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ORIGINAL ARTICLE

Dendrochronology of maritime pine in the middle of the Atlantic Ocean

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A B S T R A C T

The Azores Archipelago, located in the North Atlantic Ridge, experiences heavy rainfall and mild temperatures with weak seasonal differences due to oceanic influence. To our knowledge, there have been no dendrochronological studies in the Azores. The aim of this study is to explore the dendrochronological potential of *Pinus pinaster* Ait. growing in this archipelago and to determine what limiting factor is regulating tree growth. To do so, we have sampled adult maritime pine trees growing in a plantation, in the Pico island of the Azores.

Tree ring boundaries were not always easily distinguished, suggesting that in some years cambial activity did not stop during winter. Despite this, it was possible to successfully crossdate the tree-ring series and to establish a tree-ring width chronology with a strong common signal. Climatic correlations revealed a positive response to spring precipitation but no temperature signal in the tree-ring width chronology. Tree-ring width was also negatively correlated with the North Atlantic Oscillation (NAO) and the sea level pressure (SLP) in May − June.

Intra-annual density fluctuations (IADFs), which are anatomical features formed in response to variations in environmental conditions during the growing season, were present in 85% of the tree rings. IADFs were identified based on its position within the ring: type E^+, characterized as a transition wood from early- to latewood; type L, the most frequent, characterized as earlywood-like cells within latewood; and type L^+, characterized as earlywood-like cells between latewood and earlywood of the next tree ring. Each IADF type presented a unique climatic signal: type E^+ was positively correlated with early summer precipitation and early spring temperature; type L was positively correlated with early autumn precipitation and temperature; and type L^+ was positively correlated with late autumn precipitation.

In conclusion, the tree-ring width chronology established for maritime pine growing in the Pico Island of Azores contains a clear climatic signal for spring precipitation, whereas IADFs frequency correlated better with precipitation later in the growing season. For this reason, we suggest that IADFs should be included in future dendrochronological studies in the Macaronesia Biogeographical region since they can improve the climatic signal present in tree-ring width chronologies.

1. Introduction

The Azores are a Portuguese archipelago of volcanic origin located in the North Atlantic Ridge between the latitudes of 36°45′N and 39°43′S. It is part of Macaronesia, a biogeographical entity that includes four archipelagos: Cape Verde, the Canary Islands, Madeira and the Azores (Myers et al., 2000). The climate of Macaronesia varies from sub-tropical to arid in Cape Verde and the Canary Islands, and to temperate-Mediterranean in Madeira and the Azores. Due to the influence of the warm Gulf Stream and the Azores Anticyclone, the Azores present warm temperatures with little variability throughout the year (Cunha et al., 2010; Santos et al., 2004). Precipitation in the Azores is highly influenced by the North Atlantic Oscillation (NAO), both in winter and summer, with seasons dominated by negative NAO phases presenting higher mean precipitation values (Hernández et al., 2016). The strong influence of the Atlantic Ocean also makes these islands wetter, windier and cloudier than the continent.

To our knowledge, the only dendrochronological studies performed in Macaronesian islands were in Tenerife, belonging to the Canary archipelago, using the native species *Pinus canariensis* C. Sm. (Jonsson et al., 2002; Pérez-De-Lis et al., 2011; Rozas et al., 2013, 2011b). Jonsson et al. (2002) found that the tree-ring growth in *P. canariensis* growing in the upper tree limit, was dependent on the previous year precipitation and temperature during the four previous years. Rozas et al. (2013) also studied the climatic response of *P. canariensis* in trees growing along an altitudinal gradient in the windward and leeward slopes. They observed that tree-growth was highly influenced by trade winds and by the North Atlantic Oscillation (NAO). Although part of Macaronesia, the climate in the Azores is very different from the arid Canary Islands, thus it would be very interesting to determine what

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climatic factors are limiting tree growth and whether if it is possible to do a dendroclimatology study in these islands.

Maritime pine (*Pinus pinaster* Ait.) was introduced in the Pico Island of Azores after the last volcanic eruption in 1718 (Governo Regional dos Açores, 2002). Nowadays maritime pine is an important forest species in this island and the second most used for wood production. The Azores present quite different climatic conditions when compared with the native distribution of maritime pine in the Mediterranean region and Atlantic coast of southwest Europe (EUFORGEN, 2009). Dendrochronological studies performed on its native region showed that tree growth was enhanced by previous winter and spring precipitation and constrained by summer drought (Campelo et al., 2015; Nabais et al., 2014; Rozas et al., 2011a; Vieira et al., 2009). The climate in the Azores Archipelago is, however, milder than the Mediterranean climate. Thus it would be interesting to determine the climatic signal, if any, present in maritime pine trees growing in the Azores.

In its native distribution maritime pine frequently presents false rings or intra-annual density fluctuations (IADFs). Intra-annual density fluctuations are variations in wood density (lumen diameter to cell wall thickness ratio) that are formed in response to variations in environmental conditions during the growing season, as can be easily observed by comparing seasonal environmental conditions with the intra-ring pattern of tracheid features (Campelo et al., 2016; Carvalho et al., 2015). IADFs can be present in earlywood and latewood, being defined as latewood-like cells within earlywood (IADF type E) or by earlywood-like cells within latewood (IADF type L; Campelo et al., 2007), respectively. In trees growing in the Mediterranean region, earlywood IADFs are formed in response to a drought period during spring and latewood IADFs by above average precipitation in fall (Battipaglia et al., 2016; Campelo et al., 2007). Due to its refined climatic signal, IADFs have been recently used to improve the climatic signal of tree-ring width chronologies (Campelo et al., 2007; Vieira et al., 2010; Wimmer, 2002). Although maritime pine usually presents a high frequency of IADFs in the Atlantic coast of Portugal and Spain (Rozas et al., 2011c; Vieira et al., 2010), it is not known whether the Azores climate will trigger the formation of such anatomical features.

Our aim is to explore the dendrochronological potential of maritime pine in the context of Macaronesian Dendrochronology. The objectives are to 1) determine the limiting factors for tree growth in the Azores; 2) determine whether IADFs are formed and 3) what climatic factors trigger its formation.

2. Material and methods

2.1. Study site

The study site is located in the North side of the Pico Island, in the Azores Archipelago (Fig. 1, 38.54208 N; 28.39906 W; 175 m a.s.l.). Pico Island is the second largest island in the archipelago being 42 km long and 15.2 km wide covering 447 km^2. The Azores Archipelago is composed of nine islands distributed in three groups: the western group (Flores and Corvo), the Central group (Pico, Faial, Terceira, São Jorge and Graciosa) and the Eastern group (São Miguel and Santa Maria). Pico Island is the second largest and the youngest: it only emerged from the sea 300.000 years ago (Madeira, 1998). The last volcanic eruption in the Pico Island was in 1718 and created a vast basaltic lava area in the northeast part of the island. This area was later populated with maritime pine (*Pinus pinaster* Ait.) by the Forest Services in order to protect the coastal line from erosion (). The study site is located in this forest, a plantation dominated by maritime pine with an understory of sparsely distributed shrubs of the species *Myrica faya* Ait., *Erica azorica* (Seub.) Hochst., *Picconia azorica* (Tutin) Knobl., *Frangula azorica* Tutin and *Laurus azorica* Franco.

The climate in the Azores Archipelago is of Mediterranean type, characterized by a narrow annual temperature range, high precipitation and a moderate summer drought (Fig. 2). The annual average temperature is 17.2 °C and total precipitation is 1003 mm (annual averages calculated for the period 1961 & 2010 from monthly data downloaded from the Royal Netherlands Meteorological Institute, http://www.climexp.knmi.nl/). In the coldest month (February), the average temperature if of 11.3 °C and in the warmest month (August), 25.0 °C. Precipitation presents a seasonal distribution, mainly occurring in the fall and winter months (Fig. 2). In Spring and Summer precipitation decreases and July is the driest month (33.1 mm).

2.2. Tree-ring data

In July 2011, 30 co-dominant *P. pinaster* trees were sampled from an area of approximately 5 he. The selected trees presented an average diameter at breast height of 46.4 cm, an average height of 15.2 m and 40 years of age. Two cores were taken from each tree, at breast height, from the north-south directions. The increment cores were later glued to wood supports and sanded with progressively finer grades of sandpaper to produce a polished surface on which tree-ring boundaries and individual tracheids were clearly visible under magnification (Stokes and Smiley, 1996). Tree rings were measured to the nearest 0.01 mm using the linear table LINTAB (Frank Rinn S.A, Heidelberg, Germany) and the program TSAP-Win (Rinn, 2003), and then crossdated using standard dendrochronology techniques (Stokes and Smiley, 1996).

From the initial 30 trees, only 22 were included in the analysis. Trees presenting a correlation with the mean chronology below 0.5 or less than 20 tree rings were excluded from further analysis. A one-step detrending procedure was applied to each tree-ring series to remove age-related growth trends and competition using the packages “dplR” (Bunn, 2008) and “detrendeR” (Campelo et al., 2012 & http://cran.r-project.org) for the R freeware program. The detrending procedure consisted of fitting a smoothing cubic spline curve with a 50% frequency cut-off and response period of 25 years to each individual ring-width series. Detrended series were used to produce a standard chronology using a biweight robust estimate of the mean to reduce the influence of outliers (Briffa and Cook, 1990). An autoregressive model was applied to this chronology to remove temporal autocorrelation and maximize the common inter-annual signal. Mean sensitivity (MS) and the first-order auto-correlation (AR1) were calculated on individual series (raw and detrended) and averaged to measure the year-to-year variability and how the current-year growth is affected by the previous year’s growth, respectively. Chronology quality was evaluated using the expressed population signal (EPS) that indicates the degree to which a given chronology portrays a hypothetical perfect chronology (Wigley et al., 1984).

2.3. Intra-annual density fluctuations

Cores were visually examined for IADFs in the common interval (1961 & 2010) using a stereomicroscope (magnification up to 25 x). IADFs were identified based on its radial position within the tree ring following the classification proposed by Campelo et al. (2007). IADFs were classified as follows: type E^+, characterized as transition wood with intermediate characteristics between earlywood and latewood, in terms of lumen area and cell wall thickness of the tracheids and located in the transition from early- to latewood (Fig. 3); IADF type L, characterized by the presence of earlywood like cells within latewood (Fig. 3); and IADF type L^+, characterized by transition wood from latewood to the earlywood of the next tree ring (Fig. 3). Since it was common to observe more than one IADF per tree ring the following combinations were also analyzed: E^+L, E^+L^+ and LL^+. IADFs and their combinations were registered on each core.

The frequency of IADFs per year, F, was calculated as follows:

$$F = N/n$$

where N is the number of cores that presented a certain type of IADF in a given year and n is the total number of observed cores. To adjust for

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