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ORIGINAL PAPER

Influence of tree size, reduced competition, and climate on the growth response of *Pinus nigra* Arn. *salzmannii* after fire

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Abstract

• ***Context*** After wildfire, surviving trees are of major ecological importance as they can help in the post-fire regeneration process. Although these trees may be damaged, they may also benefit from reduced fuel hazard and competition. However, little is known about the long-term growth response of surviving trees.

• ***Aims*** This study aims to explain short- to long-term variations in the postfire growth of surviving black pines in an area burnt in 1994, focusing on levels of fire severity and tree sizes.

• ***Methods*** Relative basal area increments were used to detect time-course variations in postfire radial tree growth depending on fire severity. Linear mixed-effects models were used to describe the factors affecting postfire ring growth.

• ***Results*** In the short term, fire caused stronger reduction in growth in small trees with increasing bole char height. However, as time since fire increased, a positive effect of fire on growth due to reduced competition counteracted the short-term fire impacts. Indeed, small surviving trees demonstrated a surge in growth 15 years after the fire.

• ***Conclusion*** It was concluded that reduced competition might offset the short-term negative effects of fire in surviving black pines.

Keywords Postfire growth · Black pine · Low-intensity fire · Surface fire · Dendrochronology · Fire effects · Long-term growth

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Contribution of the co-authors Míriam Piqué coordinated the research project, contributed in the design of the experiment, and supervised the work. Bernat C. López aided with the data analysis and the supervision of the manuscript. José Ramón González-Olabarria contributed in designing the experiment, running the data analysis, and writing the paper.

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1 Introduction

Large wildfires are a common occurrence in Mediterranean forests (Gonzalez and Pukkala 2007). Climate change and social patterns are expected to increase both the recurrence and severity of wildfires in the near future (Moritz and Stephens 2008).

Fire ecologists and forest researchers are now asserting that implementing fire management policies that allow more fires to occur at low intensity, either by prescribed burning or by managing low-intensity "easy-to-control" fires should help avoid catastrophic wildfires (Pinol et al. 2005; Moritz and Stephens 2008) and even have a positive economic impact on forest stand management (Gonzalez-Olabarria et al. 2008), as the removal of smaller trees could reduce thinning costs and future risk of high-intensity fires. Nevertheless, a desirable prerequisite before contemplating the use of low-intensity fires for fuel removal purposes or as a silvicultural tool would be to understand the vegetation

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response to this type of fire, including the long-term effects of fire on the growth of surviving trees.

Most postfire research to date has focused on regeneration processes after high-intensity fires (Pausas et al. 2003; Retana et al. 2002) and on postfire tree mortality after wildland or prescribed fires (Woolley et al. 2012), whereas the ecological and forest management consequences for forest areas affected by low- to medium-intensity fires, including the development and growth of trees surviving a surface fire, remain poorly understood. The few studies analyzing postfire tree growth differ strongly in terms of origin of the fire affecting the trees (wildfire vs. prescribed burning), estimators used to assess fire severity (e.g., crown scorch volume, loss of litter and duff layer, bole char height, in-stand tree mortality, or fire recurrence), spatial scale of the study (tree level vs. stand level), and tree species studied. Even so, this variability in methodological approaches has not been reflected in the selection of different study timeframes (Keyser et al. 2010). Most studies analyzing postfire tree growth have relied on short-term data, with only rare studies extending their analysis to over 10 years after the fire scar (Keeling and Sala 2011).

Studies designed to analyze tree growth during the first few years postfire are an appropriate platform for identifying sharp reductions in tree growth due to physical damage (e.g., crown scorch or bole damage) that cause physiological dysfunctions and thus reduce photosynthesis or water use efficiency. They also show that as postfire timespan increases, tree growth can be recovered in a relatively short period of time due to the effects of tree healing and increased light and soil nutrient availability (Certini 2005). However, these short-term studies are not appropriate for capturing the potentially positive effect that a decrease in competition may have on the tree growth of surviving trees. The effects of decreased competition due to fire can only be identified through medium to long-term studies. Furthermore, in the Mediterranean basin and in drought-sensitive species such as black pine (*Pinus nigra* Arn. *salzmannii* var. *pyrenaica*), the influence of climate on postfire survivor tree growth cannot be overlooked, especially as conditions are expected to become warmer and drier in the future (Andreu et al. 2007).

The aim of this study was to analyze the effect of fire events on the radial growth of surviving black pine trees over a 15-year postfire period. The study considers a relatively traditional approach based on the idea that the amount of fire damage caused to the trees and the diameter of the trees damaged interact to explain variations in postfire growth. The study also considers the effects of reduced tree competition due to fire-induced mortality on the growth of the remaining survivor trees. The potential effect of climate on this postfire growth was also analyzed as a potential source of inter-annual growth variation.

2 Material and methods

2.1 Study site

To implement the study, we needed an area that fulfills the following criteria: affected by a relatively old fire, currently covered by forest, showed homogeneous site quality, showed no past management operation observable in the field, the forest prior to the fire had to be homogenous across the study site, and demonstrated significant variability on fire severity indicators.

The chosen study site compromised a roughly 83 ha area located at the northern side of the *Serra de la Canya*, a mountain zone in central Catalonia (Fig. 1), NE Spain (42°09′ N, 1°69′ E). The topographic features of the study site correspond to an altitude of 769.6±65.3 m a.s.l., northwest exposure, and a slope that ranged from 10 to 40 %. The climate in this zone is subhumid Mediterranean, with a mean annual temperature of 13.7 °C and a mean annual precipitation of 583.2 mm over the last 20 years.

The site was partially affected by one of the largest forest fires in the history of Catalonia, which, in July 1994, burned around 24,300 ha of land (Retana et al. 2002). Although this fire was essentially qualified as a high-intensity active crown fire, once it reached the study site, it spread downhill to become a surface fire with occasional crown torching, eventually extinguishing in the lowest areas of the site. The study site is currently covered by a semi-even-aged pure black pine forest with an understory dominated mainly by *Buxus sempervirens*.

2.2 Data collection

Within the study site, 48 circular plots of 7 m radius each were set up for measurement and sampling. Based on the criteria that plots should differ in terms of fire severity, the plots were set up into three sectors within the study site, with 16 plots in each sector. The severity levels determining the sectors were defined according to the plot's mean bole char height (BCH_p). Two sectors enclosed the fire-affected plots, described as high-severity sector (BCH_p>3 m) and moderate-severity sector (BCH_p>0 and<2.5 m) (Fig. 1). Besides the sectors affected by fire, 16 plots were set up nearby but outside the limits of the fire to create a control sector unaffected by the fire (Fig. 1). Within each plot, we measured diameter at breast height (DBH), tree bole char height (BCH_t), and total height (Ht) of all surviving trees larger than 7.5 cm in DBH. Furthermore, we measured the number of trees killed by the fire within the limits of each plot, assessing afterwards the postfire tree mortality, expressed as percentage of dead trees (TM), and the tree density (N) before (1994) and after (2009) the fire (Table 1).

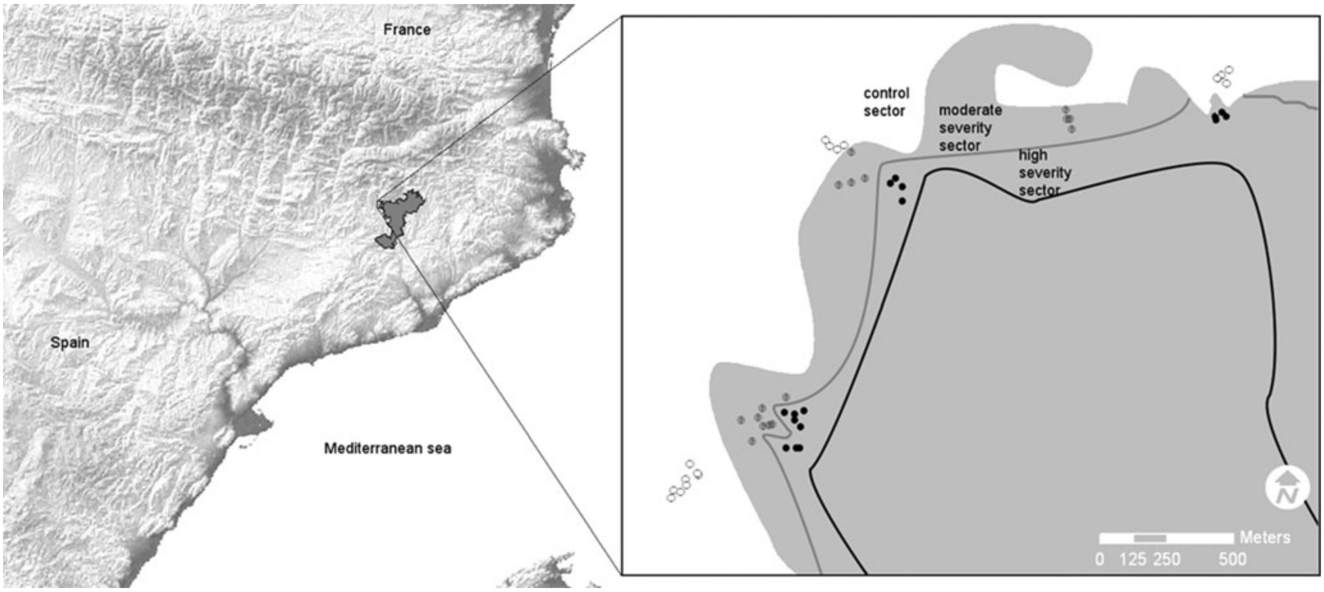

Fig. 1 Perimeter of the fire that occurred in 1994 and the severity sectors of the study site. *Black points* high-severity plots, *gray points* moderate-severity plots, *white points* control plots

In order to obtain data on the postfire growth of surviving trees, for each plot, the 10 trees closest to the plot's center that had a DBH larger than 10 cm were identified and core-sampled (480 trees). Core extraction was performed by extracting one core from each tree using an increment borer at breast height (1.30 m) as far away as possible from fire scars (Mutch and Swetnam 1995).

2.3 Tree-ring measurement and transformation

All 480 extracted cores were prepared following standard dendrochronological techniques (Stokes and Smiley 1968). Tree rings were measured to a precision of 0.001 mm using a Lintab 3 measuring system coupled to TSAP tree-ring software (Rinn 1996). All cores were dated and visually cross-dated to detect the presence of false and incomplete rings. Mean age and standard deviation of the trees selected for ring-width measurement were 75.8± 24.6 years. Within each of the BCH fire severity sectors (n=160 cores), cross-dating was validated using COFECHA software (Holmes 1983), which calculates cross-correlations among individual series of tree growths. In total, 34 low-correlation series were discarded, and 446 cores were retained for further analysis.

Tree-ring data was transformed into basal area increments (BAIs) and into tree ring indices (see Section 2.4.2 for the ring index computations). First, we calculate the basal area (BA) in square centimeters for each tree and year using Eq. (1), where r is the radius of the tree for a given year.

$$BA = \pi \times r^2 \tag{1}$$

To find individual annual increment growth in basal area (BAI_y) for a year y, we used Eq. (2) where BA_y is BA at year y and BA_{y-1} is BA of the tree the previous year, BAI being expressed in square centimeters per year.

$$BAI_y = \left(BA_y - BA_{y-1}\right) \tag{2}$$

For each core, we estimated mean annual BAI of the tree during the 5 years prior to the fire ($BAI_{1988–1993}$), mean annual BAI of the tree during the whole postfire period ($BAI_{1995–2009}$). The relative BAI (BAI_{rel}) was calculated for each tree and postfire year by dividing the annual BAI of the tree (BAI_{1995}…up to BAI_{2009}) by the mean BAI of the

Table 1 Description of the measured plots, grouped by fire severity, in terms of means± standard deviation of the plot-scale bole char height (BCH_p), tree mortality (TM), tree height (Ht), tree density in 1994 (N_{1994}), and tree density in 2009 (N_{2009})

	High	Moderate	Control
BCH_p (m)	3.1±0.9	1.6±0.5	–
TM (%)	23.2±13.4	16.3±12.5	–
Ht (m)	10.7±1.5	9.5±2.6	8.3±1.1
N_{1994} (trees/ha)	1,242.4±436.6	1,571.3 ±581.6	1,380.5±330.1
N_{2009} (trees/ha)	925.7±292.7	1,384.6±592.6	1,380.5±330.1

5 years prior to the fire ($BAI_{1989–1993}$). BAI_{rel} is a unitless variable, as it is the result of normalizing postfire growth by prefire growth rates (Reinhardt and Ryan 1988), allowing each tree to serve as its own control. This means that when BAI_{rel} value was <1, the tree decreased its growth compared to its prefire growth rates, and when BAI_{rel} was >1, the tree increased its growth.

2.4 Data analysis

2.4.1 Postfire growth variation within the plot's fire severity classes

In order to detect time variations in postfire tree growth depending on fire severity, the mean BAI_{rel} of the trees in each fire severity and tree size classes was calculated and plotted over time. For this purpose, we considered the plot-level fire severity classes (high, moderate, and control) and the size of the tree, gauged as DBH in 1994, which was classified into three classes: large (DBH>15 cm), medium (10 cm≤DBH≤15 cm), and small (DBH<10 cm) (Table 2).

2.4.2 Modeling the response of trees to postfire stress and competition release

Tree-ring indices (TRI) were used to model the factors influencing the different responses of individual trees to fire using ARSTAN software (Cook and Holmes 1984). Individual series were standardized by fitting a negative exponential or linear function (whichever best fit the actual growth trend of the individual) and then applying a second detrending by fitting a 20-year cubic smoothing spline with 50 % of variance reduction. Each ring-width value measured was then divided by the expected growth value to produce a set of TRI. Standardization removed growth trend due to increasing age and diameter of the trees, scaling all the series to mean values of 1.00 (Fritts 1976).

The impacts of fire on TRI were modeled for different periods. TRI were transformed to relative growths: the mean TRI of a given period were divided by the mean annual prefire TRI (from 1989 to 1993). The rationale for splitting the analysis into different stages was that tree response to a specific stressor event, and the factors influencing that response, may vary through time (Martínez-Vilalta et al. 2012). In order to describe the factors characterizing the impact of fire on tree growth over a period *N* (*Impact TRIN*), we used linear mixed-effects models. We modeled the impact of fire on TRI in the short-term (*Impact TRI1*) in year 1995, the mid-term (*Impact TRI2*) from 1998 to 2001, and the long-term (*Impact TRI3*) from 2006 to 2009. Thus, the impacts of fire for all periods were modeled (3) using, as independent variables, tree diameter breast height (DBH) at year 1994, bole char height expressed as the percentage of tree charred by the fire (BCH_t/Ht) and percentage of tree mortality (TM) at plot level:

$$\text{Impact TRIN } ij = \beta_0 + \beta_1 \ln(\text{DBH}_{1994}) + \beta_2 \ln(\text{BCH}_t/\text{Ht} + 1) + \beta_3 \text{TM} + w_i + e_{ij} \quad (3)$$

where β_0 is the overall intercept, β_1 to β_3 are parameters adjusting the fixed effects, *i* is the index for the plot, *j* the index for the tree, w_i is the random effect associated with plot, and e_{ij} is the error term. All mixed linear models were run in SPSS 17. This test uses fixed and random factors in the model and calculates variance components using restricted maximum-likelihood estimates. A correlation matrix was used to identify and avoid highly correlated pairs of variables. TRI were square root-transformed to improve the adjustment of the model, and quantitative explanatory variables were the natural logarithms of DBH_{1994} and BCH_t/Ht+1 to improve normality. In all models, the variables included showed a variance inflation factor below 3 and a condition index below 30, indicating no multicollinearity problems. The residuals of the mixed models presented here showed no pattern and a normal distribution, suggesting confident adjustments.

2.4.3 Climate effects on radial growth

The growth of the trees belonging to the plot's fire BCH_p-severity classes and also to the combined size–severity classes was tested against the evolution of different climatic variables to generate growth–climate chronologies. In total, 12 chronologies were calculated: 3 according on the plot's fire BCH_p-severity classes and 9 representing the combination of tree and the plot's fire BCH_p-severity classes. Using ARSTAN software (Cook and Holmes 1984), each chronology was computed by averaging the TRI (see Section 2.4.2 for the ring index computations) using a biweight robust estimation of the mean and considering the entire timespan for each chronology. Once the chronologies were generated, a dendroclimatic analysis was conducted using Pearson's correlation to analyze the relation between the 12 computed chronologies and monthly precipitations and temperatures for the prefire (1980–1994) and postfire (1995–2009) periods. The climate data, from 1980 to 2009, was obtained from the three closest (<28 km from the study site) meteorological stations.

We also assessed the quality of the standard chronologies using different statistics (Table 3), e.g., mean sensitivity (MS), which measures relative difference in ring-width from 1 year to the next ring (Fritts 1976), indicating the usefulness of the chronologies for the study of climate–growth

Table 2 Means ± standard deviation for plot-scale bole char height (BCH_p), diameter at breast height (DBH), and total height (Ht), for each of the BCH_p-severity class—size class combinations

	High BCH_p severity			Moderate BCH_p severity			Control		
	Large	Medium	Small	Large	Medium	Small	Large	Medium	Small
n: trees	33	65	50	20	63	73	21	62	59
BCH_p (m)	3.5±1.3	3.0±0.9	3.1±1.1	2.2±1.1	1.9±0.7	1.5±0.5	–	–	–
DBH_{1994} (cm)	18.1±2.9	12.1±1.4	8.0±1.2	16.8±1.0	11.9±1.4	8.0±1.2	16.8±1.0	12.2±1.4	7.4±1.7
Ht (m)	12.8±2.2	10.7±2.4	9.8±2.0	12.6±1.6	11.6±2.1	10.1±1.8	13.4±2.3	13.8±2.7	10.9±2.5

relationships; variance in first eigenvector (VFE), which measures the influence of climate on growth; signal/noise ratio (SNR); and expressed population signal (EPS) that show the usefulness of the chronologies for past climate reconstruction (Wigley et al. 1984).

3 Results

3.1 Postfire growth variation within each of the BCH_p-severity classes

All BCH_p-severity classes showed an overall growth increase throughout time (Fig. 2a). The evolution of BAI_{rel} tended to be similar among BCH_p-severity classes (Fig. 2b). However, the high BCH_p class suffered a decrease in BAI in 1995 (immediately after the fire), reaching a $BAI_{rel}<1.0$, and also in 1998, 1999, 2002, and from 2005 to 2007. The moderate BCH_p-severity class suffered a decrease in BAI every year from 1998 to 2008 except 2000 and 2004 (Fig. 2b).

When tree size was integrated as an indicator of tree exposure to fire damage, it was observed that 1 year after the fire occurred, small- and medium-sized trees with high BCH_p-severity showed a decrease in $BAI_{rel,}$ while large trees with similar BCH_p-severity increased their growth rate (Fig. 3a). From the second year after the fire until the end of the period studied, smaller trees showed a constant increase in BAI_{rel}, whereas larger and medium-size trees showed a weaker and less constant increase in BAI_{rel} over time (Fig. 3a). Trees affected by moderate BCH_p-severity showed no reduction in BAI_{rel} immediately after the fire, regardless of their size (Fig. 3b). However, in the long-term, small and medium trees affected by moderate BCH_p-severity tended to decrease BAI_{rel} (BAI_{rel} <1.0 in 8 of the 15 postfire years; Fig. 3b), whereas large trees affected by moderate BCH_p-severity kept a BAI_{rel} above 1.0 during more years than their small or medium counterparts over the period studied (Fig. 3b). Finally, trees in plots unaffected by fire grew more rapidly after 1994 than during the period prior to the fire, regardless of size, except in 1998 and from 2005 to 2007 when mostly larger trees decreased their growth (Fig. 3c).

Table 3 Selected statistics of fire BCH_p-severity chronologies and the tree size–fire BCH_p-severity chronologies of *Pinus nigra* at Sierra de la Canya (NE Spain)

Chronologies	Number of trees	MS	Common interval time span	SNR (%)	EPS	VFE
BCH_p severity						
High	148	0.09	1942–2009	15.57	6.3	0.86
Moderate	156	0.11	1947–2009	16.52	4.8	0.82
Control	142	0.10	1935–2009	14.46	5.7	0.85
High BCH_p severity						
Small	50	0.15	1960–2009	13.56	2.1	0.67
Medium	65	0.11	1947–2009	16.52	4.8	0.82
Large	33	0.12	1912–2009	19.70	1.6	0.62
Moderate BCH_p severity						
Small	73	0.10	1950–2009	15.58	4.2	0.81
Medium	63	0.15	1957–2009	22.71	8.7	0.89
Large	20	0.12	1953–2009	21.52	1.6	0.62
Control						
Small	59	0.11	1954–2009	14.18	3.5	0.77
Moderate	62	0.12	1940–2009	17.73	5.2	0.84
Large	21	0.19	1942–2009	19.77	0.9	0.48

MS mean sensitivity, *VFE* variance in first eigenvector, *SNR* signal/noise ratio, *EPS* expressed population signal

VFE, SNR, and EPS were computed for the common interval timespan on the greatest number of tree rings possible for the analysis

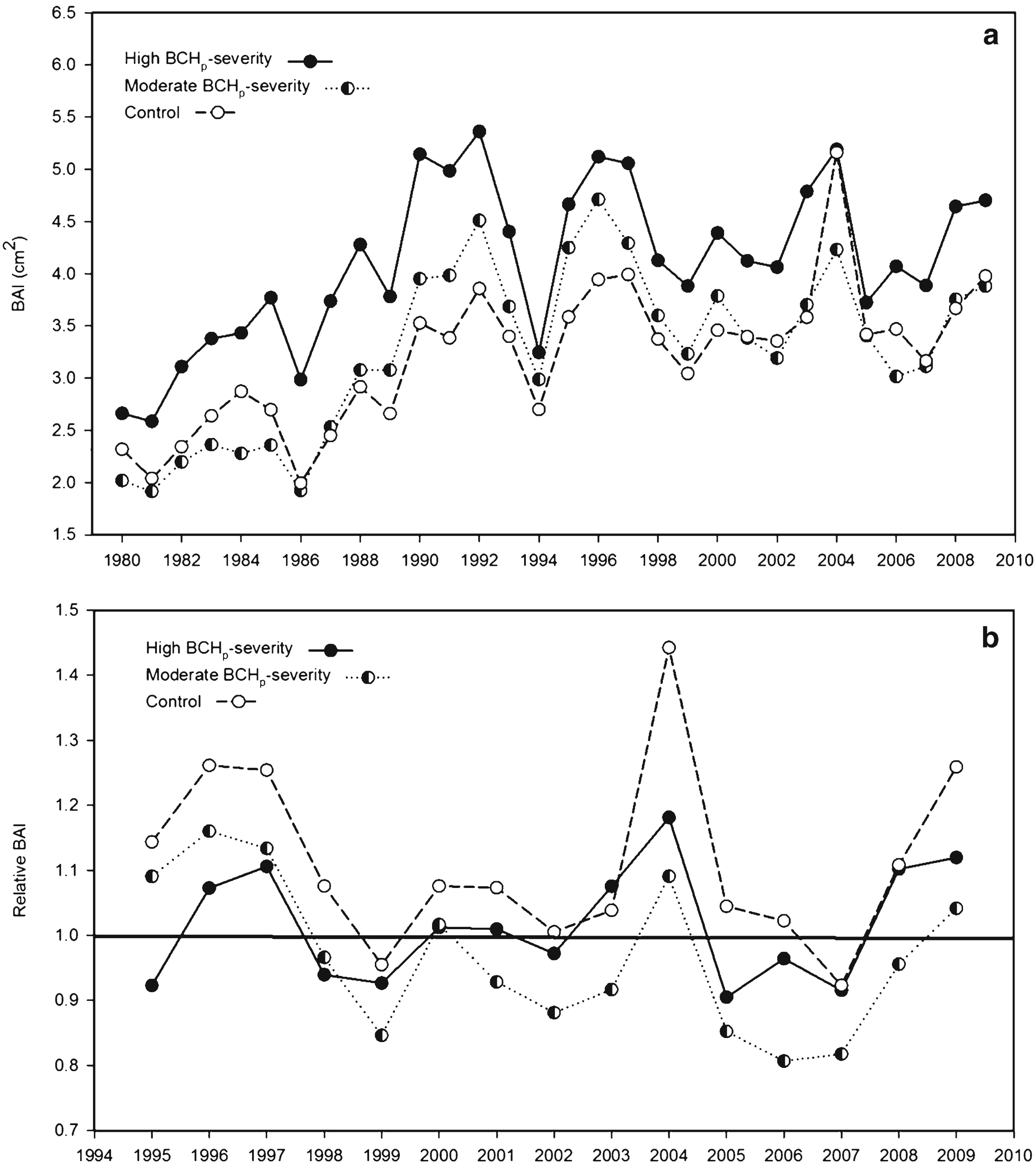

Fig. 2 BAI for the whole period studied in the BCH_p-severity classes (**a**) and relative BAI for the BCH_p-severity classes (**b**)

3.2 Modeling the response of trees to postfire stress and competition release

The assessment of the short-term impact of fire on the growth response of black pines found that BCH_t percentage was the only significant variable in the model (Table 4, *Impact TRI1*). Black pines that were more severely affected by the 1994 fire showed decreased growth in 1995 (Table 4, *Impact TRI1*), whereas TM and tree size had no significant effect on immediate postfire growth ($p<0.05$).

The mid-term (1998–2001) impact of fire on growth was characterized by decreased growth for trees with higher BCH_t percentage (Table 4, *Impact TRI2*) and increased growth for trees growing in plots were TM was higher (Table 4, *Impact TRI2*), regardless the tree size ($p<0.05$). In the long-term (2006–2009), tree size influenced the growth response of black pines, with smaller trees showing faster growth. This impact was stronger in trees growing in plots under significantly reduced tree competition (Table 4, *Impact TRI3*) and not so strong in

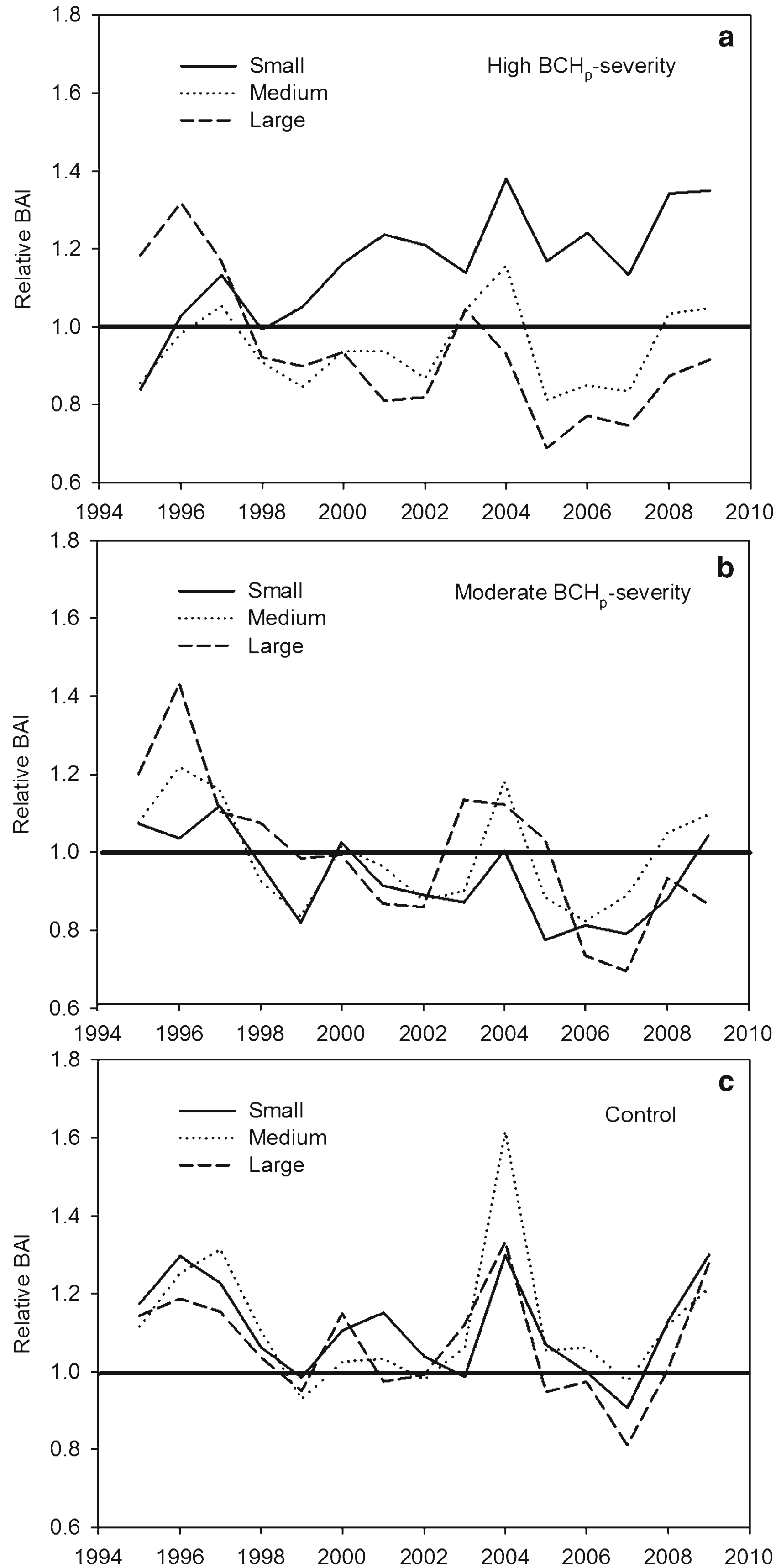

Fig. 3 Relative BAI over the time for the tree size classes for high (**a**), moderate (**b**), and control (**c**) BCH_p-severity classes

Table 4 Summary of mixed-model results for the impact of fire on short-term growth in 1995 (*Impact TRI1*), mid-term growth from 1998 to 2001 (*Impact TRI2*), and long-term growth from 2006 to 2009 (*Impact TRI3*), using Eq. (3): type III tests of fixed effects

Source of variation	*Impact TRI1*			*Impact TRI2*			*Impact TRI3*		
	Estimate	*df*	*P* value	Estimate	*df*	*P* value	Estimate	*df*	*p* value
Intercept	1.188	50.5	***	0.911	45.2	***	1.02	374.3	***
$\ln(DBH_{1994})$							−0.07	435.9	**
$\ln(BCH_t+1)$	−0.02	52.9	**	−0.036	51.6	**	−0.03	68.9	**
TM				0.003	45.1	**	0.004	51.8	**

*$p \leq 0.05$; **$p \leq 0.0.01$; ***$p \leq 0.001$

trees affected by high BCH_t percentages (Table 4, *Impact TRI3*).

3.3 Climate impacts on tree growth

Climate explained much of the intra-annual growth variation, with contrasting climate responses in both the pre- and postfire periods. Prior to the fire, the fire BCH_p-severity chronologies were significantly and negatively correlated with autumn temperature, whereas after the fire, the fire BCH_p-severity chronologies were positively correlated with winter precipitation (Fig. 4a). Similar correlations occurred for the size–fire BCH_p-severity chronologies, except for the small size–high fire BCH_p-severity chronology, which was significantly and positively correlated with spring–summer precipitation (March and July) (Fig. 4b).

According to the statistics used to assess the quality of the computed chronologies (Table 3), MS was found to be between 0.1 and 0.2 for all the chronologies while VFE ranged from 14.46 to 22.71 %. The EPS values were higher than or equal to 0.85 in three chronologies: high BCH_p-severity, control, and medium moderate-BCH_p, while SNR ranged from 0.9 to 8.7.

EPS expresses the relationships between a finite sample chronology and the theoretical population chronology (Wigley et al. 1984). EPS is highly dependent on the number of trees used in the chronology. According to Wigley et al. (1984), the EPS value must be above 0.85.

4 Discussion

The postfire growth analysis proposed in this study was designed to generate information on the recovery of tree vigor after a fire and to check the trade-offs between the expected negative and potentially positive effects of low- to medium-intensity fires on forest stand productivity. This information provides a decision support framework for future postfire stand management planning and fire management strategies.

Our results show that when the impact of fire on tree growth is assessed 1 year after a fire event, the effect of fire on individual tree growth is dependent on both the damage caused by the fire and the size of the tree. It is generally assumed that fire severity is the most important factor controlling postfire growth response of trees. Hence, many studies confirm a sharp reduction in growth in highly burned trees (Mutch and Swetnam 1995; Botelho et al. 1998; Busse et al. 2000; Gonzalez-Rosales and Rodriguez-Trejo 2004), whereas no variation in growth is expected when crown scorch volume is under a certain threshold, which varies among studies and species (Lilieholm and Hu 1987; Gonzalez-Rosales and Rodriguez-Trejo 2004). Here, we found that growth reduction immediately after fire was of greater magnitude in small surviving trees, which appears logical as the closer proximity of the crown to the surface fuel layer allows flames to consume a larger share of the tree crown foliage, leading to higher rates of transpiration, inefficient photosynthesis (Botelho et al. 1998), and thus ultimately a detrimental effect on tree growth. Another factor driving the reduction in growth of smaller trees affected by high BCH may be related to their bark thickness. Smaller trees are more expose to suffer cambial injuries, especially at higher stem heights, as there is reduction on bark thickness as the diameter of the stem decreases (Fernandes et al. 2012). In the case of large trees, the effect of fire on crown consumption and cambium damage was found to be of lesser significance than for smaller trees due to their higher crown base height and thicker bark. For moderate-severity fires, we found no significant reduction in tree growth, in agreement with the above-mentioned studies. Furthermore, as shown in Fig. 2, the second and third year after the fire, all trees experience a significant increase in radial growth. Such increased growth was likely caused by favorable climate conditions (high precipitation in 1996 and 1997) and enhanced site fertility due to nutrient release from fire (Beghin et al. 2011). If we assume that nutrient availability was the main driver of the increased growth in 1996 and 1997 and the subsequent slowdown during the following years, the results agree with the idea that nutrient availability

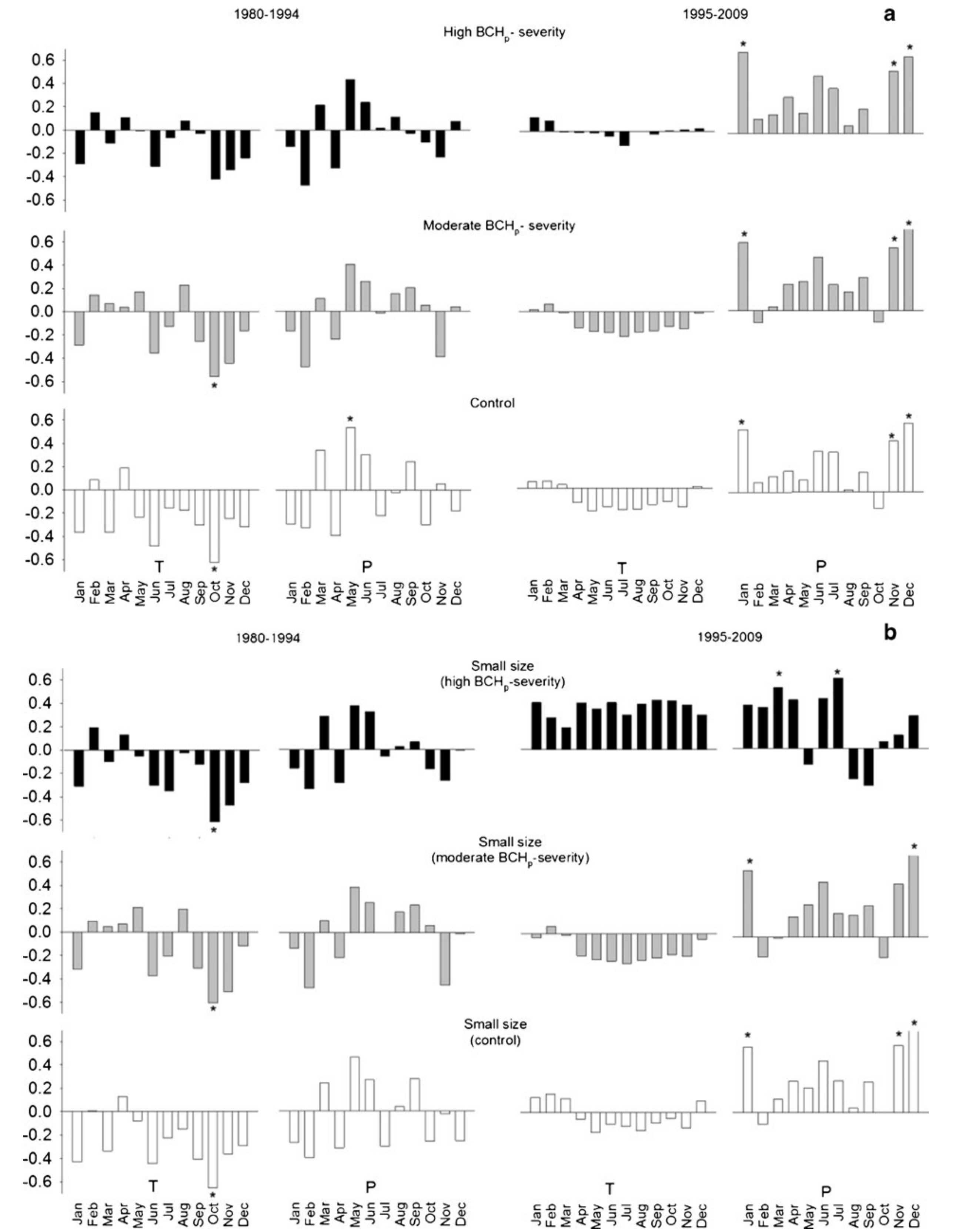

Fig. 4 *Pearson's* correlation coefficients (*bars*) between the BCH_p-severity classes (**a**) and the small size BCH_p-severity chronologies (**b**) with monthly temperature (*T*) and precipitation (*P*), for the prefire period fire (1980–1994) and the postfire period (1995–2009). *Black bars* high BCH_p severity, *gray bars* moderate BCH_p severity, *white bars* controls. *Asterisks* indicate significant correlation at $p<0.05$

increases strongly but transiently in the short postfire period. Based on the review by Certini (2005), the effect of enhanced nutrient availability has been observed to last from 1 month to 5 years depending on type of nutrient, burnt tree species, soil properties, burn intensity, and pathway of leaching processes (Kutiel and Shaviv 1992). Here, the similarity in growth patterns between nonburned plots raises questions over the stated effect of increased fertility. However, these similarities can be explained by the fact that the control plots were allocated in the lower part of the study site, which could have allowed them to benefit better from postfire fertilization through nutrient run-off from the upper burned plots. One aspect that has to be considered when interpreting the results of the present study, especially those related to the short-term response of trees to fire, is that even if they agree with previous knowledge, in contrast to most other studies dealing with the short-term response of trees to fire, our study uses BCH as a tree-level severity indicator instead of the more reliable percentage of crown scorch. The selection of BCH in our study was justified as it is a good proxy of the amount of crown scorched (Waldrop and Van Lear 1984) and is still easy to visualize and measure long after the fire occurred, as was the case in this study.

Another highlight of this study is that it shows the importance of considering stand density reduction due to fire mortality together with tree size for analyzing the effects of fire on longer-term tree growth. It was observed that even if the postfire tree-level severity can negatively affect growth in the medium and long term due to the presence of scars or attack by secondary hazardous elements, as time passes the reduction of tree competition following fire-induced mortality ultimately gains importance as the main driver of a positive effect of fire on tree growth. Nevertheless, the size of surviving trees had to be considered to improve our knowledge on the effect of fire-induced tree mortality on postfire survivor-tree growth. For example, we observed a marked increase in long-term growth rate by small trees subjected to high-severity fire, likely caused by the higher mortality rate that was to be expected among their neighboring trees, especially if they shared similar characteristics (small size and high fire severity). These results are partially in disagreement with Sutherland et al. (1991) who found that pre- and postfire growth increased with increasing tree sizes. However, Sutherland et al. (1991) also suggested that the prescribed burning used in their study was not intense enough to emulate a thinning and its positive effects. Even if in our study small surviving trees did recover growth vigor over time to reach similar or higher growth rates than unburned trees, the expected positive effect of “fire-induced pre-commercial thinning” was not found to be substantial enough along all tree size classes to consider it as a long-term enhancer of tree growth and to present fire as a tool to be generalized and used for the sole purpose of enhancing the growth of survivors.

Regarding the relationship between climate and growth, our results partially agree with the idea that black pine is a drought-sensitive species (Andreu et al. 2007). Our study showed the influence of water availability on black pine growth, represented by sensitivity to autumn and winter temperature and precipitation as drivers of interannual growth variation in most trees, except in the case of highly affected trees of smaller sizes, which are mainly influenced by summer precipitations. Even if our results on the effect of climate on growth are significant and logical, there are two points that limit the possibility of extrapolating them to other sites and conditions and at the same time warrant further studies on the topic of linking climate and postfire tree growth. On the one hand, the low MS and EPS values found in almost all chronologies reflected unacceptable values to conduct a dendroclimatic analysis of the common interval time span. On the other hand, the limited number of postfire years was not considered suitable for implementing independent estimations of these statistics, not allowing to interpreting the shift in climatic response between the pre- and postfire period and within small size classes. In addition, our study is based on data from one site and one fire and does not therefore allow comparisons between different climatic regimes. Still, we can assume that the influence of climate on postfire growth adds uncertainty to any future prediction of postfire tree growth, and partially overshadows the effect of other factors that are more controllable through fire and forest management. However, the influence of climate on tree development still has to be considered for strategic planning of fire management, especially given the forecast increase in temperature and decrease in precipitation predicted by climate change models (Sumner et al. 2003).

Black pine is considered well-adapted to low-intensity fires, being able to survive recurrent surface fires due to its thick bark and few lower branches (Fule et al. 2008). However, intense fires may endanger the persistence of black pine forests over time due to the absence of serotinous cones, together with its seed intolerance at high temperatures, which result in regeneration failures after crown fires (Retana et al. 2002). Given the findings of this study and the fire ecology of black pine, fuel management strategies based on the use of prescribed burning or fire management tactics could be recommended. These practices would reduce fuel loads and serve as a silvicultural tool to ensure the persistence of black pine forest over time (Fernandes and Botelho 2003). Finding a balance between the short-term negative impacts of fire on tree growth and the positive effects demonstrated by small trees in the long-term may be pivotal to correctly implementing fuel management operations. Still, the present study highlights how finding this balance is not an easy task, as predicting the effect of fire on tree growth is a complex issue due to trade-offs between the effects caused by fire damage to tree tissues in surviving trees, the presence of fire-induced fertilization, the reduction in competition due to the fire-induced tree mortality and removal of understory (Wyant et al. 1983), the potential pruning of non-productive lower branches, and the possibility of changing climate effects on growth between burned and unburned trees.

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