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Potential of oak tree-ring chronologies from Southern Portugal for climate reconstructions

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ABSTRACT

The present work reports a first attempt to assemble long tree-ring chronologies from Portugal potentially useful for climate reconstructions. Three oak species (*Quercus pyrenaica*, *Quercus faginea*, and *Quercus ilex*) were sampled at three sites in southern Portugal to obtain tree-ring chronologies. The longest tree ring series covers 173 years extending back to 1840. Our tree-ring records show, depending on the site, moderate-to-high correlations with precipitation in different seasons (from $r = 0.40$, $p < 0.01$, to 0.81 , $p < 0.001$) and temporal stability in the growth/climate relationship for two sites. Calibration-verification trials confirm the reliability of climate/growth models for climatic reconstructions back to periods represented by tree-ring records from these two sites. Regional precipitation for Alentejo can be estimated for the following seasons: April through August (calibration $r^2 = 0.24$); September, from previous year, to July (calibration $r^2 = 0.65$). The results are a promising kick-off for Portuguese dendroclimatology, since they represent a significant breakthrough in the Mediterranean region, especially for Iberian Peninsula, where there is a considerable lack of dendroclimatic reconstructions. Further efforts to extend the tree-ring records back in time using subfossil material should be undertaken.

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1. Introduction

The potential threats resulting from a changing climate have highlighted the importance of paleoclimatology studies in improving the current understanding of the climate system. The Earth's climate is progressively becoming warmer and this trend is projected to further enhance in future decades under anthropogenic forcing (IPCC, 2014a,b). The Mediterranean region is a climate change hotspot, as significant warming and drying are expected (Giorgi, 2006; Beniston et al., 2007; Gao and Giorgi, 2008; Nikulin et al., 2011; Diffenbaugh and Giorgi, 2012). Indeed, this region is at risk of experiencing the strongest alterations in ecosystem structure and composition, since it is already under vulnerable conditions (Cotillas et al., 2009; Sanchez-Salguero et al., 2010; Liñares

and Tiscar, 2011; Pasho et al., 2011; Candel-Perez et al., 2012). Therefore, improving the current knowledge on past climate variability in Mediterranean climates is a top priority.

However, long and high quality dendroclimatic reconstructions for Mediterranean areas are scarce (Nicault et al., 2008). This is due to the extreme difficulties to obtain long tree-ring chronologies with strong and consistent climatic signals in Mediterranean-like climates, particularly when compared to central European climates (as reviewed by Cherubini et al., 2003). Efforts to overcome this drawback have increased considerably in the very recent years. Multicentennial-long tree-ring chronologies have been used to study temperature in the Pyrenees (Büntgen et al., 2010; Dorado-Liñán et al., 2012a), event years in central Spain (Genova, 2012), water-use efficiency in eastern Spain (Andreu-Hayles et al., 2011), drought variability in northwestern Africa (Esper et al., 2007; Touchan et al., 2011), Greece (Sarris et al., 2011) and in the Mediterranean Basin (Touchan et al., 2005; Nicault et al., 2008), as well as the North Atlantic Oscillation (NAO) index (Trouet et al., 2009). Although Touchan et al. (2011) used 48 oak trees from three sites

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(out of a total of 837 trees and 39 sites) most of the aforementioned studies used conifer species.

In the South of Portugal, southwestern Iberia, tree-rings of pine species have shown a good agreement with climatic variables (e.g. *Pinus pinea*, Campelo et al., 2007b, *Pinus pinaster*, Campelo et al., 2013; Vieira et al., 2010), but the oldest pines in this area are younger than 150 years. Oaks are potentially the oldest trees in mainland Portugal. Drought-resistant evergreen Mediterranean oak species (e.g. *Quercus ilex* and *Quercus suber*) are widely distributed in the south. Moving northwards, they are gradually replaced by marcescent sub-Mediterranean species (e.g. *Quercus faginea* and *Quercus pyrenaica*), and then by deciduous temperate species (e.g. *Quercus petraea* and *Quercus robur*), already in the Atlantic biogeographical zone (Benito-Garzon et al., 2008).

The longest tree-ring series for Portugal are ca. 250 year-old, from *Q. robur* growing in sub-humid microclimates in Central Portugal, but showing very low synchrony between samples (Santos et al., 2015). Nevertheless, low-frequency variability in some of these tree ring series is in agreement with long-term trends in spring precipitation. The remaining studies with oak species have mostly analyzed short tree-ring series (<100 years). The climate/growth relationships are remarkably strong in young trees (<30 yrs) of *Q. suber* (Leal et al., 2008), and *Q. ilex* (Campelo et al., 2007a, 2010) and in old trees (>100 yrs) of *Q. ilex* (Campelo et al., 2009, Abrantes et al., 2013), even higher than those for temperate regions. However, these results were only possible to achieve by using stem cross sections resulting from authorized tree fellings. There are very strict regulations in the country concerning tree felling for these two species, particularly for *Q. suber*, which is a highly protected species because of its cork production. The transitional species, between Mediterranean and mesic oaks, such as *Q. pyrenaica* (Corcuera et al., 2002) and *Q. faginea* (Corcuera et al., 2004), because of their ring-porous wood and distinct rings, can be sampled through tree coring. This greatly improves the whole process of tree-ring chronology development, while still providing valuable climatic signals. Some studies successfully used cores from *Q. pyrenaica* to explore climatic control over this species growth in Iberia (Corcuera et al., 2006; Roig et al., 2009; Rozas et al., 2009; Gea-Izquierdo and Cañellas, 2014; González-González et al., 2014). To our knowledge, climate/growth relationships in *Q. faginea* were rarely studied using cores (e.g. Granda et al., 2014), despite its tree rings showing a response to climatic variables (Corcuera et al., 2004).

The present study is a first attempt to establish long tree-ring chronologies for dendroclimatic reconstructions in mainland Portugal. For that purpose, three oak species (*Q. pyrenaica*, *Q. faginea*, and *Q. ilex*) were sampled at three sites in southern Portugal (Fig. 1), which are characterized by Mediterranean climates – types Csa (inland sites) and Csb (coastal site), according to the Köppen–Geiger classification, updated for the period 1950–2000 (Kottek et al., 2006).

2. Material and methods

Tree-ring patterns in long-lived oaks, growing in Portugal, southwestern Iberia, and their suitability for dendroclimatic reconstructions are analyzed herein. The sampling took place at three sites in southern Portugal (Fig. 1), which are characterized by Mediterranean climates – types Csa (inland sites) and Csb (coastal site), according to the Köppen–Geiger classification, updated for the period 1950–2000 (Kottek et al., 2006).

At least 10 trees per site were sampled from three oak species making a total of 39 trees used for further analysis (Table 1). Tree ring samples were obtained as whole stem discs in the

Fig. 1. Location of the study sites (NI: North Interior, SC: South Coastal, SI: South Interior), and respective ombrothermic diagrams for the closest meteorological stations (data from 1950 to 2000). The location of the meteorological stations used for the analysis of climate/growth relationships is also outlined (x).

case of *Q. ilex* as described by Campelo et al. (2009), or through tree coring (two cores per tree) in the case of *Q. pyrenaica* and *Q. faginea*. After standard sample surface preparation, tree-ring widths (and also latewood widths in the case of ring porous species, *Q. pyrenaica* and *Q. faginea*) were measured to the nearest 0.001 mm, using an increment measurement table, LINTAB Linear Table 560/2.5 mm, connected to a stereo microscope LEICA M80 and the software TSAP-Win Scientific. Tree rings were cross-dated within and between trees by visual inspection of single curves plots. The results were checked and supported using correlation coefficients, Gleichläufigkeit values (Fritts, 1976), and Student's *t*-test across tree ring series. Using ARSTAN software (Cook and Holmes, 1986), cubic smoothing splines, with a 50% cut-off at a 60-year wavelength, were adjusted to the correctly dated series. Indexed series were obtained by dividing the original data through these curves. The effect of autocorrelation was removed and the resulting indexed series were averaged for each site using a bi-weight robust mean. The quality of the chronologies, concerning their strength of common signal and representativeness, was assessed through standard statistical indicators (Fritts, 1976; Wigley et al., 1984; Schweingruber et al., 1988; Cook and Kairiukstis, 1990): effective chronology signal (r_{eff}) and expressed population signal (EPS), using the R package *detrendR* (Campelo et al., 2012).

Climate/growth relationships were analyzed with Pearson correlations between each site chronology and climatic variables (monthly precipitation and temperature averages from previous year September to current December). Data from the closest meteorological stations were used (Fig. 1): São Mamede for NI, and

Fig. 2. Individual tree ring indices and respective site chronologies for: (a) NI; (b) NI-LW; (c) SC; (d) SC-LW and (e) SI. Corresponding sample sizes as a function of time are also shown (dotted line).

Fig. 3. Chronology statistics (EPS: Expressed Population Signal, in black; and r_{eff} : Effective Chronology Signal, in gray) calculated from 50-year running periods lagged by 1 year for: (a) NI; (b) NI-LW; (c) SC; (d) SC-LW and (e) SI. Dashed line highlights EPS values above the 0.85 level (Wigley et al., 1984). The results are truncated to a sample size >3 .

Alentejo (average of four stations: Elvas, Beja, Évora, and Grândola) for SC and SI.

Since the available climatic data from the meteorological stations cover only the period from 1950 onwards, an appropriate verification of the temporal stability of the climatic signal is not possible. Therefore a long precipitation series for Lisbon – HistPT (Camuffo et al., 2013), showing a good agreement with the meteorological stations for total annual precipitation ($r=0.75$, $p<0.001$, for São Mamede; and $r=0.92$, $p<0.001$, for Alentejo), was used. The temporal stability of the climate/growth relationships was tested using 50-year moving windows, at 1-year lags, to calculate correlation coefficients between climatic and tree-ring records. Additionally, the period covered by tree-ring and climatic records was split in two for calibration-verification tests. Each sub-period was considered as an independent dataset and used to set up calibration models (regression equations between climate and

growth records), which were verified/validated on the remaining one (Cook and Kairiukstis, 1990). The following statistical indicators were calculated to determine the model's skill to estimate climate variability on independent periods: r^2 for the calibration period; correlation coefficients between observed and estimated climatic data, using calibration equations on the verification period; reduction of error – RE (Blasing et al., 1981).

3. Results

For the ring porous species (*Q. pyrenaica* and *Q. faginea*), two cores per tree were sufficient to crossdate within-tree, as ring-width measurements showed very high agreement within trees ($r=0.70$ – 0.73 , $p<0.001$) and few missing rings. Despite having almost unmistakable tree-ring boundaries, crossdating between trees was extremely difficult and time consuming. In fact, cores from different trees depict highly variable, often non coincident, ring patterns. Nearly one third of the original samples were rejected due to poor crossdating with the remaining set. As tree ring boundaries are very difficult to recognize in *Q. ilex*, they were identified by the marginal parenchyma bands and by differences in vessel lumen area along the growth ring (for details see Campelo et al., 2009; Gea-Izquierdo et al., 2009). Stem cross-sections must be used for a proper tree ring dating, owing to diffuse porosity, highly variable ring width along the tree perimeter, and missing, interrupted and locally absent tree rings. In order to identify correctly missing rings, more than three radial directions in each disk were considered. A total of 41 missing rings were identified and all the samples were kept for further analysis.

The crossdated tree-ring series extended 173 years back in time (from 1840 to 2012), with average site segment lengths varying between 89 and 141 years (Table 2). The detrended individual tree-ring series (based on ring width and, in the case of *Q. pyrenaica* and *Q. faginea*, latewood width measurements – LW) for each site, as well as the corresponding chronology (Fig. 2), revealed an effective chronology signal increasing southwards and inland ($r_{eff}=0.42$ at SC and NI, $r_{eff}=0.60$ at SI) (Table 2). EPS values are stable during the last section of the chronologies, decreasing only during the early less replicated period (<8 trees), but for the period 1920–2000 all chronologies showed EPS values >0.85 (Fig. 3). This common variance observed for all chronologies evidences a good agreement in growth between trees at each study location.

The strongest climate/growth correlations (Fig. 4) were found between: NI and precipitation accumulated in winter (previous year December and current year January) before the start of the growing season ($r=0.40$, $p<0.01$); SC-LW and spring-summer (April through July) precipitation ($r=0.50$, $p<0.001$); SI and precipitation accumulated during autumn and winter, before the growth season onset, throughout spring and summer (previous year September through July of current year) ($r=0.81$, $p<0.001$).

The correlations between each chronology and the normalized temporal series of the respective key climatic variable, calculated from a long precipitation dataset for Lisbon – HistPT (Camuffo et al., 2013), were lower than those obtained using the meteorological stations closer to the sampling sites (Fig. 5) – NI: $r=0.23$ (n.s.) vs $r=0.40$ ($p<0.01$); SC-LW: $r=0.46$ ($p<0.01$) vs $r=0.50$ ($p<0.001$); SI: $r=0.72$ ($p<0.001$) vs $r=0.81$ ($p<0.001$).

Temporal stability on the climate/growth relationships was analyzed using the HistPT series (Fig. 6). The northernmost site, NI, exhibits a very unstable relationship, with correlation coefficients rarely above the 95% significance level. SC-LW shows a relatively constant relationship along the period covered by the chronology (1840–2011), even at the lowest sample depth (number of trees = 1), always above the 95% significance level. The exception was for 1900–1920, with lower but still statistically significant

Fig. 4. Correlation coefficients between tree-ring chronologies and monthly climatic variables (precipitation sums and temperature averages from previous September, $S(t-1)$, to December) for the period 1950–2000: (a) NI; (b) NI-LW; (c) SC; (d) SC-LW, and (e) SI. White background bars indicate the predominant climatic signal in each chronology (** $p < 0.01$, *** $p < 0.001$). Dashed lines represent the 99% confidence limit.

Fig. 5. Site chronologies and respective normalized climatic variables (precipitation sums) for the period 1950–2000, using data from the closest meteorological stations (NI: São Mamede; SC and SI: Alentejo, average of Grândola, Beja, Évora, Elvas; cf. Fig. 1) and from long-term precipitation series for HistPT (Camuffo et al., 2013): (a) December ($t-1$) and January for NI; (b) April to August for SC-lw; and (c) September ($t-1$) to July for SI. Correlation coefficients (n.s. = non-significant; ** $p < 0.01$; *** $p < 0.001$) between tree ring records and climatic data are shown in black (with closest stations) and in gray (with HistPT).

correlation coefficients. This period corresponds to a discontinuity in the chronology's reliability (Fig. 3d). Until 1892, at a sample depth of 8 trees, EPS is >0.85 excluding 1900–1920 when it falls under 0.85. At the SI site the correlations gradually drop, with the decrease in sample depth, from 0.73 ($p < 0.001$) to insignificant values (Fig. 6c).

The periods covered by tree-ring records showing the most stable climate/growth relationships, SC-LW and SI, were split into sub-periods for calibration-verification trials against HistPT data: 1899–1949, and 1950–2000 (Fig. 7).

4. Discussion

4.1. From site and species selection to tree-ring crossdating

An active survey for long lived oak tree species has been maintained. However, old trees that fulfill the principles of dendrochronology requirements (Fritts, 1976), namely growing healthy and undisturbed, in sufficient number for adequate

replication, at sites where climate is potentially growth limiting, are difficult to locate in Portugal and sampling permission is not easy to obtain. Most of the present forest in mainland Portugal is relatively recent. Oak forests, which in Medieval times occupied most of the territory (Azevedo, 1997), have been gradually replaced by exotic species (such as *P. pinaster* and *Eucalyptus globulus*) with higher economic value. Evergreen species, *Q. suber* and *Q. ilex*, are nowadays still responsible for one third of the total mainland forested area, while the remaining oak species subsist in isolated and neglected stands, representing only 2% of the total forest area (ICNF, 2013). Therefore, proper site selection and experimental design are difficult to achieve as noted by Gea-Izquierdo et al. (2011). Nevertheless, climatic sensitive tree-ring records were obtained, the longest tree ring series extending back to 1840, from Mediterranean and sub-Mediterranean oak species at three different sites, following a gradient from mesic to xeric conditions (Figs. 1 and 4).

The strength of the common signal between indexed tree-ring series, measured by the effective chronology signal, r_{eff} ,

Table 1
Sites and trees description.

Site code	Species	Soil	Altitude	Slope	Exposure	N trees
NI	<i>Q. pyrenaica</i>	Prominent relief with quartzite outcrops; schists	670 m	5%	S	12
SC	<i>Q. faginea</i>	Paleozoic schist and greywacke; shallow and poor	150 m	–	–	10
SI	<i>Q. ilex</i>	Schists; lithosols, shallow and poor	135–145 m	5%	–	17

Fig. 6. Temporal stability on the climate/growth relationships given by 50-years running correlation coefficients lagged by 1-year between the site chronologies and the respective climatic variables (precipitation sums) using climatic records from HistPT: (a) December ($t-1$) and January for NI; (b) April to August for SC-LW; and (c) September ($t-1$) to July for SI. Correlation coefficients for the total period covered by the tree ring records are shown (n.s. = non-significant; ** $p < 0.01$; *** $p < 0.001$). Dashed lines represent the 95% confidence limit and dotted lines the sample size as a function of time.

increases from mesic ($r_{\text{eff}} = 0.42$) to xeric ($r_{\text{eff}} = 0.60$) sites. The higher strength of association between different trees at SI is likely due to a higher number of trees but also to the more limiting site conditions. *Q. ilex* trees were growing under harsher conditions than the other two species, considering water availability, evidenced by a large number of missing rings. For the sites NI and NC more factors and interactions must have been at play.

4.2. Tree-ring chronologies and climate/growth relationships

The longest tree-ring series extends back to 1840 and the chronologies are representative after 1920 for the three sites ($\text{EPS} > 0.85$). All sites show a significant dominant climatic factor controlling growth (Fig. 4). The use of latewood width data

improved the signal strength in the case of SC (SC-LW) but not for NI trees. Precipitation is the climatic parameter showing the strongest influence on tree-ring growth, despite some discrepancies between sites and species. Drought has been extensively pointed out as the main growth limiting factor for trees in the Mediterranean (reviewed by Pasho et al., 2011). At the more mesic sites, NI ($r = 0.40$, $p < 0.01$ with December ($t-1$) to January precipitation) and SC-LW ($r = 0.50$, $p < 0.001$ with April through July precipitation), the climatic signal strength is weaker. Since tree growth in the Mediterranean is controlled by multiple climatic factors, tree rings usually show weak-to-moderate climatic signals, generally much weaker than in temperate climates, and often not concentrated in a single season and/or varying from year to year (Olano et al., 2012). The climatic control is more pronounced and extending throughout a longer period of the year (September ($t-1$) to July) at the most arid site, SI. The climate/growth relationship at this site is unusually high ($r = 0.81$, $p < 0.001$), given that, even for temperate climate where trees tend to show the highest climatic signals, tree ring records rarely explain more than 60% of the variability in the respective climatic factor (Hughes, 2002).

4.3. Dendroclimatic reconstructions

Many recent dendroclimatic studies report a diverging trend in the climate/growth relationship starting after the late 20th century (e.g. Briffa et al., 1998; Barber et al., 2000; Wilmking et al., 2004; Wilson and Elling, 2004; Büntgen et al., 2006; Carrer and Urbinati, 2006; D'Arrigo et al., 2008; Leal et al., 2008). The reasons for this change, or lack of climatic response, are not yet fully understood. Anyhow, this has raised great concern regarding the accuracy of dendroclimatic reconstructions, as they may be over- or underestimating past variability in climatic factors. Contrary to the aforementioned studies, climate/growth relationship is stable throughout the study period for SC-LW and SI (Fig. 6) similarly to *P. nigra* chronologies from southern Spain (Dorado-Liñán et al., 2012b) and to a recent study from Alaska (Wiles et al., 2014). Calibration and verification statistics are robust (Fig. 7), assuring that growth/climate models remain skillful when applied to independent tree-ring data sets. Therefore, a high potential for dendroclimatic reconstructions is shown for SC-LW and SI chronologies. Although the present tree ring records do not

Table 2

Characterization of the tree ring series and basic statistics for tree-ring chronologies (RW = ring width; LW = latewood width).

Site code	NI	SC	SI
First year	1883	1840	1875
Last year	2012	2012	2002
Average segment length	99	141	89
Statistical indicators of common signal strength (1950–2000)			
EPS – expressed population signal			
RW	0.90	0.88	0.96
LW	0.89	0.87	–
r_{eff} – effective chronology signal			
RW	0.42	0.42	0.60
LW	0.40	0.40	–

Fig. 7. Calibration-verification trials for climate/growth models showing observed (solid gray lines) vs estimated (dashed black lines) normalized HistPT precipitation sums from: (a) April to August using SC-LW tree ring records; (b) and September ($t-1$) to July using SI tree ring records. Time periods: 1 = 1899–1949, 2 = 1950–2000; Cal = coefficient of determination for the calibration model; Ver = correlation coefficient between observed and estimated values, when verifying the calibration model in independent periods; RE = reduction of error.

extend beyond the existing instrumental records, the crossdating potential and sensitivity to climate make older oak trees and subfossil material promising. Oak species are very important players of the Portuguese forest heritage with a long presence in the country and a high economical value in the past, e.g. for naval construction. Sub-aquatic sources of archeological wood material are common and could contribute to the extension of tree ring records.

5. Conclusions

The present study demonstrates that long-lived trees suitable for dendroclimatic reconstructions can indeed be found in Portugal and, in the case of *Q. pyrenaica* and *Q. faginea*, sampling can resort to cores; the longest tree-ring series presented in this study extends 173 years in time back to 1840. *Q. ilex* trees growing at the South interior (SI) show a very strong climatic signal; a ring-width chronology explains more than 65% of the total variability in precipitation. This is even higher than for tree-rings from central-European climates, which generally tend to show stronger signals than those of Mediterranean areas. Tree rings from *Q. ilex* and from *Q. faginea* trees, growing at the South coastal belt (SC-LW), show stable and high climate/growth relationships from 1920 onwards. Calibration models built for the period covered by the instrumental data are, therefore, reliable for the reconstruction of precipitation back to periods represented only by tree-ring records.

However, some shortcomings are still noteworthy:

- The strongest climatic signals were found for *Q. ilex*, which has to be sampled using whole stem disks, a destructive method, and taking advantage of authorized feeling's which limits the experimental design.

- The SC-LW chronology climatic signal strength, though in accordance with other studies for the Mediterranean and temporally stable, is weak for dendroclimatic reconstructions. It explains only 24% of the observed spring-summer precipitation.
- The tree ring records, although extending beyond the instrumental records for the region, do not provide additional information about the past. The historic precipitation series for Portugal from Camuffo et al. (2013) are longer than these chronologies and, as expected, show a better agreement with the regional precipitation.

Further research using older oak trees and subfossil material is needed to extend the tree-ring records in time. Nevertheless, the present study provides an important breakthrough in Iberian dendrochronology with promising results for forthcoming research on climate reconstruction in Portugal.

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