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Tree Growth Response to Low-Intensity Prescribed Burning in *Pinus nigra* Stands: Effects of Burn Season and Fire Severity

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Abstract: The study of the short-term post-burn tree growth in a mixed stand of *Pinus nigra* and *Pinus pinaster* and in a pure stand of *P. nigra* in the Cuenca Mountains (Spain) will enable us to determine the disturbance of prescribed burning conducted in two seasons. Dendrochronological methods and mixed modelling were used to investigate whether tree growth responses are influenced by stand and tree characteristics, fire season and fire severity variables. The findings revealed that prescribed burning scarcely affected tree growth. The type of stand (mixed or pure) was not critical for tree growth. The individual tree characteristics were significant factors in all the scenarios studied. The inclusion of some fire severity variables for the first time in tree growth models showed that the maximum scorch height determined a main part of the variability of tree growth. The time during which the temperature was above 60 °C in the cambium region and temperature was above 300 °C in the bark surface were only significant factors after spring burnings. The litterfall one year after the prescribed burning was not a significant factor in any of the models. Overall, the findings confirm the characteristic resistance of *P. nigra* to surface fires and favor the potential application of prescribed burning programs for this species in the Mediterranean Basin.

Keywords: forest ecology; disturbance; fire ecology; forest management; forest fires

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1. Introduction

Large wildfires are a common occurrence in Mediterranean forests. However, within the framework of global climate change, interactions between climate and fire may accentuate the effects, or at least, alter the stress on ecosystems [1,2]. Prescribed burning (PB) is an active forest management tool that can reduce the intensity and severity of forest fires, when it is strategically applied in both time and space [3–5]. Beyond fire prevention, PB may also be beneficial for the vitality of ecosystems, recovering the distribution of the most balanced vegetation layers and occasionally improving biodiversity [6–8]. Nonetheless, PB activity in southern Europe remains local in scope and the area treated is quite modest [9], although in recent years an effort is being made to include PB in forest management plans. In addition, forest managers often do not have access to accurate and research-supported information about the potential effects of prescribed burning on different forest ecosystems. This may lead to the application of unsuitable prescribed fire regimes that can cause significant damage or mortality to tree species and indirectly alter biotic and abiotic processes [10].

The responses of plant function to fire activity are complex and can vary widely [11]. Thus, fire-surviving trees can be compromised in their physiological functionality, show reduced growth and be more likely to succumb to delayed death (e.g., [12–14]). Conversely, the injured trees may also benefit in the short- and mid-term from reduced competition [15–17]. However, few studies have modelled individual growth responses as a function of tree and stand characteristics including fire intensity (e.g., residence time above a lethal temperature) and severity variables (e.g., scorch height or total amount of litterfall after fire treatment) [16,17]. In the Cuenca Mountains (Iberian System), prescribed burning is usually carried out in the early season (spring) and late season (early autumn). Although the burn season can be easily controlled in PB treatments, little is known about how the burn season affects post-fire tree growth [17]. Some studies have shown that early season burning at the beginning of the annual growth period is more likely to cause heat damage [18,19]. Conversely, late season burning is likely to be of greater intensity because the fuels are drier [20], which may exacerbate tree mortality [21].

Other specific stand and individual tree characteristics are widely recognized sources of variability in relation to tree growth (e.g., density, age, phenotypic plasticity, genetic variability and interactions with site factors) [22–24] and should be considered in tree growth studies. The present study involved a mixed stand of *Pinus nigra* Arn. ssp. *salzmannii* (Spanish black pine) and *Pinus pinaster* Ait. (maritime pine) and a pure stand of *P. nigra*. The Cuenca Mountains are representative of areas where the *P. nigra*-*P. pinaster* ecotone generates stable stands with ecosystem services of high ecological value. This species richness has previously been associated with stand-level stability in the face of disturbance [25–27], which may be explained by the aggregate properties of species. Thus, the exploration of the resilience of pure and mixed stands to perturbations such as prescribed burning is essential to establish recommendations for management and fire prevention strategies in this area. In addition, these species have been recognized to be adapted to surface fires with the following different characteristics: thick bark, high crown base height, self-pruning strategy and open structure in the case of *Pinus nigra* (e.g., [28–30]) or serotine cones and thick bark, large buds shielded by scales and by long needles in the case of *Pinus pinaster* (e.g., [28,31,32]).

Moreover, in order to achieve the management objectives of PB, the burn window must be applied to reach the desired outcomes regarding fire behavior and the associated impacts. The maximum scorch height and time of exposure to a critical temperature of 60 °C in the cambium area [33] were used in the present study as proxies for damage to the cambium and severity of burning at the tree level [34,35]. As far as we are aware, this is the first time that these variables have been included together in tree growth models. The inclusion of these variables may improve the results in relation to predicting the effect of burn intensity and duration of high temperatures on living tissues below the bark (damage or severity of fire in cambium and phloem), which have been considered the most important stress factors affecting trees [36]. In addition, the time of exposure to a critical temperature of 60 °C in the cambium area has been proposed for improving growth models [16]. At the same time, tree growth is closely related to the amount of leaf-fall [37]. Tree growth often declines after fire [38] because burning affects photosynthesis by increasing leaf-fall and, thus, reducing the photosynthetic efficiency of the remaining leaves [39] and also by altering transpiration patterns and water use efficiency [40]. However, some positive effects on tree growth after PB have been described in relation to crown damage [41]. The variables commonly used to indicate crown injury criterion include the level of crown scorched and the crown scorch height (e.g., [42]). However, nothing is known about the effects of an increase in litterfall biomass after PB on tree growth. In a recent study in the same experimental plots, we found that even low-intensity PB (with low values of crown scorched and crown scorch height) can increase the litterfall relative to that in unburned plots in the short-term [43]. Thus, litterfall biomass after PB was included for the first time in the model as a predictor of burn severity at the stand level, relating crown damage and tree growth.

In this study, we examined how PB conducted as a surface fuel hazard reduction treatment in two different seasons (spring and autumn) affected the short-term growth of two types of *Pinus nigra* stands (mixed and pure). In the context of a more comprehensive study of the introduction of prescribed fire as a management tool in Spanish forest stands [44], we hypothesize that low-intensity PB will not have an important effect on tree growth in the short-term and that the fire effects will be more notable in pure stands owing to the greater resilience of mixed stands to perturbations [25,43,45].

The study aims were as follows: (i) to ascertain any consistent variations in the post-PB growth of *P. nigra*; (ii) to examine the potential effects of burning season; (iii) to analyze the interactions between species mixture and burning on tree growth; and (iv) to explore the effect of fire severity during burning at tree and stand level.

2. Materials and Methods

2.1. Study Sites

Two areas in the Cuenca Mountains (Iberian System) separated by a straight-line distance of 14 km were selected for the study (Figure 1): a mixed stand of *Pinus nigra* (89 ± 11%) and *Pinus pinaster* (11 ± 11%) in El Pozuelo and a pure stand of *P. nigra* in Beteta. The main characteristics of both stands are shown in Table 1.

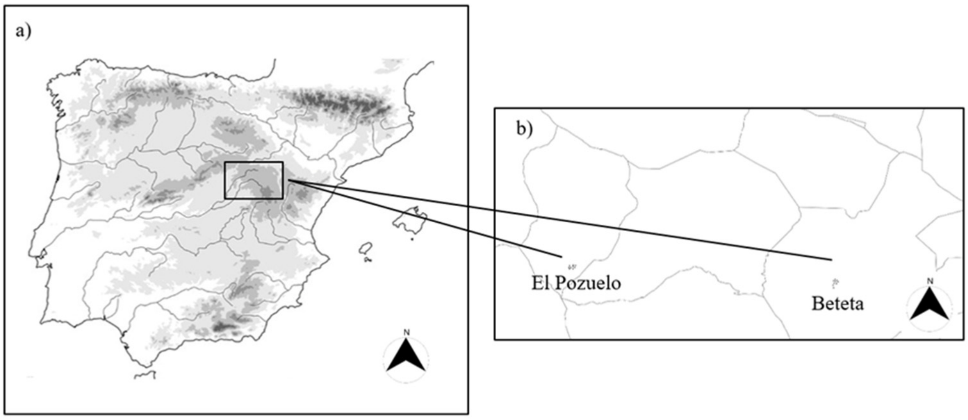


Figure 1. Locations of the study plots in (**a**) the Iberian Peninsula (1:1,250,000); (**b**) El Pozuelo (mixed *P. nigra*-*P. pinaster* stand) and Beteta (pure *P. nigra* stand) (1:50,000).

Table 1. Main characteristics of mixed and pure stands (mean and standard deviation) [46].

–	Mixed Stand	Pure Stand
Coordinates—Longitude	40°33′36″ N	40°33′06″ N
Coordinates—Latitude	002°15′56″ W	002°06′32″ W
Main species	*Pinus nigra* (89 ± 11%) *Pinus pinaster* (11 ± 11%)	*Pinus nigra* (100%)
pH of topsoil [1]	7.3 (clay texture)	6.9 (loamy-sand texture)
Elevation	1016 ± 5 m asl	1232 ± 7 m asl
Slope	3–8%	3–10%
Stand density	627 ± 238 trees ha^{-1}	1286 ± 339 trees ha^{-1}
Stand basal area	25.4 ± 9.7 m^2 ha^{-1}	36.6 ± 10.7 m^2 ha^{-1}
Dominant tree height	18.6 ± 0.8 m	17.0 ± 1.6 m
Tree height	12.2 ± 2.0 m	13.2 ± 2.7 m
Diameter at breast height (DBH)	19.8 ± 2.6 cm	18.8 ± 4.1 cm
Bark thickness	1.7 ± 0.3 cm	1.7 ± 0.4 cm

[1] Data from [45].

According to the data recorded at the Cañizares weather station (940 m asl) and provided by the State Meteorological Agency of the Spanish Government [47], the mean annual temperature was 11.3 °C and the average precipitation was 747 mm in the last 46 years.

2.2. Experimental Design

Within the study site, a total of 18 plots (n = 9 in the mixed stand and n = 9 in the pure stand), each measuring 50 m × 50 m, were selected following a completely randomized plot design in order to avoid pseudo replicates. For data collection, subplots of 30 × 30 m were established in order to prevent the edge effect. Three treatments (no burning, spring burning and autumn burning) were applied to each type of stand, with 3 replicates per treatment (for further details, see [35,43,48]). In order to obtain data on post-fire growth and temperatures during the burns, 15 *P. nigra* trees in each plot were selected for study (n = 135 in the mixed stand and n = 135 in the pure stand). The trees were chosen to represent all of the diametric classes present in each particular plot.

2.3. Burning and Fire Severity at Tree Level

Spring burning was conducted on 15 May 2016, before the main growth season; while autumn burning was carried out on 15 November 2016, after the main growth season. The strip ignition technique was applied at a distance of 1–2 m downhill, facing a headwind. This technique is the most widely used in the study area to produce low—medium-intensity fire [49]. During the burning, the temperature (T) and relative humidity (RH) (Geonica; STH-5031) and wind speed (WS) (Casella; 178031C-3) were recorded every 10 min at a meteorological station located adjacent to the study plots (about 100 m from the plot). In order to estimate burn severity at tree level during the burning, the temperature in the cambial region (inner bark) and in the bark surface of the 15 selected *P. nigra* trees in each plot was monitored at a height of 0.6 m [50] with type K 1-millimeter-diameter inconel-sheathed thermocouples (response time, 0.3 s). The thermocouples were connected to data loggers (DT-USB TCDirect®), which recorded the data with a frequency of 1 s. The time during which the temperature remained above 60 °C in the inner bark (t60) and the time during which the temperature remained above 300 °C in the bark surface (t300) were calculated with data recorded. Maximum scorch height (SMx) (hypsometer VERTEX IV) was recorded to evaluate fire severity in the trunk [51,52]. The main parameters measured during prescribed burning in the selected trees are shown in Table 2.

Table 2. Main parameters measured during prescribed burning in mixed and pure stands of *P. nigra*. Data from [35].

S	PT	T	RH	WS	RS	FLI [1]	FH	FL [1]
–	–	°C	%	$m\ s^{-1}$	$m\ min^{-1}$	$kW\ m^{-1}$	cm	cm
Mixed stand	Spring burning	21.5 (1.2)	47.7 (5.3)	0.8 (0.6)	0.65 (0.21)	20.0 (8.8)	53 (15)	30 (6)
Mixed stand	Autumn burning	11.9 (0.4)	67.0 (1.3)	0.3 (0.3)	0.59 (0.31)	11.2 (6.6)	17 (10)	23 (6)
Pure stand	Spring burning	20.4 (1.5)	32.7 (2.3)	0.8 (0.1)	0.76 (0.24)	32.6 (13.3)	43 (8)	38 (8)
Pure stand	Autumn burning	12.0 (0.9)	43.5 (0.8)	0.1 (0.1)	0.72 (0.22)	13.8 (10.7)	26 (13)	25 (9)

[1] Data from [53]. S: type of stand; PT: plot treatment; T: air temperature; RH: relative humidity; WS: wind speed; RS: fire rate of spread; FLI: fire-line intensity; FH: flame height; FL: flame length. Standard deviation in brackets.

2.4. Litterfall: Fire Severity at Stand Level

Immediately after the prescribed burning, 8 litterfall collectors (0.38 m^2) were installed in each plot (total n = 144) to evaluate fire severity at stand level (crown damage). In order to ensure the representativeness of the samples. The litterfall collection system was designed in accordance with the recommendations and parameters outlined in the Manual of the United Nations Economic Commission for Europe (UNECE), under the project entitled “International Co-operative Program on Assessment and Monitoring of Air Pollution Effects on Forests” (ICP Forests, Level II Plots) [54] to guarantee the quality and quantity of the sample (for more details, see [48]). On each collection day, the samples were transported to the laboratory and oven-dried at 65 °C to constant weight. Litterfall biomass was collected during the year immediately after spring burning and autumn burning in mixed and pure stands and used to characterize fire severity at stand level [43,46,48].

2.5. Tree-Ring Width Analysis

In November 2018 (30 months after spring burning and 24 months after autumn burning), one core was extracted from each selected *P. nigra* tree at breast height (n = 135 in each stand; they were the same trees used to estimate burn severity at tree level), perpendicular to the terrain slope, with an increment borer (0.5 cm inner diameter) [22]. All cores were prepared following standard dendrochronological techniques [55]. The cores were mounted on grooved boards and sanded until the tree rings were clearly visible.

Tree ring widths were measured using a tree ring measuring stage with a precision of 0.01 mm (Lintab ^{TM}, Rinntech, Heidelberg, Germany) and recorded in a computer with TSAP software [56]. Our study species at our study site formed clearly defined rings boundaries with abrupt transitions between late wood and early wood [57]. All cores were dated and visually cross-dated to detect the presence of false and incomplete rings. COFECHA software was used to check cross-dating and validate measurement quality [58] (Table 3). The ring widths were converted into annual basal area increments (BAI) by using the equation BAI = π ($r^2 t - r^2_{(t-1)}$), where "r" is the tree radius and "t" is the year of tree-ring formation. BAI was used as a proxy for tree growth because it is less dependent on age and thus prevents the need for detrending [59], which could also remove low frequency variability. In addition, the BAI was standardized and shown in box plots. The standardization was performed using the mean tree growth value of the immediately five preceding years unaffected by the burning treatment (2010–2015).

Table 3. Main dendrochronology statistics.

–	Both Stands	Mixed Stand	Pure Stand
Series intercorrelation	0.439	0.542	0.431
Average mean sensitivity	0.337	0.374	0.308

2.6. Statistical Analysis

The following three models were constructed in order to analyze the tree growth results: model SB, for spring burned plots; model AB, for autumn-burned plots; and model NB, for non-burned plots. For each treatment, a linear mixed model (Equation (1)) was used to describe short-term impact of PB on tree growth. BAI was selected as the target variable. A collinearity analysis was performed; tree height (H), which had a strong collinearity with DBH, was excluded. Likewise, nested effect between random variables were considered. According to the collinearity and significance, the best fit model considered the following potential predictors (fixed factors) (Table 4): tree height (H), percentage of live crown height (Hc), diameter at breast height (DBH), maximum scorch height (SMx), time during which the temperature in the cambium area was higher than 60 °C (t60) and time during which the temperature in the bark surface was higher than 300 °C (t300). Possible differences in composition and characteristics of stand (S), variability between plots (P) and total amount of litterfall collected per plot one year after PB (L) were resolved by adding a random effect.

$$ln\left(BAI_{k(jy)}+1\right)=\beta_0+\beta_1\cdot Hc+\beta_2\cdot DBH+\beta_3\cdot SMx+\beta_4\cdot t60+\beta_5\cdot t300+\gamma_{0k(j)}+\alpha_{0k(j)}+L\alpha_{k(jy)}+\varepsilon_{k(jy)} \quad (1)$$

where β_0 is the overall intercept; β_i (i = 1, . . . , 5) are the parameters adjusting the fixed effects; k is the study site index; $k(j)$ is the tree index nested in the study site; y is the month of measurement index; $\gamma_{0k(j)}$, $\alpha_{0k(j)}$ represents the random effects associated with study plots and stand, respectively; $L\alpha_{k(jy)}$ is the interaction between stand and litterfall; and $\varepsilon_{k(jy)}$ is the error term. No pattern was observed in the residuals of any models.

Table 4. Main variables used to model the impact of prescribed burning on tree growth.

S	PT	H	Hc	DBH	SMx	t60	t300	L16	L17
–	–	m	%	cm	cm	s	s	kg ha^{-1}	kg ha^{-1}
Mixed stand	No burning	12.2 (5.0)	50.3 (16.2)	19.5 (10.3)	–	–	–	3171 (649)	3532 (585)
Mixed stand	Spring burning	11.9 (5.0)	48.0 (15.2)	18.1 (10.0)	54 (50)	31 (82)	10 (26)	3257 (599)	–
Mixed stand	Autumn burning	12.2 (5.2)	50.1 (15.8)	19.4 (10.4)	46 (45)	16 (59)	6 (20)	–	2732 (325)
Pure stand	No burning	13.1 (4.9)	39.4 (14.4)	19.6 (10.1)	–	–	–	1989 (519)	2393 (739)
Pure stand	Spring burning	13.9 (4.4)	37.9 (15.1)	19.5 (9.4)	167 (201)	23 (93)	44 (167)	3482 (129)	–
Pure stand	Autumn burning	14.5 (5.3)	36.2 (12.5)	21.7 (11.3)	132 (169)	16 (81)	33 (149)	–	3629 (527)

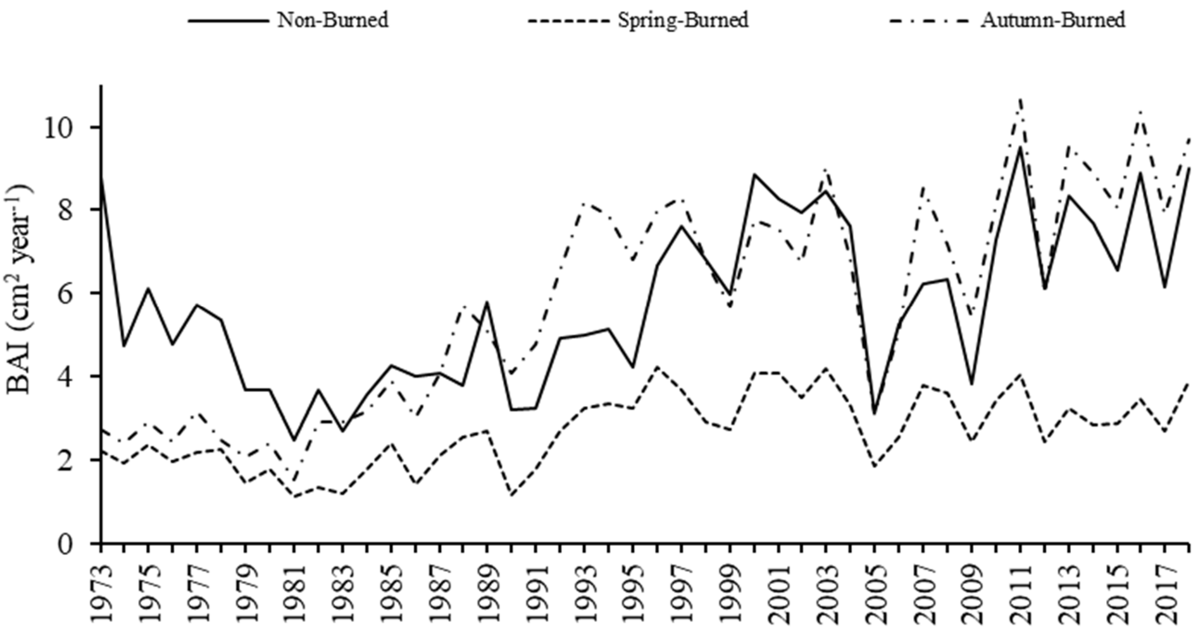
S: type of stand; PT: plot treatment; H: tree height; Hc: percentage of live crown height; DBH: diameter at breast height; SMx: maximum scorch height; t60: time during which the temperature in the cambium area was higher than 60 °C; t300: time during which the temperature in the bark surface was higher than 300 °C; L16: litterfall biomass from May 2016 to April 2017; L17: litterfall biomass from November 2016 to October 2017. Standard deviation in brackets.

All statistical tests were performed using R software (v. 3.0.1, R Foundation for Statistical Computing), specifically with the *nlme* and *lme4* packages for linear mixed-effects modelling. A significance level of 95% was established for detecting differences between treatments.

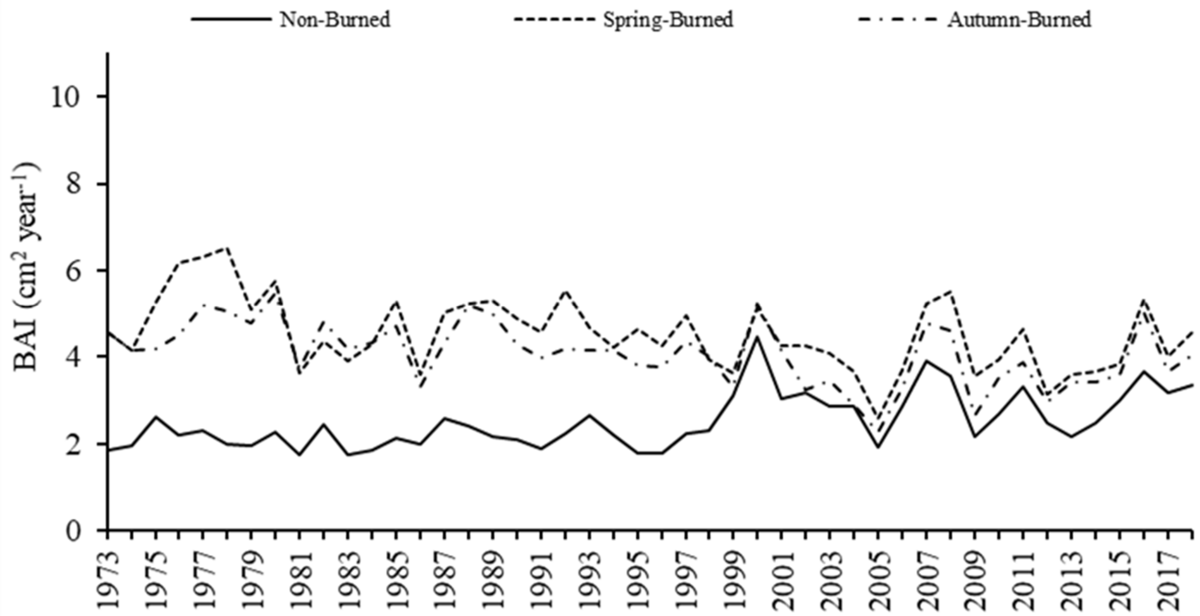
3. Results

The annual trends in the mean basal area increment (BAI) for the three treatments in the mixed and pure stand were similar (Figure 2). However, tree growth was lower in the spring burned plots in the mixed stand than in the unburned and autumn burned plots (Figure 2a). Hence, the BAI was standardized and shown in box plots per type of stand (mixed or pure) for the comparison of tree growth (Figures 3 and 4). In both stands, tree growth was lower after spring burning (Figures 3 and 4). The same trend of slight reduction on tree growth was observed in the pure stand one year after autumn burning (Figure 4). Conversely, in the mixed stand, a scarce impact on tree growth was shown in the year following autumn burning (Figure 3).

The type of stand (mixed or pure) did not have an influence on tree growth (Table 5). The tree variables, percentage of live crown height and diameter at breast height, were significant factors in the three models (although the percentage of live crown height in Model NB was not significant; $p < 0.1$) (Table 5). Regarding the fire severity variables at the tree and stand level (maximum scorch height, time during which temperature in the cambium area was higher than 60 °C, time during which temperature in the bark surface was higher than 300 °C and litterfall biomass), the maximum scorch height was a significant factor (Model SB and AB). A higher scorch height is related to a greater fire severity, which may negatively influence tree growth. The time during which the temperature in the bark surface was higher than 300 °C was only significant in Model SB, as well as t60, which was significant in the same model. In this sense, the spring burning appeared to have a greater effect on tree growth than the autumn burning. The values of the variables related with the residence time above lethal temperatures did not have an impact on the autumn burning due to the low intensity of the fire. Litterfall was not a significant factor in any of the models.



(**a**) Mixed stand



(**b**) Pure stand

Figure 2. Comparison of annual trends in mean basal area increment (BAI) in (**a**) the mixed stand and in (**b**) the pure stand. Unburned plots (solid line), spring-burned plots (dashed line) and autumn-burned plots (dotted line). Spring burning was conducted in May 2016, autumn burning was carried out in November 2016.

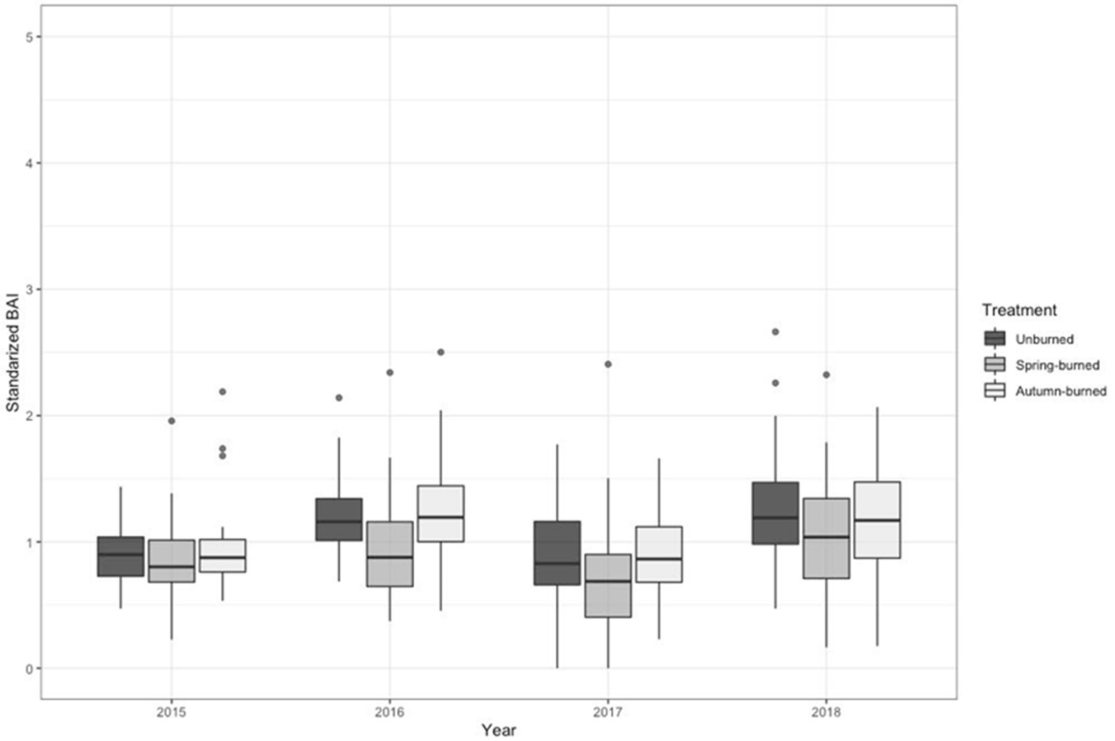


Figure 3. Box plot showing the differences in standardized BAI in the mixed stand. Spring burning was conducted in May 2016, autumn burning was carried out in November 2016.

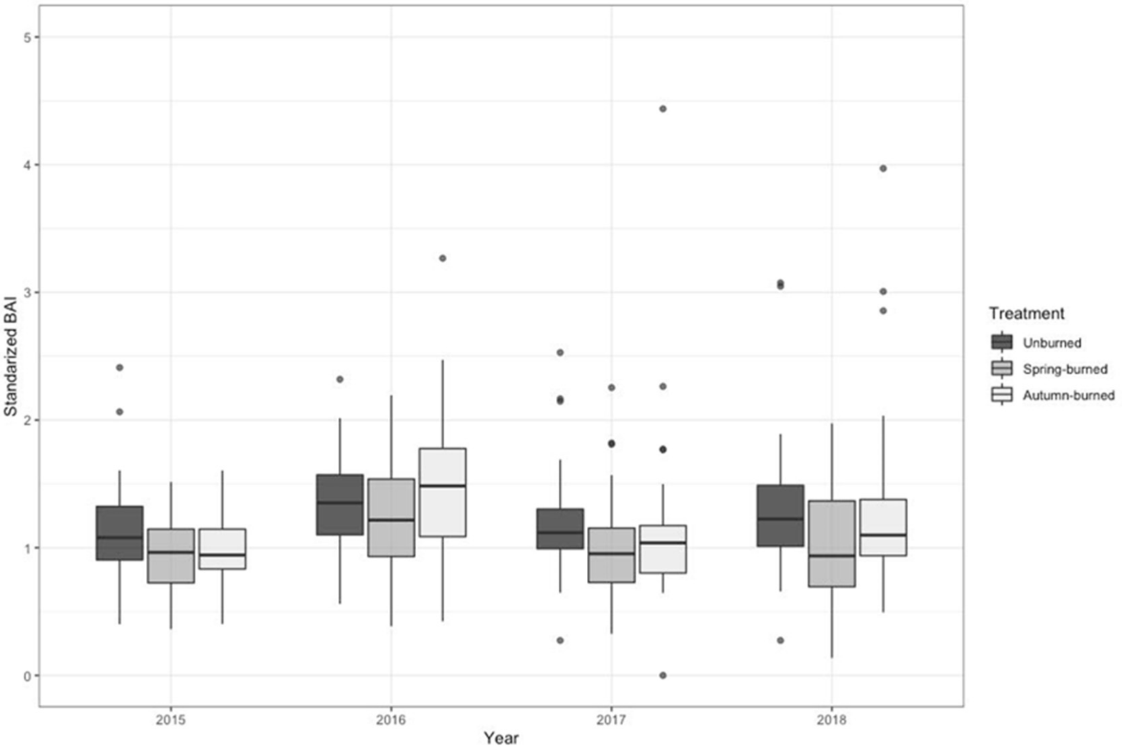


Figure 4. Box plot showing the differences in standardized BAI in the pure stand. Spring burning was conducted in May 2016, autumn burning was carried out in November 2016.

Table 5. Summary of statistical results.

Fixed Effects	**Model SB**				**Model AB**				**Model NB**			
	Estimate	**SE**	***t* Value**	***p* Value**	**Estimate**	**SE**	***t* Value**	***p* Value**	**Estimate**	**SE**	***t* Value**	***p* Value**
Intercept	1.364×10^{1}	6.925×10^{-2}	19.696	<0.001	1.297×10^{1}	9.274×10^{-2}	13.988	0.0026	1.488×10^{1}	1.397×10^{-1}	10.653	0.0087
Hc	**6.541×10^{-2}**	**9.378×10^{-3}**	**6.974**	**<0.001**	**5.233×10^{-2}**	**1.221×10^{-2}**	**4.285**	**<0.001**	1.855×10^{-2}	1.068×10^{-2}	1.738	0.0824
DBH	**6.448×10^{-1}**	**9.864×10^{-3}**	**65.367**	**<0.001**	**6.619×10^{-1}**	**8.516×10^{-3}**	**77.728**	**<0.001**	**5.093×10^{-1}**	**1.037×10^{-2}**	**49.138**	**<0.001**
SMx	**-3.762×10^{-2}**	**8.500×10^{-3}**	**−4.426**	**<0.001**	**-2.291×10^{-1}**	**3.092×10^{-2}**	**−7.411**	**<0.001**	–	–	–	–
t60	**-1.264×10^{-2}**	**5.560×10^{-3}**	**−2.273**	**0.0231**	-1.790×10^{-1}	1.175×10^{-1}	−1.524	0.1277	–	–	–	–
t300	**-2.796×10^{-2}**	**6.159×10^{-3}**	**−4.540**	**<0.001**	-1.039×10^{-1}	$7.387 \times$x 10^{-2}	−1.406	0.1598	–	–	–	–
Random effects	Model SB				Model AB				Model NB			
	Variance	SE	Pr (>Chisq)		Variance	SE	Pr (>Chisq)		Variance	SE	Pr (>Chisq)	
S	0.0000	0.0000	1.0000		0.0030	0.0554	0.8590		0.0287	0.1696	0.2553	
P	0.0177	0.1330	1.0000		0.0190	0.1379	1.0000		0.0013	0.0364	1.0000	
L	0.0105	0.1028	1.0000		0.0188	0.1373	1.0000		0.0287	0.1696	1.0000	

Hc: percentage of live crown height; DBH: diameter at breast height; SMx: maximum scorch height; t60: time during which the temperature in the cambium area was higher than 60 °C; t300: time during which the temperature in the bark surface was higher than 300 °C; S: type of stand; P: plot; L: accumulated litterfall during the year following the burning treatment; SE: standard error. Values shown in bold indicate significant effects ($p < 0.05$).

4. Discussion

The study findings highlight the importance of modelling tree growth response to PB as a function stand and tree characteristics, fire season and fire severity variables to gain some insight into individual tree responses. As far as we know, this the first time that variables associated with fire severity, such as the time of exposure to a critical temperature in the bark surface and cambium area and the effect of litterfall after PB, have been included in a model of tree growth response to prescribed burning. These variables play a key role in determining the stress level in trees after fire and they may be essential to enable the estimation of post-burn growth and mortality rate [60].

The findings showed that prescribed burning at a short-term scarcely affected tree growth. Similar findings have been reported by other authors (e.g., [16,61,62]). In spring-burned plots in the mixed stand, and in spring- and autumn-burned plots in the pure stand, a decrease in tree growth was observed after burning. The trend in the reduction in tree growth has generally been described as short-term (1–3 years), with growth rates returning to approximately pre-fire levels thereafter [63]. The reduced growth of *Pinus ponderosa*, *P. contorta* and *P. palustris* has been observed one and two years after burning by [64–66], respectively. Although, other authors pointed to an increase in tree growth after burnings, mainly because fire acts as a mineralizing agent releasing nutrients instantaneously, in contrast to slower natural decomposition processes [67–69]. However, such nutrient pulses are usually temporary, and the values return to or fall below pre-treatment values within 1–2 years [61]. However, other longer growth recovery rates have also been reported, such as the slight decline in tree growth observed 6 years after fire in *Pinus ponderosa* and *Pinus sylvestris* [70,71].

The present findings did not allow for confirmation of a lower disturbance on tree growth after prescribed burning or a faster recovery in a mixed stand compared to pure stands. Nevertheless, several authors have reported that mixed stands are more stable than pure stands, e.g., [72–74]. Even studies involving soil properties and litterfall carried out in the same experimental plots [43,48] have revealed this positive effect on mixed stands after prescribed burning.

Although there is an abundant literature relating growth responses to climate and to the potential decline in vitality in Mediterranean forests, e.g., [75,76], the relationships may depend on many stand- and tree-level factors [24,77]. Our study findings showed that the tree variables included in statistical analysis (percentage of live crown height and DBH) are significant factors in all three models (although the percentage of live crown height showed less significance in Model non-burned). Therefore, regardless of the type of stand (mixed or pure), the particular characteristics of each tree may explain the variability in growth after fire. This may be partly explained by the low percentage of *Pinus pinaster* in the mixed stand or the low intensity of burning. In this regard, some researchers proposed that factors affecting tree growth rate before fire continue to affect post-fire growth (e.g., [64]), although others have suggested the opposite [70].

The maximum scorch height was a significant variable that negatively influenced tree growth after spring and autumn burning. It is, therefore, possible that higher scorch heights may imply greater added stress on trees and should, therefore, be avoided. Indeed, fire-damaged trees require stored carbohydrates to replenish tissues, depleting carbohydrate reserves, often compromising tree growth [60]. Despite these results, maximum scorch height proved to be a random variable regarding litterfall in the same experimental plots, although it was probably due to the fact that the maximum scorch height was reached below the mean height of the first live branch [43].

The time during which the temperature remained above 300 °C in the bark surface had a significant response regarding tree growth only during spring PB; in addition, the time during which the temperature remained above 60 °C in the inner bark (cambium area) was also significant during spring PB. Although, as mentioned, the maximum scorch was a significant variable after spring and autumn burning treatments, it seemed to have a slightly greater effect after spring PB. Overall, spring burning has been described to be more disruptive to trees because carbohydrate reserves are at their lowest levels at the beginning of the annual growth period [18,19]. Furthermore, a higher level of damage to fine roots (abundant during this period) has been pointed out [78,79]. Hence, PB carried out in autumn seemed to have less of an impact on tree growth; however, the disturbance in other tree and stand processes (e.g., impact on litterfall) should be also considered in the prescription plans [43]. In this regard, fuels have been described as typically drier later in the year [20], which corresponds with the regular autumn burning season, which may imply higher mortality rates [21]. The relationship between tree growth and t60 may be because the insulating capacity of bark completely protects the cambium at a low-intensity PB [35]. *Pinus nigra* is known to possess thick bark (especially in the lowest part of stem), as a result of the adaptation to frequent surface fires, which protects the cambium against overheating by fire (e.g., [29,80,81]). In addition, the bole scorch height does not necessarily imply an effect on the cambium if it does not affect the entire bole circumference [63], which in turn disturbs the supply of water and nutrients to the leaves and the translocation of photosynthates to the roots [82]. Furthermore, [62] also suggested that the minimal presence of fire scars associated with heat damage to the cambium and other live tissues does not significantly affect tree growth. However, this reflected the importance of including variables associated with the flame residence time in the tree growth models.

The total litterfall biomass collected one year after prescribed burning was not a significant variable in the tree growth response. The low-intensity of the prescribed burning and the high height of the first live branch may explain the weak significance of this variable. Nevertheless, litterfall was found to be beneficial to tree growth, in some cases. In this regard, PB improves tree efficiency by eliminating the unproductive lower branches [41] and less efficient needles from the lower part of the crown [39], which may enhance tree growth [83,84]. Or, by contrast, fire disturbance in the crown is typically related to the reduction in tree growth [70], which represents photosynthetically active tissue and a source of energy (e.g., [38,85]). Indeed, some authors maintain that allocation of resources prioritizes foliage and buds [86–88]; therefore, an increase in litterfall may mobilize resources in these parts (mainly to guarantee photosynthesis) at the expense of tree growth. However, the findings obtained did not allow us to confirm the significance of this variable on tree growth, at least in the short-term.

5. Conclusions

The findings suggest that PB (spring and autumn) is a potentially valuable management tool for reducing fire hazard, with a scarce effect on short-term tree growth. The overall trend was for a reduction in growth. A longer-term study may be necessary to establish the recovery rate of the stands, particularly in a pure stand. The differences between the mixed and pure stands were not critical to tree growth, which do not allow for a confirmation of the initial hypothesis about the weaker effect of perturbation in the mixed stand. Individual tree characteristics proved to be more important for growth than the type of stand, treatment or fire severity in low-intensity PB. The differences between the burning seasons were notable. The inclusion of some post-burn severity variables for the first time in tree growth models showed that the maximum scorch height influences tree growth. This is an easily measurable variable that must be considered in burning prescriptions. The recognized surface fire adaptations of *Pinus nigra*, such as the insulating capacity of the thick bark and the high crown height, completely protected the tree; however, special attention should be given to the variables related to exposition to a critical temperature in the outer and inner bark, particularly after spring burning. Although autumn prescribed burning seemed to have less of an impact on tree growth, disturbance in the other stand dynamics should be also considered. The litterfall biomass one year after prescribed burning was not a significant variable for tree growth. These findings could be used to improve burn prescriptions and the evaluation of PB in *P. nigra* stands.

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