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Disentangling the effects of crown scorch and competition release on the physiological and growth response of *Pinus halepensis* Mill. using $\delta^{13}C$ and $\delta^{18}O$ isotopes

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ABSTRACT

Prescribed burning (PB) can decrease the likelihood of crown fires by increasing canopy base height via canopy scorching and sometimes by reducing tree density through fire-induced tree mortality, especially in fire-prone stands. However, little is known about the effect of moderate PB on tree functioning, especially in Mediterranean species such as *Pinus halepensis* Mill. In this study we combined dendrochronology and isotope analysis to understand the physiological effects of PB that determine the short-term post-burning growth response of crown-scorched and unscorched *P. halepensis* with different levels of competition release. PB was carried out in spring 2013. Scorched and unscorched pines showed higher post-burning growth rates than before PB as well as control pines. In the first year post-burning, unscorched pines had similar growth rates and $\delta^{18}O$-$\delta^{13}C$ values to the control pines, which indicates that PB only had a minor impact on tree functioning. In contrast, scorched pines showed a significant reduction in growth and wood $\delta^{13}C$, but had similar $\delta^{18}O$ as the unscorched and control (no-PB managed) pines. This suggests that the pines' response mechanism to scorch was to reduce their photosynthetic capacity. At two years post-burning (2015), the growth of scorched pines was similar to control pines. Moreover, the radial growth of pines increased significantly when PB resulted in a relevant competition release and crown volume scorch was low. At two years post-burning (2015), a smaller change in $\delta^{13}C$ in scorched trees compared to 2014 was found and no changes in $\delta^{13}C$ in unscorched pines; however, lower $\delta^{18}O$ was found in scorched and unscorched pines compared to the controls, which suggests an increase in stomatal conductance probably due to improved water availability through fire induced thinning. The increase in stomatal conductance in scorched and unscorched pines coincided with an extreme drought year (2015), which indicates that the control pines adopted a more conservative water-use efficiency. No effects of burning on needle N content or $\delta^{15}N$ were detected. As a management conclusion, our study suggests that moderate PB can be implemented to disrupt the vertical continuity of fuels in crown fire prone landscapes, enhancing water availability during drought episodes with only minor effects on tree functioning.

1. Introduction

Prescribed burning (PB) is the planned use of fire under specific and predetermined fuel and weather conditions to manipulate the environment and achieve a desired outcome (Wade et al. 1989), including reducing fuel hazard (Fernandes and Botelho 2003). PB can benefit the productivity of trees by nutrient deposition after fire (Certini 2005) and reducing plant competition by removing the understory (Battipaglia et al. 2014b). However, in crown fire prone ecosystems, a higher burning intensity could be useful for decreasing the likelihood of crown fires by increasing canopy base height through crown scorching and inducing the death of small trees. In this case, although in general PB aims to maintain forest productivity without negatively impacting standing trees, the growth and performance of remaining trees may be reduced. High intensity PB may negatively impact tree growth through foliage, root and stem injuries, leading to changes in their photosynthetic capacity and tree water relations (Chambers et al. 1986, Ryan 1993). However, higher intensity PB can improve the growth of standing trees by reducing the competition with small and medium trees (Py et al. 2006). Although the scientific community has studied

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the impact of these contrasted factors on tree growth, little is known about the interaction among them and this has become a priority for planning successful PB.

Crown fire injury can have important impacts on photosynthetic rate (Wallin et al. 2003), stomatal conductance (Cernusak et al. 2006), transpiration (Clinton et al. 2011), xylem pressure potential (Ryan 1993), sap flow rate (Cernusak et al. 2006), phloem transport (Alexou and Dimitrakopoulos 2014) and chemical defenses (Alonso et al. 2002). While partial defoliation can improve tree water relations and increase the photosynthetic efficiency of the remaining foliage, severe defoliation may result in a decrease in carbon uptake, and hence, a reduction in growth (Waldrop and Van Lear 1984, Lilieholm and Hu 1987, Ryan 1993). This may potentially lead to carbon starvation and ultimately tree death (Galiano et al. 2011). Moreover, the functioning of scorched trees facing future stressful events, such as drought, could be constrained by the physiological changes caused by the fire.

Studies using reconstructed or direct measures of fire thinning intensity have shown either positive (Mutch 1995, Py et al. 2006, Valor et al. 2013, Alfaro-Sánchez et al. 2015), negative (Wooldridge and Weaver 1965) or no effect (Morris and Mowat. 1958, Sutherland 1989) on tree growth (see Landsberg, 1994 for review). These discrepancies may be attributed to differences in the reduction of tree competition in the different studies, the scale used to compute the competition release (stand vs. tree level) and the degree of fire damage sustained by surviving trees. Fire induced thinning can be expected to have a positive effect on growth and also impact intrinsic water use efficiency ($WUE_{i,}$) in surviving trees when water availability is a limiting factor, similarly to mechanical thinning (McDowell et al. 2003, Martín-Benito et al. 2010, Giuggiola et al. 2016). Furthermore, fire can enhance nutrient availability through ash deposition and stimulation of post-fire mineralization, leading to an increase in N concentrations in plant tissues (Carter and Foster 2004), which potentially enhances WUE_i and tree growth (Guerrieri et al. 2011). Nonetheless, increases in WUE_i do not always lead to an enhancement in tree growth because other environmental factors or alternative carbon sinks may limit growth (Peñuelas et al. 2008). WUEi is the ratio between photosynthetic rates (A) and stomatal conductance (gs), which is the amount of water that is lost by the leaf for each CO_2 molecule assimilated by photosynthesis (Farquhar et al. 1989). The dual-isotope approach (Roden and Farquhar 2012), which combines the analysis of $\delta^{13}C$ and $\delta^{18}O$, can be used to differentiate between the effects of the photosynthesis rate (*A*) and stomatal conductance (*gs*) on WUE_i, especially in drought sensitive species and after fire events (Battipaglia et al. 2014a, Battipaglia et al.2016). The $\delta^{13}C$ is a good indicator of plant intrinsic WUE_i (Farquhar et al. 1989), which is given by the ratio of net photosynthetic rate (*A*) and stomatal conductance (*gs*). The $\delta^{18}O$ of plant organic material is related, for a similar water source, to the ratio of atmospheric (ea) to leaf intercellular (ei) water vapor pressure (ea/ei), which is strongly affected by changes in gs (Barbour 2007). As plant $\delta^{18}O$ is related to *gs* but unaffected by *A* (Barbour 2007) simultaneous estimations of $\delta^{13}C$ and $\delta^{18}O$ can isolate the impacts of *A* and *gs* on $\delta^{13}C$ (Scheidegger et al. 2000; Moreno-Gutiérrez et al. 2012).

In the Mediterranean basin, *P. halepensis* is the pine with the lowest canopy base height (Mitsopoulos and Dimitrakopoulos 2007) and forms highly flammable stands that are particularly prone to crown fires (Tapias et al. 2004). Thus, moderate-intensity burns in *P. halepensis,* scorching the crown of larger trees to increase the canopy base height, could be advisable for reducing the risk of fire crowning, as long as crown injury does not lead to irreversible damage to tree functioning. In recent years, research on post-fire *P. halepensis* growth has indicated that the overall effect of low-intensity fires is small (Fournier et al. 2013, Battipaglia et al. 2014b, Alfaro-Sánchez et al. 2015, Valor et al. 2015). This study analyses the effects of a moderate-intensity PB executed in 2013. PB affected the crown of dominant trees and induced tree mortality. We combined dendrochronological and stable isotope techniques to determine the mechanisms underlying the short-term physiological and tree growth responses of dominant *P. halepensis* in relation to certain levels of crown-fire damage and competition release. In addition, taking advantage of the extreme drought that occurred in the year 2015, we explored the drought sensitivity of scorched and unscorched trees compared to control trees. We hypothesized that scorching would improve the water relations of *P. halepensis* due to foliage loss, but in turn the loss in the total leaf area of the tree would reduce tree growth. In unscorched pines, we expected an increase in post-burning growth caused by fire-induced fertilization and thinning leading to a reduction in the competition for soil resources (i.e. water and nutrients). In contrast, the effects of fire induced thinning and fertilization on the growth of scorched pines may be more complex as fire injury may cancel out the positive effects of PB.

2. Material and methods

2.1. Study site

The study was carried out at a 2-ha site situated in the El Perelló locality, in the southern part of Catalonia (Spain). The climate is typically Mediterranean with a mean annual rainfall of 610 mm and mean temperature of 15.5 °C. Based on Spanish Meteorological Agency (AEMET) data, over 1975–2015, the warmest and coldest months were August (mean $T = 24.5$ °C) and January (mean $T = 8.2$ °C), respectively. The driest and wettest months were July ($P = 15.8$ mm) and October ($P = 62.6$ mm), respectively. The site is situated on a flat terrain, soils have developed from limestones (0.4–0.5 m depth) and are classified as Leptic Regosol (FAO I 2006). The forest is an even-aged forest of *P. halepensis* planted during the decades of the 1950s and 60s. The average diameter at breast height (DBH) of the trees was 20.6 ± 2.7 cm. Site tree density (DBH > 2.5 cm) before burning was 727 tree ha^{-1} and the basal area was 23 m^2 ha^{-1}. The understory is dominated by *Pistacia lentiscus* L. and *Quercus coccifera* L., which occupies about 604 m^3 ha^{-1}.

2.2. Prescribed burning and fire severity measurements

Before PB, two plots (30 × 30 m) were set up to monitor fire behavior, tree mortality and the growth of surviving trees. In addition, an unburned plot, adjacent to the burned site, was established as a control. In each plot, trees were identified with a metal tag. For each tree, we measured the distance and angle to the center of the plot and the DBH.

PB was conducted in spring on 13 May 2013, by the Forest Actions Support Group (GRAF) of the Autonomous Government of Catalonia (Generalitat de Catalunya) using a strip headfire ignition pattern. PB was of moderate intensity with the aim of increasing canopy base height of dominant trees and reducing tree density. The average meteorological conditions during the PB were: 19.5 °C air temperature; 58% relative humidity; 3.2 km h^{-1} wind speed; and 7.5% mineral soil water content. The combustion time (minutes) above 60 °C and the maximum temperature at the base of the stem, placed at the surface of the soil litter, was measured in a total of 18 trees with K-thermocouples (4 mm diameter) connected to dataloggers (Testo 175) packed with a fireproof blanket and buried in the soil. Temperatures were recorded every 10 s. The mean combustion time above 60 °C ranged from 2 min to 241 min, while maximum temperatures ranged from 65 °C to 750 °C. Between 70 and 80% of the surface fuel load was consumed (Fuentes et al. 2018). One week after PB, the crown volume scorched (CVS) was visually estimated to the nearest 5% as the change in needle color resulting from heat transferred via convection. In each plot, tree mortality