Forest Ecology and Management 334 (2014) 201–208

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

The effects of prescribed burning on *Pinus halepensis* Mill. as revealed by dendrochronological and isotopic analyses

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ARTICLE INFO

Article history:
Received 3 June 2014
Received in revised form 10 September 2014
Accepted 10 September 2014

Keywords:
Prescribed burning
Dendrochronology
Aleppo pine
Tree physiology

ABSTRACT

Prescribed burning is used in several countries to manage Mediterranean ecosystems mainly to reduce the risk of high-intensity wildfires. As the physiological response of overstory trees to prescribed burning has received scant attention in the scientific literature, the main objective of this study was to determine whether prescribed burning impacts the growth and ecophysiological responses of stands of the Aleppo pine (*Pinus halepensis* Mill.). Basal area, carbon, oxygen, and nitrogen isotopic compositions were analyzed before and after the burning event at an experimental site and at a nearby unburned area used as control, both in the co-existing old dominant *P. halepensis* trees and in the youngest individuals. Our results suggest that the oldest pines experienced more favorable growing conditions after prescribed burning probably through higher water and nutrient availability, at least in the short term. The youngest individuals mostly likely suffered from an increase in competition with the older co-existing trees. These differences in physiology suggest the need to understand and evaluate, in the prescribed burning management plans, the growth and survival of burned trees of different ages in order to maximize the positive effects and reduce possible negative impacts.

1. Introduction

Prescribed burning is increasingly being recognized and incorporated as a management tool for wildfire reduction in several European forests (Fernandes et al., 2013), especially in the Mediterranean regions where wild and man-induced fires represent a major environmental problem, causing a large destruction of forests and a considerable increase of greenhouse gas emissions (Moriondo et al., 2006). Prescribed burning can be described as the careful application of fire under specific fuel and weather conditions to meet specific objectives and long-term management goals (Wade and Lunsford, 1989), such as silvicultural improvement, control of insects and diseases, habitat management, biodiversity conservation and, especially, the reduction of the risk of wildfires (Fernandes and Botelho, 2003). Several studies investigated the sustainability of prescribed fire in reducing wildfire hazard, avoiding negative effects on different ecosystem components, such as soil (Catalanotti et al., 2010), seeds (Keyser et al., 2012), shrubs (Fernandes et al., 2013) and trees (Fernandes and Rigolot, 2007). Ducrey et al. (1996), studying the ecophysiological responses of *Pinus halepensis* to heat-caused stem injury, verified that no trees died with less than 85% of the trunk circumference destroyed by fire. In addition, reduction in tree mortality and crown scorch were reported for the North American *Pinus ponderosa* stands that were treated by prescribed burning some years before a natural wildfire occurred (Wagle and Eakle, 1979; Martin et al., 1988; Pollet and Omi, 2002). Indeed, moderate damages seems to be recorded after experimental fires in several European pines species (Fernandes et al., 2008) even if quantification of the influence of prescribed burning on trees' growth and ecophysiology remains elusive. Understanding the effect of prescribed burning in the short and mid-term on tree productivity and on plant ecophysiological responses is of crucial importance for fuel management plans and burning prescriptions, especially in widespread flammable plantations, such as *P. halepensis* stands. Aleppo pine (*P. halepensis*) is one of the most extensively studied Mediterranean pine (Ne'eman, 2000), abundant in fire-prone habitats within the Mediterranean basin and considered highly vulnerable to fire events (Trabaud, 2000; Kazanis and Arianoutsou, 2004). Recently, it has been demonstrated not only that *P. halepensis* is able to survive to wildfires (Fournier et al., 2013) but also that with its great plasticity it has developed various anatomical and ecophysiological adaptations to past fire events (De Micco et al., 2013; Battipaglia et al., 2014b).

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http://dx.doi.org/10.1016/j.foreco.2014.09.010
0378-1127/

Tree rings are considered a valuable archive of information concerning changes in tree growth in response to environmental stress factor, such as fire (Schweingruber, 1988). However, the combination of the three isotopes $\delta^{13}C$, $\delta^{18}O$ and $\delta^{15}N$ in tree rings can provide more specific information on the underlying ecophysiological processes (Guerrieri et al., 2011; Leonelli et al., 2012, 2013). In particular, plant $\delta^{13}C$ is inversely and linearly correlated with the ratio of intercellular (ci) to atmospheric (ca) CO_2 concentrations in leaves (Farquhar et al., 1989). The ci/ca ratio reflects the relative magnitudes of net photosynthetic rate (A) and stomatal conductance (gs), and thus $\delta^{13}C$ is a good indicator of plant intrinsic water-use efficiency (WUE_i), which is given by the ratio A/gs (Farquhar et al., 1989; Dawson et al., 2002; Battipaglia et al., 2010a, 2014a). The $\delta^{18}O$ of plant organic material is strongly related to the isotopic signature of source water, which may change with depth of water uptake due to evaporative isotopic enrichment of soil water near the surface (Dawson et al., 2002; Barbour, 2007). Plant $\delta^{18}O$ is also inversely related to the ratio of atmospheric (ea) to leaf intercellular (ei) water vapor pressure (ea/ei), and thus it is strongly affected by changes in gs (Barbour, 2007). Hence, simultaneous measurement of $\delta^{18}O$ and $\delta^{13}C$ in plant tissues allows discrimination between biochemical and stomatal limitations to photosynthesis (Scheidegger et al., 2000; Moreno-Gutiérrez et al., 2012; Tognetti et al., 2012) and, since plant $\delta^{18}O$ is related to gs but is unaffected by A, it can help separate the independent effects of A and gs on $\delta^{13}C$ (Barbour, 2007). Finally, $\delta^{15}N$ can provide indications of changes in ecosystem N cycling and its availability for plant uptake in response to fire treatments (Beghin et al., 2012).

The main goal of the present study was to evaluate the sustainability of the prescribed burning application in relation to the productivity and ecophysiological processes of *P. halepensis* forest. In particular we analyze the effects of prescribed burning, carried out in Southern Italy in 2009, on the physiological performance and wood growth of *P. halepensis* in the short and medium term and in relation to plant age, by means of a combined approach of dendrochronology and stable isotope measurements.

We hypothesized that prescribed burning would reduce competition for water by removing burning coexisting shrubs and herbaceous species, and would improve the water status of the remaining dominant tree species, thereby increasing nitrogen inputs in the soil. Thus we predicted that trees in low-density stands, especially the dominant older individuals, would not only show higher radial growth rates after the prescribed burning than those in the control site, but also variations in the isotopic ratios triggered by an increase in photosynthetic activity (lower $\delta^{13}C$, no variation in $\delta^{18}O$ and higher $\delta^{15}N$).

2. Materials and methods

2.1. Study area

In the framework of the FIRE PARADOX project (Rego and Montiel, 2010), prescribed burning was undertaken in May 2009 in a *P. halepensis* plantation in Capo Palinuro (40°01′34″N; 15°16′50″E ; 160 m a.s.l.) in the Cilento and Vallo di Diano National Park (PNCVD), one of the most fire-prone areas in southern Italy (Mazzoleni et al., 2001; Ricotta et al., 2006). During the prescribed burning the average air temperature was 20 °C, relative humidity 46%, wind speed 4 km h^{-1} and surface litter moisture: 17%. Fire was characterized by following behavior: average (±SE) rate of fire spread 0.22 ± 0.06 m min^{-1}, flame length range 0.2–1.0 m; average (±SE) fireline intensity 52 ± 10 kW m^{-1} (Ascoli et al., 2010). Further details on the experimental fire are reported in Ascoli et al. (2010).

The climate of the area is typically Mediterranean with warm dry summers. Monthly mean temperature and precipitation data (1964–2012) are recorded at the meteorological station of Capo Palinuro, 300 m from the sampling site. The mean annual temperature is 17.7 ± 7.1 °C (mean ± standard deviation, SD) and the mean annual precipitation 714 ± 25 mm. Vegetation is dominated by *P. halepensis* with a dense shrub understory dominated by *Erica arborea* and scattered tall grasses, such as *Ampelodesmos mauritanicus*, and other Mediterranean shrub species.

In autumn 2011, tree sampling was realized at the site interested by the prescribed fire (ES), of 0.60 ha, and at an unburned site (CS), adjacent to the first (distance between plots 10 and 12 m), of the same size, with the same tree density (355 ± 9 trees per hectare), the same aspect, elevation, and soil but unaffected by fires and used as a control site (to exclude other environmental influences on the stands apart from the prescribed burning).

2.2. Tree-ring sampling

In each site two size classes of pines were recognized: a young class, including all the individuals with a circumference at breast height < 50 cm (mean circumference 39 ± 7 cm; mean height = 11 ± 1 m) and an old class including all the individuals with a circumference > 50 cm (mean circumference 80 ± 16 cm; mean height = 14 ± 3 m). For each size class and each site 20 Aleppo pines were randomly selected and cored, extracting with a 5 mm increment borer (Haglöfs, Finland) two cores per tree at 50 cm maximum above ground, with an angle of 120° between them, for a total of 160 cores.

Cores were polished using sand paper of different grain-size and ring-width (TRW) measurements made with a resolution of 0.01 mm, using LINTAB measurement equipment fitted with a stereoscope and analyzed with TSAP software (Frank Rinn, Heidelberg, Germany). After visually cross-dating to identify common marker years and ring width patterns (Schweingruber, 1996), samples from each site were correlated according to Gleichläufigkeit, a statistical measure of the year-to-year agreement between the interval trends of the chronologies based upon the signing of the agreement (Kaennel and Schweingruber, 1995) and a Student *t*-test, which determines the degree of correlation between curves. The program COFECHA (Holmes, 1993) was run to validate the cross-dating and measurements and to find potential errors. Once all measurement series had been validated, tree-ring chronologies were developed. Series were detrended to remove long-term growth trends embedded in the raw tree-ring series, which were thought to be induced by non-climatic influences, such as ageing and competition between trees (Fritts, 1976). Afterwards, an autoregressive model (AR), based on the pooled autoregressive procedure in the programme ARSTAN (Holmes, 1993), was applied to remove the autocorrelation with the previous ring width. Tree-ring indices were calculated as residuals from the estimated age trend. The following parameters were calculated within each site: Expressed Population Signal-EPS (indicating to what extent the chronology based on a limited number of trees is representative of the 'hypothetical' true chronology, Wigley et al., 1984), r-bar (mean correlation among all possible pairings of the individual series within a chronology) and MS (mean sensitivity, indicating the degree to which TRW changes from year to year and how it is influenced by high-frequency climatic variations).

In order to perform tree radial growth comparisons between sites, the chronologies were converted in tree basal area (BA):

$$BA_n = \pi r_n^2 - \pi r_{n+1}^2$$

where n is the number of tree rings (increasing toward the tree centre) from the outermost whole ring (where $n = 1$), r_n is the radius minus the radial increment contributed by bark and the current year partial ring formation at $n = 1$, and r_{n+1} is the radius at