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Original Article

Spatiotemporal variability of stone pine (*Pinus pinea* L.) growth response to climate across the Iberian Peninsula

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ABSTRACT

Climate warming and increasing aridity have impacted diverse ecosystems in the Mediterranean region since at least the 1970s. *Pinus pinea* L. has significant environmental and socio-economic importance for the Iberian Peninsula, so a detailed understanding of its response to climate change is necessary to predict its status under future climatic conditions. However, variability of climate and uncertainties in dendroclimatological approach complicate the understanding of forest growth dynamics. We use an ensemble approach to analyze growth-climate responses of *P. pinea* trees from five sites along a latitudinal gradient in Spain over time. The growth responses to April-June precipitation totals were stronger in the north than in the south. Since the 1950s, the sensitivity of growth to April-June precipitation increased in the north and decreased in the south. Meteorological drought usually started in May in the southern sites, but in June-July in the northern sites. The water deficit in the southern sites is thus greater and more limiting for tree growth, and this likely accounts for the lower growth sensitivity during these months. Our results indicate that *P. pinea* has a high degree of plasticity, suggesting the species will withstand changing climatic conditions. However, growth response to drought regimes varies among *P. pinea* populations, suggesting that different populations have different capacities for acclimation to warmer and drier climate, and this may influence future vegetation composition.

1. Introduction

Climate forecasts for the Mediterranean region indicate there will be an increase of temperature, decrease of rainfall, longer dry spells, more frequent heat waves, and more heavy precipitation events, all of which will exacerbate the existing problems of soil loss and desertification (Kovats et al., 2014). Significant changes in climate and related social dynamics, such as land use and food production, migration, and social conflicts, make the Mediterranean region a major climate change "hotspot" (Giorgi, 2006; Scheffran and Battaglini, 2011). The Iberian Peninsula, located in the western sector of the Mediterranean basin, has diverse climatic conditions: the northern zones have a Eurosiberian climate, and large parts of the peninsula have a Mediterranean-type climate, with warm summers and cold winters in the center and hot summers and mild winters in the south. The Iberian Peninsula has become drier in recent decades, and research indicates this change will continue (Pérez and Boscolo, 2010). There is evidence that climate change has already impacted forest ecosystems in this region. These impacts include shifts in species distributions and phenology (Peñuelas et al., 2002), decreases of growth, at least in the southern provenances and at lower edges of species altitudinal ranges (Jump et al., 2006; Martín-Benito et al., 2010), reductions of non-wood forest products (Büntgen et al., 2015a), stand decline processes and

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increased mortality (Carnicer et al., 2011; Natalini et al., 2016), and increased disturbances such as pests and fires (Hódar et al., 2003; Pausas, 2004). Distribution shifts of tree species are also expected for the future (Benito Garzón et al., 2008).

Pinus pinea L. is an important tree species of Iberian Mediterranean forests. This species occurs throughout southern Europe and the eastern and southern Mediterranean coasts, and is native to the Iberian Peninsula (Martínez and Montero, 2004). *P. pinea* forests in Spain have considerable socio-economic value and, because of the easy access to areas where it grows (for the most part flat terrains at low elevations), it is exposed to human disturbances. Most *P. pinea* forests in Spain originated from plantations during the 20th century. These forests occupy more than 500,000 ha and are managed as multifunctional forests that provide timber, biomass, non-wood forest products (especially pine "nuts"), soil protection, sand dune stabilization, biodiversity refuge, space for public and recreational activities, and carbon sequestration (Montero González et al., 2004). It is necessary to understand the effects of climate change on the ecology of *P. pinea* forests to assess the adaptive capacity of this species and to develop management programs that ensure the conservation of this environmentally and socio-economically important species.

P. pinea tree ring data can provide accurate information about the relationships between growth and climate (Campelo et al., 2006). Natalini et al. (2015) studied *P. pinea* tree ring growth in relation to climate change in southern Iberian Peninsula. In particular, they focused on temporal shifts of growth-climate relationships and increasing high-frequency variability and synchrony of growth in different populations as common responses to drier and warmer climate. However, trees also have diverse responses to climate depending on site-specific conditions (e.g. de Luis et al., 2013; Mazza et al., 2014). In fact, *P. pinea* grows under very different environmental conditions (Montero González et al., 2004), and variable growth responses to climate may be therefore expected across its geographical distribution range. The range of climatic conditions to which a species is adapted potentially determines its capacity to acclimate to future climatic conditions, and this should be considered when investigating the effects of climate change on forest dynamics (Tardif et al., 2003). For a proper assessment of growth-climate relationships, tree-ring detrending procedures also must be carefully considered. In particular, detrending curves with different degree of flexibility enhance the climatic signal and remove the non-climatic variance at different frequencies, and their suitability depends on the frequency domain of the tree-ring series (Helama et al., 2004). Moreover, uncertainties in growth-climate relationships can derive from the climate data, especially the choice of climate parameters and the lack of homogeneity of meteorological records (Frank et al., 2007; Büntgen et al., 2015b). Therefore, the spatiotemporal variability of species' response to climate, and the influence of different dendroclimatological approaches, make the assessment of climate-related forest growth dynamics more complex.

The purpose of this study is to provide a better understanding of climate-related *P. pinea* forest growth dynamics in Spain. We hypothesize that the species-specific growth response to climate varies over space and time in association with climatic spatial variability and temporal changes. To test our hypothesis, we examined growth-climate relationships and their variability over time in climatologically distinct sites along a latitudinal gradient in Spain. We tested the suitability of different tree-ring detrending methods and we used a comprehensive set of climatic parameters and climate data sources to check for uncertainties in climate data that could influence the assessment of growth-climate relationships. Finally, we discuss the observed variability of growth response to climate and its potential implications in Iberian *P. pinea* forest dynamics.

2. Materials and methods

2.1. Sampling sites

The sampling sites are along a latitudinal gradient in Spain and present different environmental conditions (Fig. 1, Table 1). Two sites ("Carrascal" – hereinafter CAR – and "Viana de Cega" – VIA) are in the province of Valladolid on the "Meseta Norte" (northern Spain), one site ("Hoyo de Pinares" – HOY) is in the province of Ávila (Central Spain), on the "Sistema Central" mountain range, and two sites ("Hinojos" – HNJ – and "Valverde" – VAL) are in the province of Huelva, Southwestern Spain. The Meseta Norte is a vast plateau of Tertiary and Quaternary deposits with altitudes of ~600 to ~900 m a.s.l., where *P. pinea* grows within nemoro-Mediterranean vegetation, i.e. transitional areas where evergreen sclerophyll and deciduous broad-leaf forests occur (Allué, 1990). The Sistema Central is composed of Paleozoic and Mesozoic granitic rocks with patches of Cenozoic sediments, runs in an ENE-WSW direction (between the Meseta Norte to the north and the Meseta Sur to the south). Here, several peaks are higher than 2000 m a.s.l., and *P. pinea* grows at 600–1000 m a.s.l. within Mediterranean and nemoro-Mediterranean vegetation. VAL is on the southernmost limit of the "Sierra Morena" mountain range, HNJ is on the coastal zone of the Baetic depression (alluvial plain of the Guadalquivir river), and both have Tertiary and Quaternary deposits and low elevations (under 300 m). In this area, vegetation is Mediterranean including the most xeric *P. pinea* forests of Spain. In Carrascal and Viana de Cega, they are on flat terrains and are managed as protection forests (with an important function of fixing continental fossil dunes) and for production of timber and pine nuts. In Hinojos and Valverde del Camino, *P. pinea* forests are on flat terrains, they are primarily managed for timber production and nowadays biomass, and secondarily for pine nuts. Silvicultural measures for productive functions typically involve thinning and pruning for improving wood production and crown development. In Hoyo de Pinares, *P. pinea* trees grow on a south-facing slope within less disturbed protection forests, where productive functions are not important. The sampled stands in VIA, HOY, VAL and HNJ are pure, even-aged, single-canopied *P. pinea* stands, and the stand in CAR is a single-cohort stratified mixture, with a dominant storey of *P. pinea* trees and a lower storey of *Quercus ilex* L. subsp. *ballota* [Desf.] Samp. and *Juniperus thurifera* L. Climatic conditions are similar between the two northern sites (VIA and CAR) and between the two southern sites (VAL and HNJ), but differ along the latitudinal gradient. Annual precipitation and mean temperature are 404 mm and 12 °C in CAR, 357 mm and 12 °C in VIA, 548 mm and 11 °C in HOY, 525 mm and 17 °C in VAL, 527 mm and 18 °C in HNJ (climate values calculated over the period 1950–2013 using the E-OBS gridded climate dataset).

2.2. Tree-ring chronologies

All samples (2 cores per tree) were extracted with an increment borer at breast height from the largest dominant or co-dominant trees. The cores were glued onto wooden mounts and sanded along the transverse sections to make the rings visible. Tree ring widths were measured with a stereomicroscope and a LINTAB™ table connected to a TSAP-Win™ tree ring analysis system (Rinntech®). Ring width curves were plotted for visual inspection and cross-dated by determination of the coefficient of parallel variation (*Gleichlaeufigkeit*, Glk; see Speer, 2010), *t*-value, and cross-date index (CDI) using TSAP-Win™ software. The cross-dating was verified using COFECHA (Grissino-Mayer, 2001).

The stands in the study sites are subjected to forestry treatments that affect growth trends and may mask the climatic signals stored in the ring width measurements. To remove the non-climatic