Dendrochronology of *Quercus ilex* L. and its potential use for climate reconstruction in the Mediterranean region

F. Campelo, C. Nabais, I. García-González, P. Cherubini, E. Gutiérrez, and H. Freitas

Abstract: Holm oak (*Quercus ilex* L.) is a long-lived species widely distributed across the Mediterranean Basin, with potential value for dendrochronology and dendroclimatology. However, tree-ring dating in *Q. ilex* is a complex task that has limited the number of dendrochronological studies using this evergreen species. In the present work, it was investigated if old *Q. ilex* trees showed annual tree rings and whether they can be used as climate proxies. A long tree-ring chronology (126 years) of *Q. ilex* was developed using cross sections of 20 trees from the Guadiana river basin (Portugal). The high correlation among tree-ring series suggested that tree growth was controlled mainly by climate. Response function analysis showed a positive correlation between tree-ring width and precipitation from October$_{(t-1)}$ of the previous year to January$_{(t)}$ of the current year and in May$_{(t)}$. Tree-ring width was negatively correlated with the North Atlantic oscillation that exerts a strong influence on the precipitation over Iberia. Negative pointer years were triggered by dry years and became more frequent during the last decade of the 20th century. In conclusion, it is possible to accurately date old *Q. ilex* trees, and their tree rings could be used for climate reconstructions across the Mediterranean.

Résumé : Le chêne vert (*Quercus ilex* L.), une espèce longévive très répandue dans le bassin méditerranéen, a une valeur potentielle en dendrochronologie et dendroclimatologie. Cependant, la datation des cernes annuels de *Q. ilex* est une tâche complexe qui a limité le nombre d'études dendrochronologiques chez cette espèce sempervirente. Dans cette étude, nous avons examiné si les vieilles tiges de *Q. ilex* montrent des cernes annuels et si ces cernes peuvent être utilisés comme témoins du climat. Une longue chronologie (126 ans) de *Q. ilex* a été développée à partir des sections radiales de 20 arbres provenant du bassin de la rivière Guadiana (Portugal). La forte corrélation entre les séries dendrochronologiques indiquait que la croissance des arbres est contrôlée principalement par le climat. L'analyse d'une fonction de réponse a montré qu'il y avait une corrélation positive entre la largeur des cernes annuels et la précipitation du mois d'octobre$_{(t-1)}$ de l'année précédente au mois de janvier$_{(t)}$ de l'année en cours et celle du mois de mai$_{(t)}$. La largeur des cernes annuels étaient négativement corrélée à l'oscillation nord-atlantique qui exerce une forte influence sur la précipitation au-dessus de la péninsule ibérique. Les années caractéristiques négatives étaient dues à des années sèches et elles sont devenues plus fréquentes durant la dernière décennie du 20^{e} siècle. En conclusion, il est possible de dater avec exactitude les vieilles tiges de *Q. ilex* et leurs cernes annuels pourraient être utilisés pour les reconstitutions du climat partout en Méditerranée.

[Traduit par la Rédaction]

Introduction

Tree-ring chronologies are useful proxies to infer past climate variability, since the period for which instrumental data are available is short. Several studies have shown the value of tree-ring chronologies to study past climate in different regions (Briffa et al. 1990; Touchan and Hughes 1999; Büntgen et al. 2005). Although there is still a lack of long chronologies in the Mediterranean Basin (Martinelli 2004), ring-width data have been used to reconstruct the North Atlantic oscillation (NAO) index (Trouet et al. 2009) and drought frequency in the Mediterranean Basin (Touchan et al. 2005; Nicault et al. 2008) and northwest Africa (Esper et al. 2007). A major problem in establishing long chronologies in the Mediterranean Basin is that the oldest trees found in this region are evergreen species that produce frequent double rings with unclear ring boundaries (Cherubini et al. 2003). Although these species are commonly considered of low dendrochronological value, some authors have proposed that tree rings of long-lived Mediterranean evergreens, such as *Juniperus* spp. or *Quercus ilex* L., could indeed be dated

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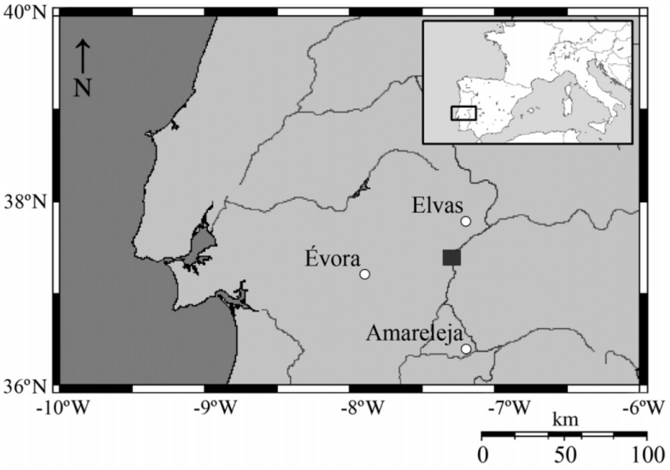
Fig. 1. Location of the study area (solid square) and the three nearest meteorological stations (open circles).



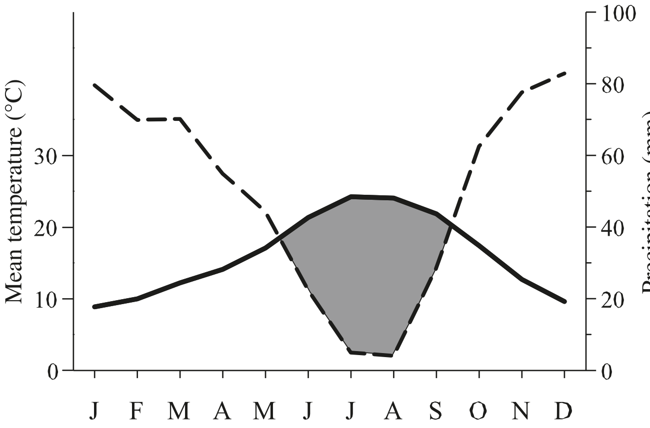
and used for dendrochronological and dendroclimatological studies (Cherubini et al. 2003; Campelo et al. 2007*a*).

The geographical location of the Iberian Peninsula, influenced by both the Atlantic Ocean and the Mediterranean Sea, makes it very attractive for climate studies. In spite of this, climate reconstructions in the western Mediterranean, and specifically in the Iberian Peninsula, are mainly based on the available instrumental records and historical documents (Martín-Vide and Vallvé 1995; Barriendos 1997; Rodrigo et al. 1999), with very few studies based on tree-ring reconstructions (Büntgen et al. 2008; Nicault et al. 2008).

Quercus ilex (Holm oak) is a long-lived tree widely distributed throughout the Mediterranean region. Panaïotis et al. (1997) estimated the maximum age of Holm oaks in Corsica at about 200 years, using tree-ring counting. However, tree-ring-width chronologies longer than 65 years have not been published for this species (Nabais et al. 1998–1999; Cherubini et al. 2003). Longer tree-ring-width chronologies of *Q. ilex* would be very useful for dendroclimatological studies in the Mediterranean area. To do this we need to know if it is possible to cross-date tree rings in older trees (>65 years) and whether these chronologies have a strong climatic signal. To understand the complex relationship between climate and tree growth, response functions and pointer years analyses can be applied (Briffa and Cook 1990; Schweingruber et al. 1990; Lebourgeois et al. 2004). Response functions are unable to detect less frequent and time-dependent growth-limiting factors (Lebourgeois et al. 2005). The analyses of pointer years, associated with single extreme years, can be used with different purposes, either to aid the correct dating of wood rings or to better understand the growth-limiting factors (Neuwirth et al. 2004). Thus the identification of pointer years in evergreen Mediterranean trees can be extremely useful for the correct dating of tree rings, increasing their dendrochronological and dendroclimatological value.

The aims of this study were (*i*) to confirm the annual nature of tree rings in older *Q. ilex* growing under Mediterranean climate, and (*ii*) to evaluate the strength of the climatic signal of the tree-ring chronology of *Q. ilex*, using response function and pointer years analyses, and its value for dendroclimatic studies.

Fig. 2. Climatic diagram using average data from the three closest meteorological stations (Évora, Elvas, and Amareleja) for the period 1941–2001. Data are from the Instituto Nacional de Meteorologia, Portugal. Precipitation (P) is represented by a broken line and temperature (T) by a solid line, and the grey area denotes the drought period ($P \leq 2T$).



Methods

Study area and climate

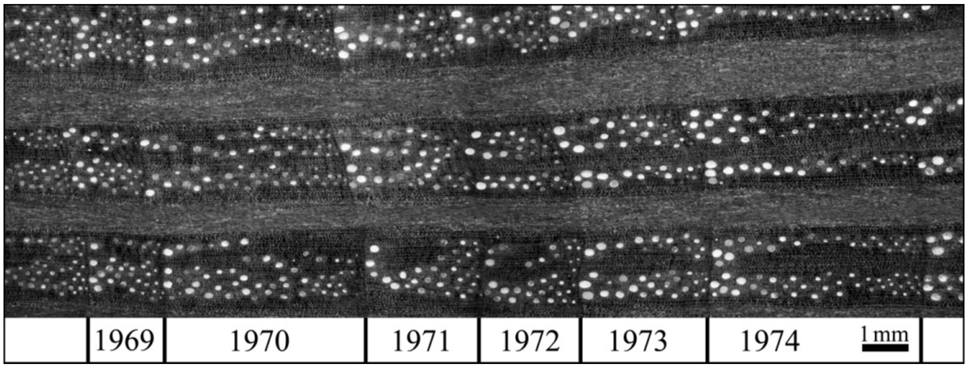
The study was conducted in an area near the Guadiana river (southern Portugal; 38°36′N, 7°15′W), where all the vegetation was cut during the construction of the Alqueva dam (Fig. 1). The climate is typically Mediterranean (Fig. 2), with a mean accumulated annual rainfall of 601 mm and a mean temperature of 16.1 °C. Precipitation mainly occurs from October to March, and a drought period can last 3–4 months, from June to August. Climate data were from the three closest weather stations (Fig. 1): Elvas (38°54′N, 7°12′W; 208 m a.s.l.), Amareleja (38°12′N, 7°12′W; 192 m a.s.l.), and Évora (38°30′N, 7°48′W; 308 m a.s.l.).

Tree-ring data

Twenty trees in a high forest (seed regeneration) of *Q. ilex* were felled and cross sections taken at a height of 30 cm aboveground. The samples were air dried and polished with sandpaper. Tree-ring boundaries of *Q. ilex* were analysed using a stereomicroscope (magnification 6.3–40×). For each tree, at least two radii were selected and visually cross-dated by matching the pattern of narrow and wide rings between all trees (Stokes and Smiley 1996). Tree-ring widths were measured to the nearest 0.01 mm with an incremental measuring table, LINTAB (Frank Rinn S.A., Heidelberg, Germany), and the program TSAP-Win (Rinn 2003). The visual cross dating was statistically confirmed using the program COFECHA (Holmes 1983). In total, 60 radii from 20 trees were successfully cross-dated.

An individual series was obtained for each tree after fitting a horizontal line through the mean and averaging the resulting ring-width indices by tree. These mean tree-ring series were detrended using a cubic smoothing spline with a 50% frequency response of 60 years (Cook 1985), and an autoregressive modelling was used to remove persistence. A residual chronology, composed of 20 trees, was obtained by averaging all single tree series and using a biweight robust

Fig. 3. Wood surface of *Quercus ilex* with annual rings from 1969 to 1974.



mean, which covered the period 1876–2001. All steps of the chronology building were performed using the program ARSTAN (Cook 1985). Finally, to guarantee that our trees were well dated we compared our chronology with a previously established chronology of *Pinus pinea* L. for this region (Campelo et al. 2007*b*).

The quality of the chronology was evaluated using the mean correlation between trees (r_{bt}) and Expressed Population Signal (EPS) statistics (Wigley et al. 1984). The r_{bt} statistic is the mean correlation coefficient for all possible pairs of tree-ring series from individual trees over a common time interval and is independent of sample size. The EPS measures the degree to which a chronology represents the hypothetical chronology or a chronology that has been infinitely replicated (Briffa and Jones 1990) and is sensitive to both variations in r_{bt} and sample size. Values of r_{bt} and EPS were used to quantify the degree to which the chronology signal is expressed when series were averaged, meaning that chronologies showing high values can incorporate a strong climatic signal. According to Wigley et al. (1984), a chronology is acceptable for dendroclimatic studies when the EPS is higher than 0.85. To achieve the temporal stability of the common signal strength, running r_{bt} and EPS statistics were calculated for 40 year periods lagged by 1 year, when sample depth was larger than three trees.

Tree-ring growth and climate

Regional climatic data for the studied area were computed by averaging metereological data from the three nearby stations (Fig. 1). For the period 1942–2001, the relationships between tree-growth and climate were investigated by bootstrapped response function analysis, using the program PRECON (Briffa and Cook 1990; Serre-Bachet and Tessier 1990). This method is particularly appropriate when climatic series are short and do not allow independent periods of calibration and verification. The residual chronology was used to evaluate climate–growth relationships, and therefore, response function was calculated without considering prior growth, since autocorrelation was successfully reduced by the detrending and autoregressive modelling. To establish whether tree-ring width of *Q. ilex* exhibited links with the large-scale atmospheric circulation in the Northern Hemisphere, we investigated the correlation between the residual chronology and the NAO data (http://climexp.knmi.nl/getindices.cgi?CRUData/nao+NAO-Gibraltar+i+someone@somewhere), for the period 1941–2001.

Pointer years

Under unfavourable conditions it is normal to find several trees with narrower rings, and the year during which this happens can be considered as a negative pointer year (Schweingruber et al. 1990). On the other hand, positive pointer years are formed when several trees, growing in the same region, show wider rings in response to better conditions for tree growth. In the present study, pointer years were defined as calendar years when at least 75% of all cross-dated trees were at least 40% narrower or wider than the mean of the previous 5 years (Lebourgeois et al. 2004).

Results

Cross dating and chronology quality

In *Q. ilex*, tree-ring boundaries can be identified by the marginal parenchyma bands and by differences in vessel lumen area throughout the annual ring (Fig. 3). A total of 60 radii out of 20 trees was successfully cross-dated, measured, and averaged by tree to reduce the noise (Fig. 4). Forty-one missing rings were found, representing 0.89% of all tree rings, and most of them (40) were partially missing or discontinuous, i.e., occurring only in some parts of the cross section. Sixteen partially missing rings were dated to the year 1995, ten to 1992, and seven to 1981. Only seven out of 20 trees did not show any missing ring.

To compare and validate our chronology we used as reference a previously established chronology of *P. pinea* for this region (Campelo et al. 2007*b*). The agreement between both chronologies ($r = 0.66$, $n = 70$, $p < 0.001$; Fig. 4) suggested that their common variance should be related to climate and confirmed that the chronology of *Q. ilex* was correctly dated.

The time span of the residual chronology was 1876–2001 (126 years). For the common interval (1937–2001), the residual chronology showed high EPS and r_{bt} values (Table 1). Considering the moving window analysis (Fig. 4), the EPS values never fell below 0.79, and only during the early less replicated period (1876–1912) were they lower than the 0.85 threshold suggested by Wigley et al. (1984).

Tree-ring growth and climate

According to the response function analysis, climate accounts for a high amount of tree-ring-width variability ($R^2 = 0.76$, $p < 0.001$, Fig. 5). Precipitation from October of the previous year (October$_{(t-1)}$) to January of the current

Fig. 4. (A) Individual ring-width index series of *Quercus ilex* (grey line) and mean (black line). Dotted line represents the number of trees. (B) Comparison between residual chronologies of *Q. ilex* (black line) and *Pinus pinea* (grey line). (C) The temporal signal strength of the chronology is shown by expressed population signal (EPS) (grey line) and r_{bt} (black line) statistics. Running r_{bt} and EPS statistics were calculated for 40 year periods lagged by 1 year.

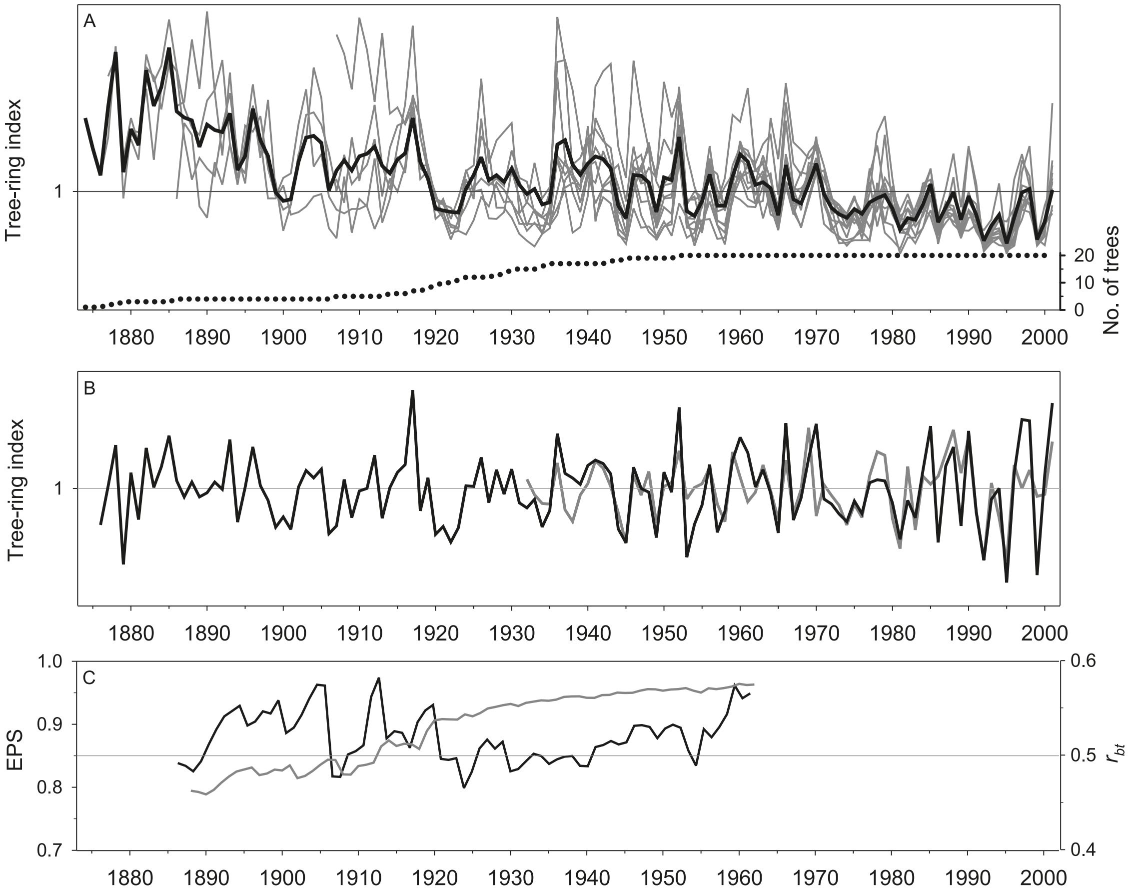


Table 1. Descriptive statistics of the tree-ring-width chronologies of *Quercus ilex* and *Pinus pinea*.

	Quercus ilex	*Pinus pinea*
Time period		
Start	1874	1917
End	2001	2002
Length (no. of years)	128	86
No. of trees (no. of radii)	20 (60)	17 (34)
Mean (1/100 mm)	195	277
Median (1/100 mm)	170	247
Mean sensitivity	0.50	0.38
First-order autocorrelation		
Raw series	0.54	0.70
Residual series	0.02	0.02
Common interval analysis		
Time span	1937–2001	1940–2002
No. of trees	17	9
Signal-to-noise ratio	20.40	7.74
Variance of first PC (%)	57.86	52.35
EPS	0.95	0.89
Mean correlation		
Between trees (r_{bt})	0.55	0.46
Radii vs. mean	0.75	0.70

Note: PC, principal component; EPS, expressed population signal.

year (January$_{(t)}$) and in May$_{(t)}$ had a positive effect on tree-ring width. Regarding the temperature effect, tree-ring width exhibited a positive relationship with temperature in February$_{(t)}$ and a negative one in May$_{(t)}$.

A negative correlation was found between precipitation and the NAO index between December$_{(t-1)}$ and March$_{(t)}$ ($r = -0.77$, $n = 61$, $p < 0.001$). The NAO index between December$_{(t-1)}$ and March$_{(t)}$ also showed a negative correlation with tree-ring width of *Q. ilex* ($r = -0.45$, $n = 61$, $p < 0.001$).

Pointer years

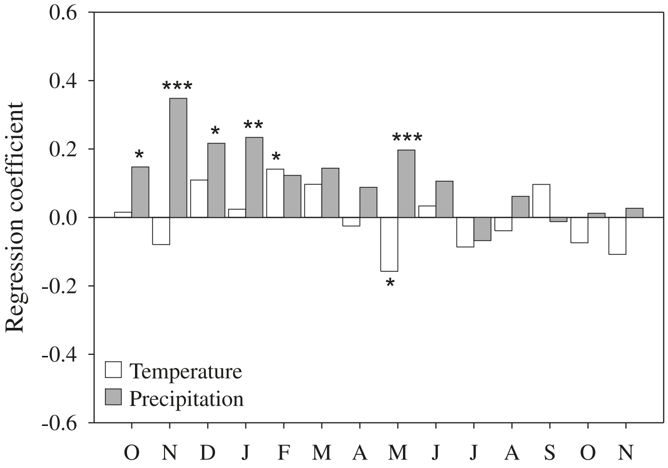
For the period with instrumental climatic data (1942–2001), nine pointer years (5 negative and 4 positive years) were detected, with four of them occurring in the 1990s (Table 2). Positive pointer years (1952, 1960, 1985, and 1997) were triggered by above-average precipitation from October$_{(t-1)}$ to January$_{(t)}$ and in May$_{(t)}$ and by below-average temperatures in May (Table 2). The strongest positive pointer year occurred in 1997, when 95% of all trees showed a growth increase higher than 40%. Negative pointer years (1945, 1965, 1992, 1995, and 1999) were associated with drier and warmer air temperatures in May and lower accumulated precipitation from October$_{(t-1)}$ to January$_{(t)}$ (Table 2). The greatest decrease in ring width occurred in

Table 2. Climatic conditions of pointer years.

			Temperature		Precipitation	
	Year	Growth (%)	Feb.$_{(t)}$	May$_{(t)}$	Oct.$_{(t-1)}$ – Jan.$_{(t)}$	May$_{(t)}$
Mean	1942–2001		10.0	17.1	298.7	43.9
Negative pointer year	1945	–63	10.3	17.5	234.2	16.5
	1965	–51	8.4	20.3	162.1	6.7
	1992	–72	10.1	19.8	129.1	46.5
	1995	–71	11.4	20.0	170.7	28.9
	1999	–65	10.2	18.3	96.6	40.1
Positive pointer year	1952	95	9.4	16.5	379.6	65.9
	1960	67	10.6	17.4	368.8	101.3
	1985	92	12.0	14.9	412.8	52.1
	1997	190	12.5	17.6	464.5	71.8

Note: Pointer years were defined as those calendar years when at least 75% of all cross-dated trees were at least 40% narrower or wider than the mean of the previous 5 years.

Fig. 5. Response function analyses between the residual tree-ring chronology of *Quercus ilex* and monthly climatic data from October$_{(t-1)}$ to November$_{(t)}$ for the period 1942–2006 (*, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$).



1992, in 95% of the trees. Contrary to the response function analysis, it seems that pointer years were not influenced by the temperatures in February$_{(t)}$.

Discussion

This is the first work reporting that a long (>65 years) and well-replicated chronology of *Q. ilex* was successfully developed, validating this species for dendrochronological studies. The occurrence of discontinuous rings in *Q. ilex* made the identification and correct dating of tree rings difficult. However, these discontinuous rings could be easily detected by tracking the ring boundaries around the whole cross section (Worbes 1995; Cherubini et al. 2003). The strong correlation between the chronologies of *P. pinea* and *Q. ilex* suggested that climate affected both species in an identical way and confirmed the annual nature of tree rings in *Q. ilex*.

The quality of a tree-ring chronology is not always stable over time and usually shows a lower statistical quality during the earlier period. For almost the entire length of our residual chronology (1913–2001), EPS values were higher than 0.85 even with only five trees, which is characteristic of tree-ring-width chronologies of conifers from semiarid sites (Briffa and Jones 1990). In addition, the high values of mean sensitivity and r_{bt} suggest a strong common signal.

In our study area, the percentage of tree-ring-width variation in *Q. ilex* explained by precipitation and temperature was higher (76%) than in other semiarid areas (Fritts and Dean 1992) and almost identical to the climatic signal of *P. pinea* from the same area (Campelo et al. 2007*b*). The extreme environmental conditions associated with low stand density and thus low competition between trees may explain the high dependence of tree-ring growth on climate (Cherubini et al. 1998).

In our study area, tree-ring width of *Q. ilex* was strongly controlled by winter precipitation, as previously observed by Nabais et al. (1998–1999) in northeast Portugal and by Cherubini et al. (2003) in Italy. In warm and low-elevation sites, autumn and winter precipitation refills soil water reserves, which is extremely important for tree growth during the following growing season (Nabais et al. 1998–1999; Corcuera et al. 2004*a*). In contrast with our results, in northeast Spain, where winter is cooler and soils show lower water-holding capacity, the tree-ring width of *Q. ilex* resprouts show no significant correlation with autumn and winter precipitation from the previous year (Campelo et al. 2007*a*). Resprouts can probably take advantage of the well-developed root system of the previously established individuals, so that they obtain water from a higher volume of soil for the small resprouting shoots (Castell et al. 1994; Clemente et al. 2005) and thus are less dependent on winter precipitation.

Higher temperatures in February led to larger tree rings by promoting an early bud-opening, which consequently increased the length of the growing season, as observed for *P. pinea* in the same area (Campelo et al. 2007*b*). On the other hand, low precipitation associated with higher temperatures in May, increasing evapotranspiration, induced the formation of narrow rings. In fact, water availability was the main limiting factor of the radial growth of *Q. ilex* (Nabais et al. 1998–1999; Corcuera et al. 2004*b*; Campelo et al. 2007*a*). Contrary to these studies, no relationship was found between summer precipitation and radial growth, suggesting that cambial activity ceased in summer (Cherubini et al. 2003), i.e., the amount of precipitation during the warmest months of the year was not enough to alleviate water stress and, therefore, to allow cambial activity. Also, the effect of climate after $\mathrm{May}_{(t)}$ was not recorded in the tree rings, since growth at the base of the stem may stop earlier than at the upper parts of the tree.

The NAO and the Southern Oscillation are the major sources of interannual variability of weather and climate around the world (Hurrell and van Loon 1997). The amount of winter precipitation in the Mediterranean area is inversely correlated with the NAO index (Hurrell 1995; Piovesan and Schirone 2000; Goodess and Jones 2002). Tree-ring width of *Q. ilex* showed a strong link with the large-scale atmospheric circulation in the Northern Hemisphere, and the negative correlation between tree-ring width and the NAO index confirms the importance of winter precipitation for tree growth. Similar findings were obtained by Piovesan and Schirone (2000) for *Fagus sylvatica* L. growing in central Italy and by Mäkinen et al. (2003) for *Picea abies* (L.) Karst. in Norway and Finland.

Pointer years are produced during extreme climatic events and are useful for confirming the correct dating of wood samples. The comparison of pointer years with climate data can also reveal the impact of rare extreme climatic events on tree-ring growth, which is usually not possible with a traditional response function analysis (Schweingruber et al. 1990; Esper et al. 2001; Lebourgeois et al. 2004). Weather conditions in May were determinant for the formation of pointer years in *Q. ilex*, with lower or higher than average precipitation inducing a negative or a positive pointer year, respectively. The higher number of pointer years and discontinuous rings in the 1990s could be related to an increase in the occurrence of extreme climatic conditions. Severe droughts and short episodes of heavy rain became more frequent in southern Spain and Portugal in the last decades (Rodrigo et al. 2000; Rodrigo and Trigo 2007). Similar findings were also observed in *Pinus nigra* Arnold, *Pinus sylvestris* L., *Pinus uncinata* Ram. (Andreu et al. 2007), *Pinus pinaster* Ait. in Spain (Bogino and Bravo 2008), and *Quercus petraea* Mill. in France (Lebourgeois et al. 2004). A strong single-year drought has a short-term reversible effect on tree growth (Martín-Benito et al. 2008), whereas multiyear droughts could cause tree decline, as observed by Bigler et al. (2006) for Scots pine growing in Valais, Switzerland. Several studies have suggested that *Q. ilex* may be progressively replaced by other species more resistant to summer droughts (e.g., *Phillyrea latifolia* L.), if droughts become more frequent, as is predicted by climate models for the Mediterranean area (Peñuelas et al. 2000; Martínez-Vilalta et al. 2003; Corcuera et al. 2004*b*).

During the 1990s, the tree rings for 1992 and 1995 were negative pointer years for *Q. ilex* and were narrow rings for *P. pinea* in the same area (Campelo et al. 2007*b*), and 1995 was also a narrow ring for *P. pinaster* in central-west Portugal (Vieira et al. 2009). The occurrence of narrow rings in the same year in different tree species, across large areas, could be a useful tool to study macroclimatic signals at the regional scale. This kind of analysis should give valuable information to understand the frequency and intensity of severe droughts in the past and to identify areas more susceptible to processes of desertification in the western Mediterranean area.

To our knowledge, this study provides the first evidence that old trees of *Q. ilex* show a strong climatic signal that was attained with few trees. Tree-ring-width chronologies of *Q. ilex* contain valuable information for reconstructing past climate conditions in the Mediterranean and the NAO index. Longer chronologies of *Q. ilex* can also be used to reconstruct the frequency of extreme drought events in the Iberian Peninsula. This information is important within the framework of climate change because an increasing frequency of extreme droughts is expected in the Mediterranean region (Pal et al. 2004).

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