resistance of the cambium to fire; and (iii) to compare the results obtained in the laboratory with those obtained in experimental low intensity prescribed burning treatments conducted in the field. We hypothesized that heat exposure and bark flammability should have an important effect on bark resistance to wildfires and prescribed fires under canopy.

2. Material and methods

2.1. Fire resistance tests in the laboratory

A mass loss calorimeter device was used to determine how bark resists fire in laboratory tests. Protocols have previously been established for determining bark flammability and fire resistance with a mass loss calorimeter (Dehane et al., 2015; Madrigal et al., 2019). However, this is the first time that an MLC device has been used in a vertical position. In this configuration, the radiation is distributed over the samples in a more realistic way, i.e. as in the field (Fig. 1a). Four heat fluxes were used, covering a wide temperature range, simulating conditions observed in prescribed burning or in a wildfire.

Pinus nigra trees were extracted from a pure stand located in El Pozuelo (Central Spain; 40° 34′ 45″ N / 002° 14′ 30″ W) with similar characteristics to those described in section 2.2. and in Espinosa et al. (2018). A total of 40 trees were selected to represent the absolute ranges of bark thickness previously measured in the study areas (Espinosa et al., 2018). Two circular samples of thickness 10 cm were obtained at a height of 0.50–0.70 m from the ground in each tree. Graves et al. (2014) recommended sampling at a height of 0.5 m from the ground because this is an ecologically relevant height for trees in low-intensity fire prone habitats. In the laboratory, each circular sample was divided into four subsamples of 10 × 10 cm to adapt to the dimensions of the MLC. The samples were stabilized at room temperature (20 °C) until constant weight. The absolute bark thickness (BT, mm) was measured (before and after the tests) in three positions in each sample (maximum, minimum and mean bark thickness) on the most representative face. The coefficient of variation of bark thickness was also calculated (CV, expressed in times 1), as the ratio between the standard deviation and the mean value for the samples. This coefficient was used as proxy for bark roughness. The thermocouples were placed in three holes drilled between the outer and inner bark. Another thermocouple was located on the surface of the bark, in the centre of the sample (for more details, see Madrigal et al., 2019). All samples were weighed before and after the test, and the weight loss was calculated (W, %). The distance between the MLC and the sample was 23 mm (Madrigal et al., 2019). Four heat flux rates (HF, kW m^{-2}) of 20, 25, 50 and 70, corresponding to air

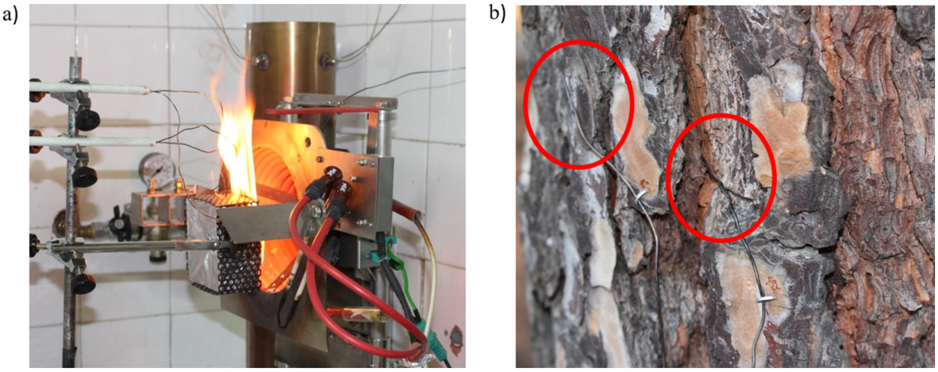

Fig. 1. (a) Laboratory test: mass loss calorimeter (MLC) device in a vertical configuration. (b) Field prescribed burning: thermocouples located in inner and outer bark.

Table 1
Summary of variables.

	Abbreviation	Variable	Unit
RESPONSE VARIABLES	t60	Time during which the temperature of the sample was higher than 60 °C in the cambium area	s
	HT	Heating rate in the cambium area	$^\circ C\,s^{-1}$
	Tmx	Maximum absolute temperature reached in the cambium area	°C
PREDICTOR VARIABLES		**Bark traits**	
	BT	Bark thickness	mm
	CV	Coefficient of variation of bark thickness	times 1
		Fire intensity	
	HF	Heat flux	$kW\,m^{-2}$
	te300	Time during which the temperature of the sample was above 300 °C at the surface	s
	Temx	Maximum absolute temperature reached at the surface	°C
		Sustainability	
	tf	Flame residence time	s
		Ignitability	
	ti	Time to ignition	s
		Consumability	
	W	Weight loss	%
	Bpo	Bark burned	%

Table 2
. Mean and standard deviation (in brackets) values of variables studied.

	–	–	**Heat flux rates**			
	Variable	Unit	H20	H25	H50	H75
RESPONSE VARIABLES	t60	s	548 (538)	880 (601)	1708 (736)	1907 (290)
	HT	$^\circ C\,s^{-1}$	0.0876 (0.0382)	0.1027 (0.0713)	0.1227 (0.0967)	0.1139 (0.0755)
	Tmx	°C	74 (37)	87 (47)	135 (112)	133 (80)
PREDICTOR VARIABLES				**Bark traits**		
	BT	mm	16.4 (9.6)	17.9 (10.7)	17.4 (9.1)	16.4 (8.7)
	CV	Times 1	0.49 (0.20)	0.50 (0.13)	0.44 (0.17)	0.51 (0.17)
				Fire intensity		
	te300	s	218 (123)	289 (129)	329 (84)	325 (18)
	Temx	°C	645 (175)	695 (158)	798 (190)	899 (83)
				Sustainability		
	tf	s	234 (98)	285 (82)	339 (59)	323 (8)
				Ignitability		
	ti	s	58 (18)	49 (33)	19 (49)	4 (2)
				Consumability		
	W	%	4.8 (2.0)	6.0 (2.0)	10.1 (2.7)	10.6 (2.9)
	Bpo	%	28 (24)	35 (17)	40 (24)	48 (16)

temperatures of 567, 620, 813 and 896 °C (calibrated with a radiometer: Madrigal et al., 2009), were selected. These temperatures are within the range of those measured or estimated in low and moderate-high intensity fires (Cheney, 1981), which can easily reach 1000 °C (Wotton et al., 2011). Thirty replicate samples were tested for each heat flux, except $HF = 20\ kW\,m^{-2}$, for which a total of 15 replicates were tested ($n = 105$). A pilot ignition system was used in the tests. Once the samples were exposed to the radiant heat, the delay between the beginning of the test and sample ignition was recorded (ti, s). Any event or anomaly (e.g. multiple ignitions) that occurred during the test was also recorded. Each test was continued until extinction of the flame (flame residence time; tf, s) or for up to 5 min (maximum exposure time). Finally, the samples were stored at room temperature until the temperature at the depth of the cambium fell below 60 °C. The maximum period of time chosen for simulation of the experimental surface fire is consistent with the typical duration of surface fires, i.e. 2–9 min (Vines, 1968; Hengst and Dawson, 1993). In order to characterize fire resistance, the time during which the temperature of samples was higher than 60 °C (t60, s) and the maximum temperatures reached in the cambium (Tmx, °C) were recorded. The heating rate at the depth of the cambium (HT, $^\circ C\ s^{-1}$) was also calculated. Kaloustian et al. (1996) established the temperature at which some Mediterranean plants lose weight by volatilization to be 300 °C, which is within the range of temperature at the flame tip (200–400 °C) reported by Wotton et al. (2011). Thus, the time during which the temperature of the samples was higher than 300 °C (te300, s) and the maximum absolute temperature (Temx, °C) were also recorded, by the surface thermocouple. The moisture content of the samples (H, %) was measured before each experiment with an electric resistance xylohygrometer equipped with insulated electrodes, graduated up to 30% in fractions of 1% (maximum). Corrections were made regarding the species and the air temperature (UNE-EN 13183–2). Prior to the experiment, each sample was scanned (scan type, 600 ppp) on the face on which the thermocouples were placed, to determine the area of bark and wood. The sample was rescanned after the test to establish the percentage of bark that had burned (Bpo, %). The images were processed with ImageJ® software. A complete summary of the variables used is shown in Tables 1 and 2.

2.2. *Field experiments*

The study was conducted in two areas in Central Spain (El Pozuelo and Beteta). El Pozuelo is characterized by a mixed stand of *Pinus nigra* (89%) and *Pinus pinaster* Ait. (Maritime pine) (11%) and Beteta by a pure stand of *Pinus nigra*. The mean tree density was 627 and 1286 trees ha^{-1} in El Pozuelo and Beteta, respectively. The mean height and diameter at breast height were 12.2 m and 19.8 cm respectively in El Pozuelo and 13.2 m and 18.8 cm in Beteta. Both stands are natural. Spanish black pine forests in the Cuenca Mountains have traditionally been managed using the shelterwood method, with a shelter-phase of 20–25 years and a rotation period of 100–125 years. Although this method changed in the last decades to an

Table 3
. Main parameters measured during and after prescribed burning treatments.

Z –	PT –	T °C	RH %	WS m s^{-1}	RS m min^{-1}	FLI* Kw m^{-1}	FH cm	FL* cm	SMx cm	SMn cm	C60% %
El Pozuelo	Spring burning	21.5 (1.2)	47.7 (5.3)	0.8 (0.6)	0.65 (0.10)	20.0 (8.8)	53 (15)	30 (6)	70 (41)	16 (9)	16 (–)
El Pozuelo	Autumn burning	11.9 (0.4)	67.0 (1.3)	0.3 (0.3)	0.59 (0.24)	11.2 (6.6)	17 (10)	23 (6)	34 (11)	5 (5)	18 (–)
Beteta	Spring burning	20.4 (1.5)	32.7 (2.3)	0.8 (0.1)	0.76 (0.09)	32.6 (13.3)	43 (8)	38 (8)	160 (16)	40 (18)	11 (–)
Beteta	Autumn burning	12.0 (0.9)	43.5 (0.8)	0.1 (0.1)	0.72 (0.03)	13.8 (10.7)	26 (13)	25 (9)	59 (26)	4 (3)	5 (–)

Note = Z: zone; PT: plot treatment; T: air temperature; RH: relative humidity; WS: mean wind speed; RS: fire rate of spread; FLI: fire-line intensity; FH: flame height; FL: flame length; SMx: mean maximum scorch height; SMn: mean minimum scorch height; C60%: total percentage of trees in which the maximum temperature in the cambium was higher than 60 °C. Standard deviation in brackets. (*) Byram, 1959.

uneven-aged system due to the difficulties in achieving successful natural regeneration (Tiscar Oliver et al., 2011). The topographic features of the study site correspond to an elevation of 1093 ± 122 m a.s.l. and flat ground, with a slope of between 3 and 10%. More information and details are reported in Espinosa et al. (2018). In order to carry out the PB, 12 experimental plots (n = 6 in El Pozuelo and n = 6 in Beteta) of 30 × 30 m were established. Two types of treatments were applied in each zone: spring burning (conducted in May 2016) and autumn burning (conducted in November 2016). Triplicate samples were included in each treatment. The strip ignition technique was applied at distances of 1–2 m downhill and with upslope wind. This technique is the most widely used in the study area to produce low-medium intensity fire (Vega, 2001). The main characteristics of the PB treatments are shown in Table 3.

Bark thickness was measured (to the nearest mm) with a bark gauge. The gauge was inserted to the point of resistance of the cambium. Bark thickness was defined as the distance from the cambium to the bark surface. When the bark was uneven, the maximum thickness was measured at the highest point and the minimum thickness at the lowest point of the bark surface. However, because of the irregularity in the bark surface and the difficulty in estimating the exact measurement location, bark thickness measurements are estimated to be accurate to approximately 0.5 mm (Butler et al., 2005).

A total of 15 trees per plot were chosen on the basis of the diameter class. In each prescribed burning, two thermocouples were placed in each selected tree, one beneath the bark at the cambium and other in the outer area of bark at 0.6 m from the base (Graves et al. 2014) (Fig. 1b). At each location, a hole was drilled through the tree to insert the corresponding thermocouple at the cambium level. The hole was then covered with aluminum foil to prevent heat from entering during the PB. The thermocouples (type K 1 mm diameter inconel-sheathed, with response time of 0.3 s) were connected to data loggers (DT-USB TCDirect®), which recorded the temperatures every second. The data loggers were buried to prevent them being destroyed by the fire.

2.3. Data analysis

Three types of response variables were chosen to determine the damage to the cambium for each heat flux: time during which the temperature of cambium was above 60 °C, heating rate of cambium and maximum absolute temperature in the cambium. As shown in Table 1, predictor variables were related to bark traits, fire severity, sustainability, ignitability and consumability (White and Zipperer, 2010).

Initially, exploratory data analysis (EDA) was carried out in order to summarize the main characteristics of the data set. EDA was a critical first step to determine what the data might indicate beyond the Bayesian approach or starting assumptions. Scatter plots were constructed in order to map each variable to an x- or y-axis coordinate, and relationships between explanatory variables were established.

Generalized linear models (GLMs) are commonly used to model relationships between variables. The response and variable parameters are assumed to be random in the Bayesian approach, and a distribution must therefore be assigned to the parameters, i.e. the "prior distribution". Any parameters that define the prior distribution are called hyperparameters. A Bayesian version of the Gaussian GLM with an identity link can be described as follows. Let (x_i, y_i), $i = 1, \cdots, n$ be a set of observations. It is assumed that y_i follows a Gaussian distribution with mean $\mu_i$and variance σ^2, the identity link function (i.e., $g(\mu_i) = \mu_i$) and linear predictor $\eta_i = \beta_0 + \beta_1 x_1$. That is,

$$\tilde{y}_i N(\mu_i, \sigma^2)$$

$$\tilde{\mu}_i \beta_0 + \beta_1 x_{i1} + \cdots + + \beta_n x_{in}$$

$$\widetilde{\beta_0} f_1$$

$$\vdots$$

$$\widetilde{\beta_n} f_n$$

$$\sigma^{2\sim} f_m$$

Note that the model is the same as in the frequentist approach, but that it is now assumed that $\beta_0, \cdots, \beta_n$ and σ^2 are realizations from distributions $f_0, \cdots, f_n$ and f_m respectively. To implement this type of model in R (statistical software version 3.6.0), the integrated nested Laplace approximation (INLA) was used via INLA function in the INLA package (Rue et al., 2009).

To evaluate the model fit, we applied the Watanabe-Akaike information criterion (WAIC) (Watanabe, 2010). WAIC has been suggested to be appropriate for estimating the out-of-sample expectation in a fully Bayesian approach. This method starts with the computed log pointwise posterior predictive density and then adds a correction for the effective number of parameters, to adjust for overfitting (Gelman and Shalizi, 2013). The Watanabe-Akaike information criterion works on a predictive probability

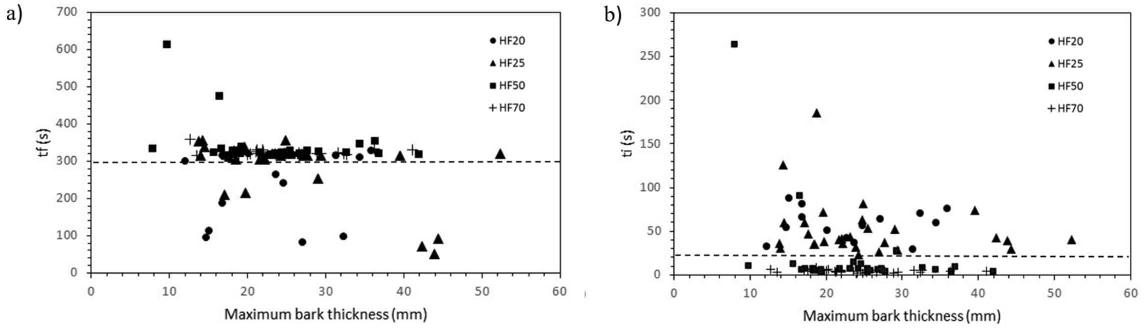

Fig. 2. (a) Relation between maximum bark thickness and flame residence time (tf) for the different heat fluxes (HF). (b) Relation between maximum bark thickness and time to ignition (ti) for the different heat fluxes (HF).

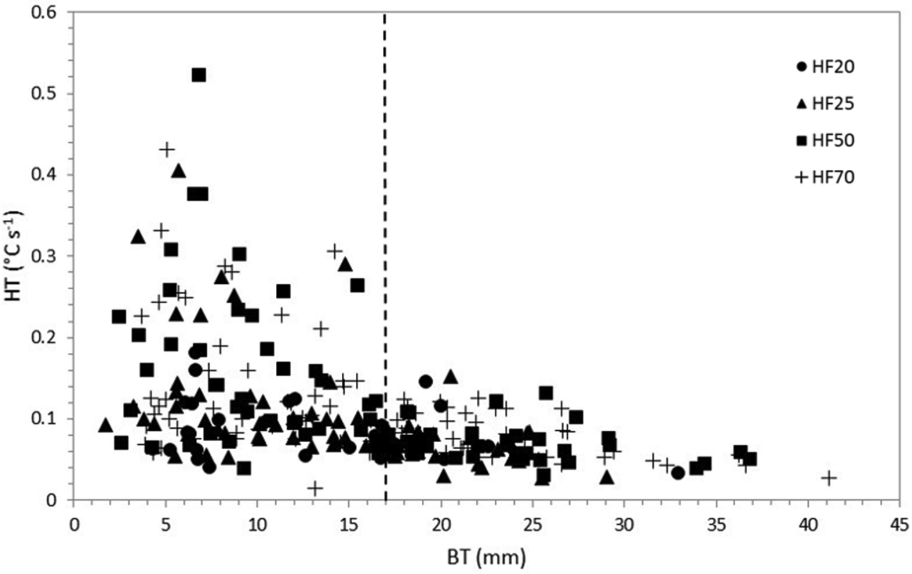

Fig. 3. Relation between bark thickness (BT) and heating rate in the cambium (HT) at the different heat fluxes (HF) tested.

density of detected variables rather than on the model parameter, and it can therefore be applied in particular statistical models (i.e. models with non-identifiable parameterization) (Li et al., 2016).

3. Results

3.1. Laboratory tests of fire resistance

The thickness of the bark samples (n = 315) ranged from 1.8 to 52.3 mm (standard deviation 9.5 mm). The samples can be considered dry, according to the mean moisture content (7.3 ± 1.5%). The relationship between maximum bark thickness and flame residence time is shown in Fig. 2a. In samples subjected to heat fluxes of 50 and 70 kW m^{-2}, the flame was extinguished shortly after the maximum exposure time (300 s) in most cases. The relationship between maximum bark thickness and time to ignition (Fig. 2b) revealed a threshold at around 20–23 s, with different responses for the two lowest heat fluxes HF20 and HF25 (ti ranged from 23 to 185 s) and the two highest heat fluxes HF50 and HF70 (ti ranged from 2 to 20 s with three peaks). The lowest ti variability was related to higher HF.

The heating rate in the cambium is shown in Fig. 3. The exponential trend suggests that HT tended to be constant for bark of thickness > 17–20 mm, showing higher variability with bark thickness lower than 17 mm.

The median temperature curves at the cambium level for each HF are shown in Fig. 4. The critical temperature of 60 °C was not reached at HF = 20 kW m^{-2}. The temperature of the cambium continued to increase 5 min after of maximum exposure time, indicating that the bark continues to provide heat to the cambium during combustion. After 6–7 min, the cambium temperature exceeded 60 °C at almost all the HF (except 20 kW m^{-2}), reaching a maximum of 100 °C at the highest HF tested.

3.2. Bayesian models

The estimated fixed effects in the laboratory data are graphically represented in Fig. 5, in which the variables and their relationships with t60 (Fig. 5a), HT (Fig. 5b) and Tmx (Fig. 5c) are shown. The variables distributed on the positive side of each figure contribute to higher response values; by contrast, variables distributed on the negative side in each figure contribute to negative response values. This distribution is

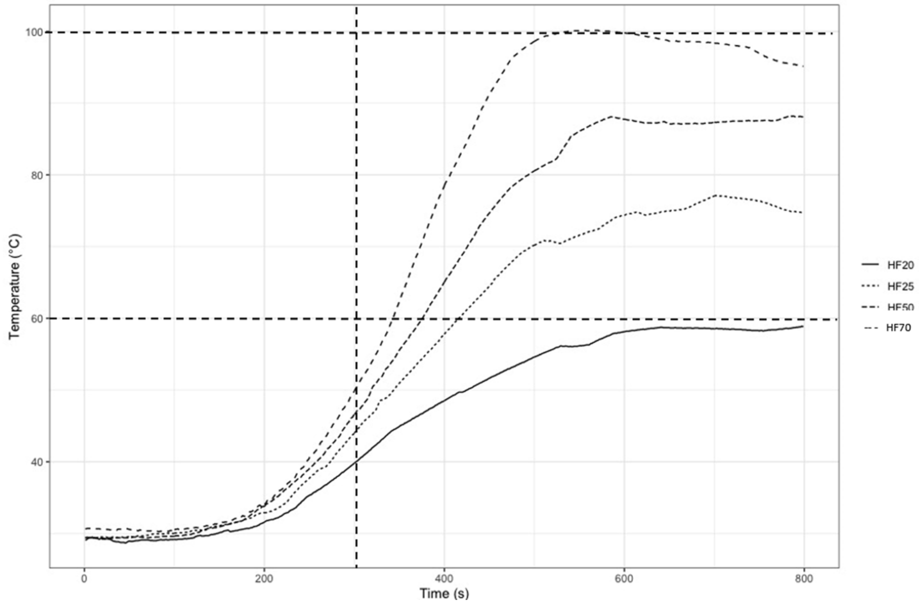

Fig. 4. Median temperature curves at the cambium level for each heat flux (HF) tested.

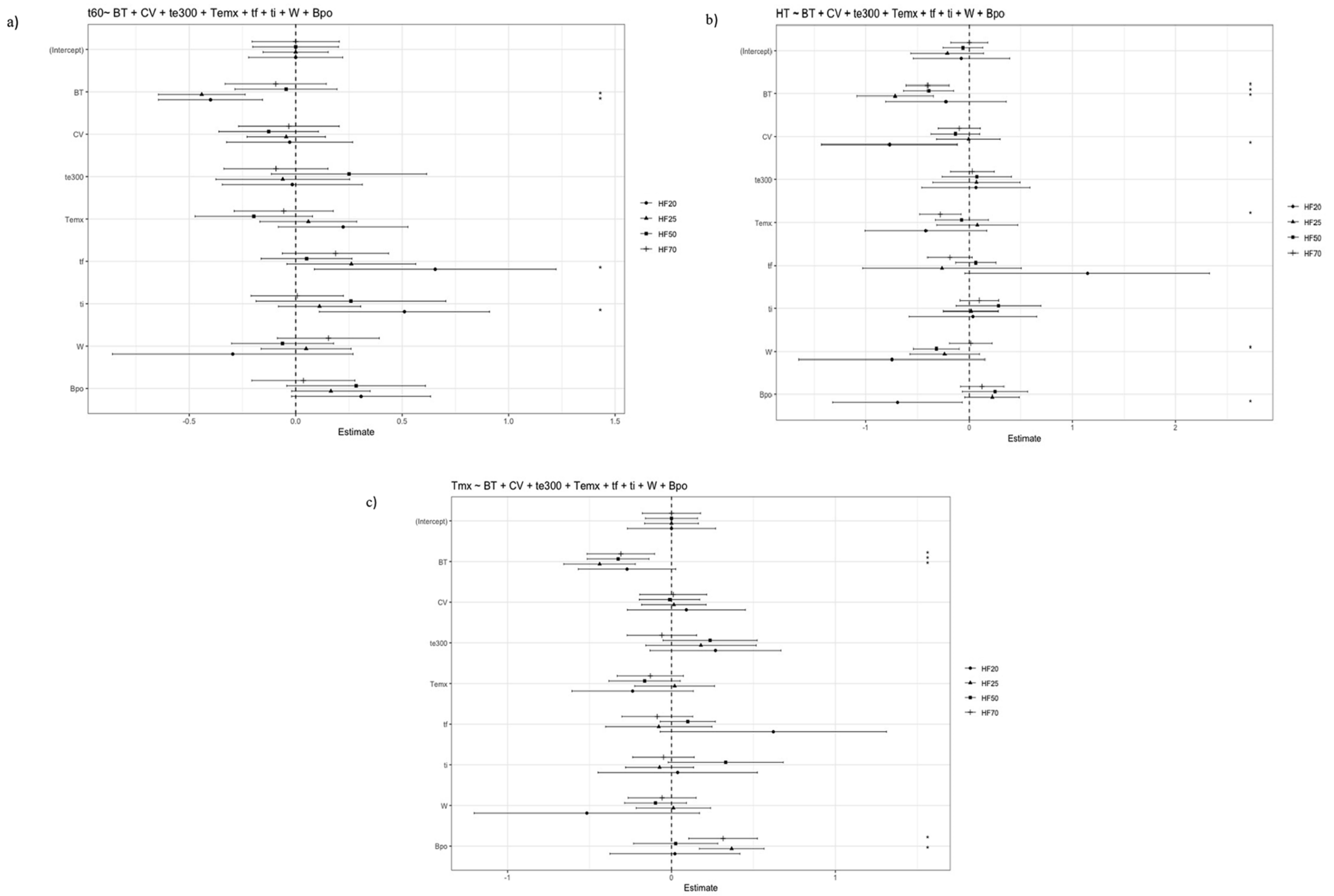

Fig. 5. Graphical representation of fixed effects of (a) time during which the temperature of the samples was above 60 °C (t60); (b) heating rate (HT); (c) maximum absolute temperature reached in the cambium area (Tmx) for laboratory data. * indicates a significant difference. The abbreviations are explained in Table 1.

summarized in more detail in Table A.1 (supplementary material) with mean, standard deviation and 95% credible interval for the different variables. Variables in both areas (positive and negative) in Table A.1 are not clearly related to the response variable.

The different variables behaved differently depending on the heat flux applied. Analysis of the relationships between t60 and the covariates BT, CV, te300, Temx, tf, ti, W and Bpo (Fig. 5a) revealed a negative relationship between BT and t60, but which was only significant for HF20 and HF25. A positive trend was also observed for tf, ti and Bpo, although only tf and ti in HF20 were significant.

Fig. 5b shows the relationships between HT and the same covariates as in Fig. 5a. In this case, there was a significant relationship between BT for all HF, except 20 kW m^{-2}. However, CV and Bpo were significant variables at this lowest HF. No significant relationship was observed for tf and ti. Similarly, Fig. 5c shows the relationship between BT and Bpo.

In order to compare the laboratory and field results, a graphical representation of the estimated fixed effects in the field data is presented in Fig. 6 and Table A.2 (supplementary material). Common descriptor variables were used (BT, CV, te300 and Temx), as some variables cannot be reproduced in the field. Data from spring burning and autumn burning were analysed separately. Bark thickness and CV were randomly related to t60, HT and Tmx in both seasons. Significant results were obtained for te300 (in response variables t60 and Tmx) and Temx (in response variables t60 and HT), especially in spring burnings, in which the fire intensity was highest.

4. Discussion

Information about the way in which bark properties and fire behavior interact is important in relation to fire management decisions. Previous analysis of data showed that once the samples were no longer exposed to radiant heat, the flame tended to be extinguished within a short period of time (Fig. 2a). In addition, the time to ignition indicated a threshold heat flux of 25 kW m^{-2} (Fig. 2b). Two types of responses were observed. For the two lowest heat fluxes ($\leq$25 kW m^{-2}), the time to ignition was longer than 20 s, while for the highest heat fluxes ($>$ 25 kW m^{-2}), the time to ignition was shorter than 20 s. This limit of heat radiance has been proposed as representative of a low-moderate intensity fire (Cruz et al., 2006; Madrigal et al., 2019). Madrigal et al. (2019) observed (by cluster analysis) two different types of response in samples of *Pinus pinea*, with BT higher than 20 mm and less than 20 mm. However, this was not observed in the present study, and a good fit to the curve was not achieved, partly due to the different sample sizes and the wide range of bark thicknesses selected in this study. Nevertheless, a limit of around 17–20 mm can be seen in Fig. 3, where the curve tends to stabilize. Thus, a bark thickness of 17 mm can be considered the critical threshold at which the probability of cambium death decreases. Both of these values are remarkably similar to those reported for deciduous trees in Bolivia ($\geq$18 mm) (Pinard and Huffman, 1997), for three species of *Eucalyptus* ($>$ 20 mm) (Wesolowski et al., 2014) and for tropical eucalypt species ($\geq$24 mm) (Lawes et al., 2011b). In the series of tests carried out, heating flux increased from 20 to 70 kW m^{-2}, conditions that can be reached in prescribed burning or in wildfire. Considering that a maximum exposure time of 300 s can be considered a high level of exposure (corresponding to a high intensity fire or a very low rate of spread), the median temperatures in the cambium were reached after an exposure time of 300 s. These findings show that (i) the bark was exposed to a high level of radiation, but the damage to the cambium is negligible or low for all heat fluxes tested, at least during 300 s; (ii) the highest level of cambium damage (temperatures above 60 °C) was detected after radiant exposure corresponding to the bark combustion phase: bark burns slowly sustained by the

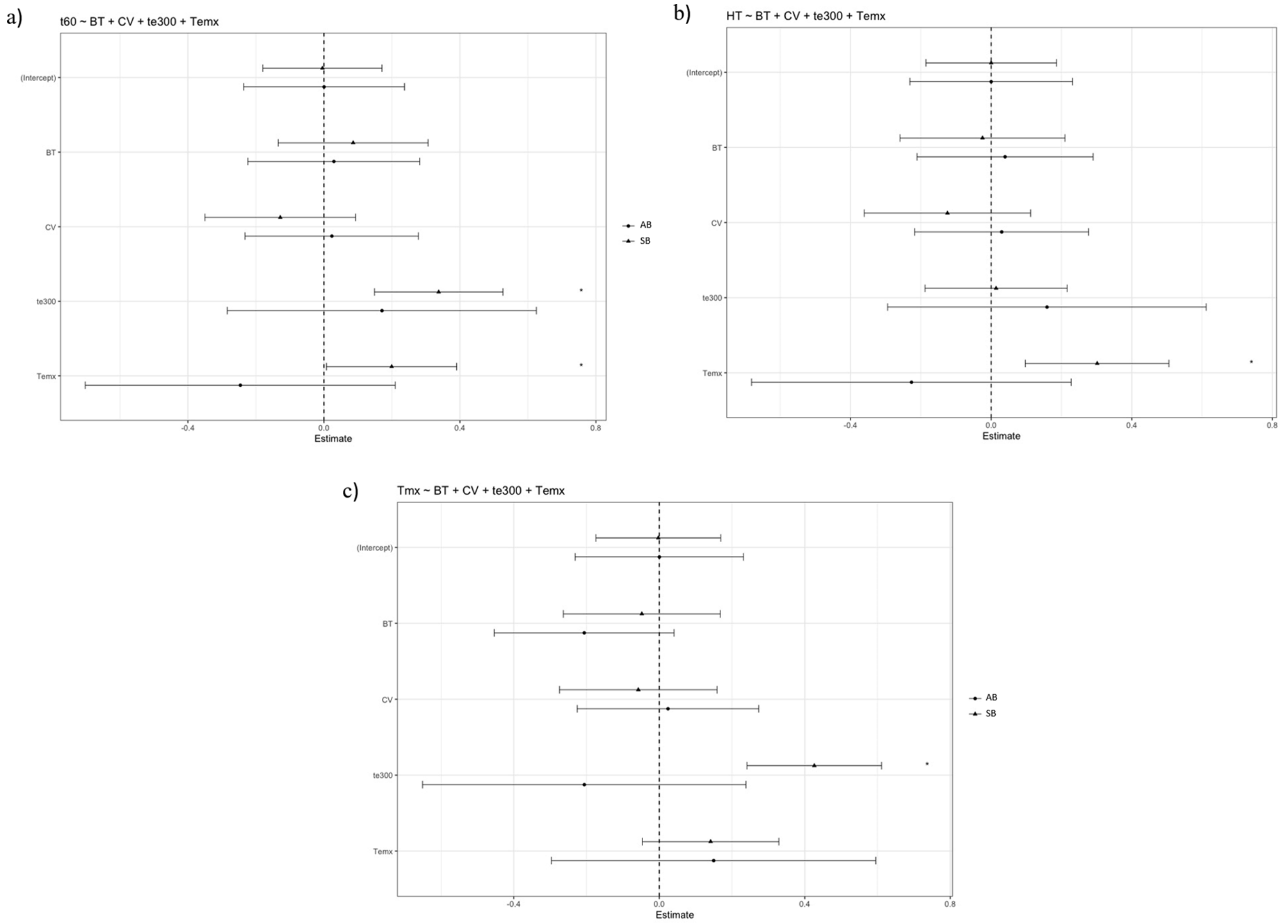

Fig. 6. Graphical representation of fixed effects of (a) time during which the samples were heated above 60 °C (t60), (b) heating rate (HT) and (c) maximum absolute temperature reached in the cambium area (Tmx) for field data. SB, spring burning; AB, autumn burning. * indicates significant difference. The other abbreviations are explained in Table 1.

heat without flame (smouldering). Furthermore, the intensity and exposure time at radiant source were proposed as a critical combination for establishing cambium damage (especially in thin bark). To our understanding, this is the first experimental evidence that the potential damage to the cambium caused by the combination of heat and exposure is exacerbated by bark flammability.

The study findings confirmed the key role of bark thickness in protecting the cambium against fire for all variables considered as predictive of cambium damage (time that the cambium is above 60 °C, heating rate and maximum absolute temperature in the cambium). Other studies have also shown the role of bark in protecting the stem (e.g. Lawes et al., 2011a; Brando et al., 2012; Pausas, 2017). This relationship was not significant at HF20 for HT and Tmx, possibly because the insulating capacity of bark provides complete protection at lower HF (Fig. 4) and thus other variables, such as the flame residence time (tf), may be more meaningful. These findings are consistent with those reported by Seifert et al. (2017), confirming that the time of exposure to fire is a determining factor in causing damage to the cambium.

Coefficient of variation of bark thickness seemed to have a slightly positive effect on protection of the cambium via two response variables, t60 and HT (although the relationship was only significant for HT at low heat flux). Although there is not sufficient data to support the role of bark roughness in protecting the stem, it has been suggested that it provides protection against sun scald, extreme diurnal temperature fluctuations, pathogens, nutrient losses and the adaptation of dead cells to the increase in diameter (Glitzenstein and Harcombe, 1979). Bauer et al. (2010) and Odhiambo et al. (2014) explained that the spaces within the dead outer bark layers are filled with air, which enhance the resistance to heat. The same explanation was given by Pinard and Huffman (1997), who stated that the air trapped in void spaces of structured bark increases heat insulation due to low heat conductivity. Furthermore, habitat has been considered a predictor of roughness, with fire prone areas having rougher bark than fire sensitive species (Graves et al., 2014). However, Frejaville et al. (2013) did not observe any significant influence of bark roughness in fire resistance in trees in an Alpine ecosystem. Despite having positive effects, roughness, density and the moisture content of bark have been shown to have little effect relative to bark depth (Hengst and Dawson, 1993; Pinard and Huffman, 1997; Brando et al., 2012). The present findings show that roughness is a significant variable in reducing cambium damage only at low heat flux, which is consistent with ecological evidence of species adapted to low intensity fires (Pausas, 2017).

The time during which the temperature was above 300 °C in the outer bark (air surface) appeared to have different effects for temperatures above 60 °C, heating rate and maximum absolute temperature in the cambium, varying among heat fluxes, but with no clear relationship. As thermocouples were located on the outer bark (at 23 mm from radiant flux) and radiation fluxes ranged from 20 to 70 kW m^{-2}, it is reasonable to expect temperatures above 300 °C during the time that thermocouple were exposed to heat. This does not therefore seem to be a good indicator of cambium damage, at least in laboratory tests. Similarly, the maximum absolute air temperature was not a good predictor of cambium damage, producing random responses for the different variables (t60, HT and Tmx) and heat fluxes. Temperature peaks may not affect the cambium if they are not prolonged. This is due to the insulating capacity of bark (Graves et al., 2014), described as a combination of thermal conductivity and the ease at which a temperature pulse moves through a given thickness of bark (thermal diffusivity). Thus, one-off heating of bark does not imply a response in the cambium area. Costa et al. (1991) reported that temperature at a specific location inside a tree is actually influenced by the distribution of temperature over the whole bark surface, which is very irregular under fire conditions.

A longer flame residence time was expected to have negative effects on the cambium area. According to experimental results (Fig. 4) flame residence time higher than 5–6 min could be critical for cambium damage. In this context, a significant relationship between tf and t60 was observed at HF20 (Fig. 5a) and although not significant for HT and Tmx, it was notable (Fig. 5b and 5c). As already mentioned, at lower heat fluxes (HF20), bark thickness completely protects the cambium cells, and the findings indicate that variables related to flame residence time may be more important. Madrigal et al. (2019) reported that the duration of heating required to damage or kill the cambium is proportional to the squared value of bark thickness. Likewise, the findings showed that a longer time to ignition (what implied a longer exposure time in laboratory test) may produce higher values of t60 and HT. Although not clear, it is possible that there is a positive relationship between tf and ti for HF20 (correlation coefficient of -0.2) (Fig. 5a). Frejaville et al. (2013) suggested that flammable bark would increase the heat transfer to the cambium due to a reduction in bark thickness and blackening of the bark surface. Likewise, other studies have emphasized that high flammability may potentially generate an increase in fire vulnerability (Dehane et al., 2015). Information about the relationship between flammability and thermal conductivity of bark is scarce despite being important for characterizing the vulnerability of living tissues in the trunk (Dehane et al., 2015).

Two variables were selected in order to measure the consumability: percentage weight and bark consumed. There did not seem to be a clear relationship between weight and time that the cambium remained above 60 °C, heating rate and maximum absolute temperature in the cambium for any heat flux. However, a greater reduction in bark surface had a negative effect on the cambium. The percentage weight loss is probably related to water loss and volatilization of gases. However, reduction in bark surface would be related to the loss of bark thickness and therefore to less protection of the cambium. In fact, small differences in bark thickness produce large differences in fire resistance (Bond and van Wilgen, 1994; Moreira et al., 2007).

The results obtained in the mass loss calorimeter were compared with those obtained in PB conducted in the field (Fig. 6) for a more realistic representation of how bark is affected by fire (Molina et al., 2018). No significant results were observed in relation to the cambium damage and BT or CV. During spring burnings, temperatures of 60 °C in the cambium were only exceeded in 16% of the trees in El Pozuelo and 11% of those in Beteta. In the autumn burnings the percentages were 18 and 5% respectively in El Pozuelo and Beteta (Table 3). These values may be indicative of low intensity fires, and thus the bark (near the ground level) presumably protects the cambium (Graves et al., 2014), particularly in species with thick bark, such as *Pinus nigra*, which are more tolerant of this type of fire. The lack of a significant relationship therefore makes sense. However, time during which the temperature of the sample was above 300 °C and maximum absolute temperature at the surface had significant effects on t60 and Tmx and on t60 and HT respectively. Variables such as te300 or Temx showed some capacity to predict cambium damage as a value of punctual severity at tree level. These variables indicate individual overheating of the tree, which did not occur in laboratory tests, as the trials are more homogeneous. Higher heating was mainly due to the natural accumulation of branches fall around the tree or lichens growing along the stem, which led to a longer residence time of the fire. However, radiation from intense, more distant flames may have the same effect (Vines, 1968). Therefore, the choice of the prescribed burning technique (e.g. strip ignition) should favour rapid advancement of the fire front, which should prevent the trunk overheating and excessive consumption of organic matter (Vega, 2001), even in a low-intensity fire. In addition, the removal of fuel accumulations at the base of the trunk is recommended to reduce the residence time of the flames. Additional data from more intense PB trials are needed in order to confirm these findings and for comparison with laboratory-acquired data. Nevertheless, the findings for the *Pinus nigra* stands and the additional values obtained in the laboratory (see above) confirm the idea that these stands are not very vulnerable to low-intensity fires, because of the high resistance of bark to fire (Valor et al., 2015) and because only local conditions at tree level can generate local burn intensities that can potentially cause damage to the cambium (Jiménez et al., 2017, Madrigal et al., 2019).

5. Conclusion

In this study, a mass loss calorimeter device was used in a vertical configuration for the first time in laboratory tests. A threshold at 25 kW m^{-2} was detected as representative of low-moderate intensity fires, so that below this value, negligible cambium damage is expected. This could be considered a reference value for improving fire prescriptions or evaluating potential mortality rates after surface wildfires.

The flame tends to become extinguished shortly after the end of radiant heat exposure (300 s), even at high heat fluxes, although smouldering fire on bark increases the temperature of cambium. The process described demonstrates for the first time that bark flammability (duration of flame and bark surface burned) significantly affects the potential damage to the cambium. These findings lead the way to new studies relating ecological and combustion properties of tree bark and the potential influence of these properties in protecting living tissues after fire. The study findings confirm the influence of bark thickness in preventing cambium damage during the passage of fire in *Pinus nigra* stands. A bark thickness of 17 mm was found to be critical regarding cambium death. There is no consensus about how bark roughness contributes to protecting against low-intensity fire; however, the results obtained for two variables representative of cambium damage indicate that roughness may have a positive effect in protecting the cambium during low heat exposure.

The results of laboratory tests and field burning suggest that, at low heat flux, other variables, such as flame residence time, may be more important than bark thickness for protecting the cambium from the effects of fire. Thus, the combination of intensity and time of heat exposure appear to be decisive.

The time during which temperature remains above 300 °C at the bark surface and maximum absolute temperature in the cambium were not good predictors of cambium damage in laboratory tests, in which the burning was homogeneous. However, they were good indicators in field trials, as the PB generated different levels of heating in the tree. These findings show the importance of confirming laboratory findings with additional field data.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2020.118372.

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