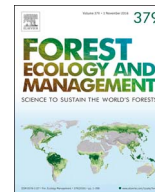




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Reprint of “Managing drought-sensitive forests under global change. Low competition enhances long-term growth and water uptake in *Abies pinsapo*”[☆]

Victor Lechuga^a, Vinicio Carraro^b, Benjamín Viñepla^a, José Antonio Carreira^a,
Juan Carlos Linares^{c,*}

^a Departamento de Biología Animal, Biología Vegetal y Ecología, Universidad de Jaén, Ed. B3, Paraje las Lagunillas s/n, 23071 Jaén, Spain

^b Dept. Land, Environment, Agriculture and Forestry, University of Padova, v. le dell'Università, 16, 35020 Legnaro, PD, Italy

^c Departamento de Sistemas Físicos, Químicos y Naturales, Universidad Pablo de Olavide, Ctra. Utrera km. 1, 41002 Sevilla, Spain

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ABSTRACT

Understanding forest responses to the current climate change requires to investigate the effects of competition, buffering or enhancing process of forests decline. Here we attempt to place intra-specific competition in a climate change context, using as experimental system the drought-sensitive fir *Abies pinsapo*. We conducted a decade-long (2004–2015) investigation at four permanent plots (two thinned plots and two controls), where all trees were identified, tagged and mapped. Experimental thinning was performed attempting to enhance stand structure diversity by (1) reducing tree competition, (2) increasing the equitability of size classes (i.e. diversity) and (3) randomizing tree spatial pattern. We focus on tree basal area increment and sap flow density, as regards microclimate and competition, to quantify the extent to that thinning alleviates drought in the remaining trees. The results support that lower competition fosters short- to long-term tree-level physiological responses, specifically, improved growth and water uptake in the remaining trees. Density reduction provides a promising strategy for minimizing climate change effects on drought-sensitive tree species by improving resources availability to the remaining trees. Nevertheless, our results also support a higher air temperature and soil water depletion according to density reduction, suggesting that lower competition might also increase soil and understorey evapotranspiration. Adaptive management, as the experimental thinning reported here, may increase tree-level resources availability, but the long-term stand-level effectiveness of this approach at sustaining forest ecosystem functioning remains uncertain.

1. Introduction

Increasing variability and uncertainty regarding future environmental conditions provide new challenges for forest management (Franklin et al., 2002; Puettmann, 2011; Messier et al., 2013; Ameztegui et al., 2017). Rising temperatures and changes in precipitation patterns may translate into shifting species composition and changing processes and functions of forest ecosystems over broad geographic regions (Breshears et al., 2005; Goetz et al., 2012; Vayreda et al., 2012). Increases in drought frequency and intensity are expected to elevate mortality rates for those drought-sensitive tree species, as widespread tree mortality has been documented in forests worldwide (Allen et al., 2010).

Despite climate change appears as a main driver of this worldwide reported forest die-off, usually related to tree growth decline and widespread mortality, the modulating effect of stand structure has been also widely recognized (Floyd et al., 2009; Lines et al., 2010; Moreno-Gutiérrez et al., 2012; Martínez-Vilalta et al., 2012). Competition is a critical demographic concern for determining tree growth and mortality, forest dynamics and, consequently, ecosystem function and carbon cycling (Canham et al., 2006; Ruíz-Benito et al., 2013; Fernández-de-Uña et al., 2015; Ford et al., 2017). Specifically, trees subjected to higher competition show lower radial growth and are more prone to die following extreme drought events (Carnwath and Nelson, 2016; Diaconu et al., 2017; Gleason et al., 2017).

In southern Europe, increasing tree mortality has been related not

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* Corresponding author.

E-mail addresses: vlechuga@ujaen.es (V. Lechuga), vinicio.carraro@unipd.it (V. Carraro), bvinepla@ujaen.es (B. Viñepla), jafuente@ujaen.es (J.A. Carreira), jlinalca@upo.es (J.C. Linares).

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Table 1

Main characteristics of the studied plots located at the lower elevation limit of *Abies pinsapo*. Values between parentheses show the standard error.

Treatment	Plot	Location			Pre-thinning			After-thinning				
		Latitude	Longitude	Elevation	DBH	Basal area	Stand density	DBH	Basal area	Stand density	Basal area reduction	Stand density reduction
		(N)	(W)	(m)	(cm)	(m ² ha ⁻¹)	(trees ha ⁻¹)	(cm)	(m ² ha ⁻¹)	(trees ha ⁻¹)	(%)	(%)
Control	C1	36°43'28"	4°57'59"	1173	11.8 (0.5)	34.1	2085	–	–	–	–	–
	C2	36°43'29"	4°58'10"	1232	14.2 (0.9)	28.8	1146	–	–	–	–	–
Thinned	T1	36°43'27"	4°58'01"	1181	17.2 (0.8)	28.7	995	15.6 (1.0)	14.4	581	50.0	41.6
	T2	36°43'26"	4°58'01"	1188	14.8 (0.8)	27.2	1114	12.7 (1.2)	12.4	581	54.4	47.9

only to increased drought, but also reduced forest management, which has potentially led to increased competition between trees (Gómez-Aparicio et al., 2011; Vayreda et al., 2012; Sánchez-Salguero et al., 2015a). Competition for resources (primarily for irradiance, water and nutrients) is a key biotic factor that affects the growth and functioning of plants at the individual, population and community levels (Carnwath and Nelson, 2016). In forests, competition affects tree mortality, size structure and species composition (Canham et al., 2006; Anderegg et al., 2016). Increasing stand density causes a decrease in soil water availability, which induces stomatal closure to prevent hydraulic failure and results in carbon uptake reduction by photosynthesis (Breda et al., 2006; McDowell, 2011). As a result, the response of drought-sensitive dense forests to a warmer and drier climate in future will likely be modified by competitive relationships among trees, which may potentially affect species composition and cause a need to change forestry practices (Puettmann, 2011; Ameztegui et al., 2017).

As regards the course involved in this recent large-scale forest decline, drought-induced tree mortality drives the functional and structural dynamics of forest ecosystems, both as a sink/source of carbon and nutrients, and as a mechanism of change in forest structure and species diversity (Galiano et al., 2010; Anderegg et al., 2012; McDowell et al., 2013; Rigling et al., 2013). However, managing stand structure, including sizes diversity and tree spatial patterns, may boost the adaptive capacity of drought-sensitive tree species (D'Amato et al., 2013; Giuggiola et al., 2013; Sohn et al., 2013; Elkin et al., 2015; Aldea et al., 2017). Hence, it seems mandatory to investigate stand structure effects, buffering or enhancing process of forests decline (Sohn et al., 2016; Diaconu et al., 2017; Gleason et al., 2017; Ameztegui et al., 2017).

Our study concerns the responsiveness of individual trees to changing climate variables with respect to their competitive status in the local neighbourhood. Here we attempt to place intra-specific competition in a climate change context, assessing the effects of forest structure under drought stress. We focus on tree growth and water fluxes to quantify the extent to that changing stand structure (by an experimental thinning) might alleviate drought stress in the remaining trees. We used *Abies pinsapo* forests as experimental system. This drought-sensitive Mediterranean fir was subjected to centuries of intense perturbation, by grazing and logging by the local inhabitants (Linares and Carreira, 2009). From the middle 20th Century onwards, *A. pinsapo* forests underwent the abandonment of traditional uses, increasing stand density during recent decades (Linares and Carreira, 2009). Nowadays, episodic *A. pinsapo* decline and mortality has been related to dry site conditions and high stand density (Linares et al., 2010).

We aim to test the main hypothesis that density-dependent factors and structural diversity, as a legacy of previous forest management, are among the main determinants of forest growth and climate sensitivity through the effect of competition. Our specific aims are: (1) to quantify the extent to that stand density alters microclimate, as regards soil

water availability, air temperature and vapour pressure deficit; (2) to investigate how stand density modulates climate-growth sensitivity; and (3) to analyze the inter-annual patterns of sap flow and secondary growth of individuals subjected to contrasting competition, dealing to spatially-explicit assessment of their competitive environment.

2. Material and methods

2.1. Study species and thinning design

The study was carried out at natural stands of *Abies pinsapo* Boiss., a drought-sensitive fir, located near the lower elevation limits of the altitudinal species distribution range (Sierra de las Nieves Natural Park; 36°43'N, 4°57'W, 1200 m, aspect NW, slope ca. 40%; Linares et al., 2010). *A. pinsapo* forests in the study area were subjected to intense grazing and logging by the local peoples up to about the middle 20th Century (Supporting Information, Fig. S1). During the second half of the 20th Century, until present, these forests were protected, while they underwent the abandonment of traditional uses (Linares and Carreira, 2009). The suppression of the perturbation regime initiates the processes involved in stand regeneration, leading currently to near-to even-aged dense stands (Linares and Carreira, 2009). Often, these stands maintain their even-aged structure until the next major disturbance occurs, as seems to be the case of extreme drought events and diseases, observed since the onset of the 1990s decade (Linares and Carreira, 2009; Navarro-Cerrillo et al., 2014). As a consequence, the studied stands were mainly formed by medium to small trees, generally spindly, with vigour suppressed by canopy closure (Linares et al., 2010).

We selected four circular plots, about 1300 m² surface and 100 m apart, where all trees with more than 3 cm diameter at 1.3 m from the ground (DBH) were identified (tree species; tree status: alive, dead, stump), tagged and mapped, and DBH was measured (Table 1). The studied stands were dominated by *A. pinsapo* (mainly 5–25 cm DBH) and scattered *Pinus halepensis*; mean stand density were 1335 trees ha⁻¹, while mean total basal area were 29.7 m² ha⁻¹ (Table 1). Two plots were randomly selected for thinning while the others were kept as control.

Experimental thinning was designed and performed in October 2004, attempting to enhance stand structure diversity by (1) reducing tree competition, (2) increasing the equitability of size classes (i.e. diversity) and (3) randomizing tree spatial pattern (Franklin et al., 2002). To achieve this objective of enhance stand structure diversity, the thinning was focused on the size classes with the highest tree density (Fig. 1). Thus, the diversity of size classes (the range of DBH sizes) was preserved, while equity of basal area for each size class was newly achieved (Fig. 1). Finally, the selection of trees to be felled were randomized to generate a heterogeneous spatial structure, where horizontal and vertical variability provided contrasting regeneration niches, enhanced gap colonization and boosted canopy cover recovery

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