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Climate response of cork growth in the Mediterranean oak (*Quercus suber* L.) woodlands of southwestern Portugal

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ABSTRACT

In the Mediterranean climate regions, drought events are expected to affect the growth of forests ecosystems by changing trees growth rates and eventually inducing shifts in their growth patterns. Cork oak (*Quercus suber* L.) is a strictly western Mediterranean tree species periodically harvested for its bark, the cork. So far, cork oak has received limited attention for dendroclimatological studies due to its typical faint and erratic tree wood rings. Moreover, its distinct cork rings chronologies have been completely neglected. In this study we introduce an approach using cork ring chronologies dated back 9–10 years for climate response. Despite enhancing interannual variability and increasing statistical response to short-term climatic variability, still poorly understood, this study will possibly allow infer long-term climate response. We analyzed the cork ring chronologies of 55 cork samples collected in mature (under exploitation) trees in three distinct locations in southwestern Portugal. Cork growth recorded a high climate signal, with highly significant and coherent responses to the yearly climate-related sources of variation. We successfully assessed trends of cork growth via correlation analysis including selected climate variables among mean monthly temperature, monthly precipitation and, on an annual basis, eight precipitation indices. The high mean sensitivities and inter-series correlations found for cork ring chronologies combined with the significant variance explained by climate variables suggest that climate is likely one dominant signal that affects cork growth, but local environmental stresses can decisively affect this (climate) signal. Assuming cork growth as a proxy for cork oak growth, it seems conceivable that despite the trees being highly resistant to drought stress, cork oak woodlands in southwestern Portugal would have to face lesser growth in a global warming scenario.

1. Introduction

In temperate regions, tree-ring width analysis has been extensively used to assess the influence of climatic factors on growth. In these regions, precipitation and temperature regimes impose regular periods of dormancy which cause a clear annual banding in wood formation (Fritts, 1976). The detection of tree-ring width anomalies can usually be assigned to changes in intra- and interannual climate conditions (Martínez-Vilalta et al., 2012) and thus allow reconstruct forest responses to past environmental changes (Patón et al., 2009).

In temperate regions with a typical Mediterranean climate, the summer dormancy period is defined as a “drought-imposed rest” period (Cherubini et al., 2003) as tree species are well adapted to the water limitations during the hot and dry season (Tessier et al., 1994; Campelo et al., 2006). In these regions, the relationships between tree-rings and climate can be strongly species- and environment- dependent (Gea-Izquierdo et al., 2009), and tree-ring width chronologies are difficult to establish as annual banding may be indistinct (Lebourgeois et al., 2004; Campelo et al., 2007,2009; Patón et al., 2009).

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Cork oak (*Quercus suber* L.) is a tree of high economic and ecological importance in Portugal, south-western Iberian Peninsula (Costa and Oliveira, 2015). Is a strictly Mediterranean evergreen oak species with drought avoidance adaptations such as deep-reaching root systems (Oliveira et al., 1992; Kurz-Besson et al., 2006), relatively long leaf longevity (Oliveira et al., 1996), sensitive stomatal regulation (David et al., 2004) and a thick bark, the cork, to control water loss directly to the air from the stem and branches (Oliveira and Costa, 2012).

Cork, is a highly valuable non-timber forest product, periodically removed from stems and branches throughout the cork oak tree's lifetime. In response to cork harvesting, cork growth is a priority for the tree survival (Oliveira et al., 2002), and it is artificially enhanced within each cork production cycle (nine years in Portugal) (Costa et al., 2002, 2015). As involve a short-term transfer of reserves for the production of a new phellogen and new cork layers (Oliveira and Costa, 2012), the cork growth may negatively influence other tree physiological processes (e.g., wood growth) (Leal et al., 2008).

Recently, over small geographic areas, the seasonality of main climatic drivers of cork oak growth, precipitation and temperature, have been recently found clearly imprinted in the cork rings (Oliveira et al., 1994; Caritat et al., 1996, 2000; Costa et al., 2002, 2015). Unlike the wood rings, which are often faint and indistinct (Natividade, 1950; Sousa et al., 2009), cork rings have clear boundaries and climate seems to be likely the dominant signal. A strong direct cork growth response has been found with previous year's winter precipitation, (Caritat et al., 1996, 2000; Costa et al., 2001) together with a generally inverse relationship with monthly (summer) temperature (Caritat et al., 2000). Moreover, the different physiological adaptations of the cork oak trees across distinct dryer Mediterranean environments suggest, however, that the climate-cork growth relationship is not straightforward, and that other internal and external factors may dominate cork growth and determine site-specific patterns of drought-induced cork growth. The primary driver of phellogen activity periodicity should be the tree water stress, a function of seasonal environmental factors such as soil-site conditions decisively determining the soil-water availability (Costa et al., 2008) and the tree access to belowground water (Vaz et al., 2010).

The influence of climate on cork growth has been a rather disperse case-study research, and no study have yet evaluated this question over larger geographic range. Thus, so far, there is still not a full understanding of this relationship when it comes to predicting the consequences of direct global climate change, at a regional level, on cork yield. It is therefore crucial that, in Mediterranean environments, we unravel the role played by climate, and specifically by precipitation, on cork growth patterns under the climate change forecasts of an increasing frequency of extreme events in precipitation, such as reduction of the mean precipitation, changes to duration of the rainy season and of spring rainfall, and the increase of anomalous dry spells (Miranda et al., 2002; Giorgi and Lionello, 2008; Philandras et al., 2011).

In this context, in three study areas in southwestern Portugal, under varying in soil characteristics and, consequently, under distinct environmental stress, we examine climate-driven deviations in cork ring widths in full-synchronized cork production cycles (2000–2010), including the extreme drought event recorded in the hydrological year 2004/05 (IPMA, 2015). Our main goal is to reinforce the existing knowledge of the climate-cork growth relationship and to characterise the climate responses of cork oak, improving our understanding of cork growth sensitivity to increased future climatic fluctuations, at a regional scale. We hypothesize that: (i) climate is likely the dominant signal affecting cork growth at regional level in southwestern Portugal; (ii) environmental conditions at local level, constraining the soil-water availability, may affect the climate signal strength and the year-to-year variability of cork growth; and (iii) cork ring widths can be used for dendroclimatological studies: allowing to infer climate responses of cork oak among distinct drought-induced Mediterranean environments; and assessing the forcing trends on the response to drought events and vigor of extant cork oak trees, under the future scenarios of climate change in the Mediterranean basin.

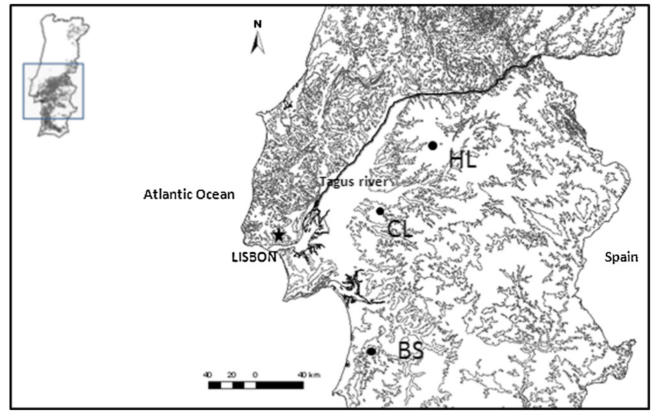

Fig. 1. National (Portugal) cork oak area distribution (in grey). The location of the three study areas in the Southern Portugal: Montargil (HL), Samora Correia (CL) and Grândola (BS). Contour lines (in grey) of elevation classes, beginning at 0 m in the Tagus alluvial area and with a gap of 50 m.

2. Material and methods

2.1. Study areas

The study areas, Montargil (Herdade dos Leitões, HL) (39° 8′ N, 8° 11′W, 170 m a.s.l.), Samora Correia (Companhia das Lezírias, CL) (38° 49′ N, 8° 49′ W, 20 m a.s.l.) and Grândola (Herdade de Barradas da Serra, BS) (38° 11′ N, 8° 37′ W, 270 m a.s.l.), are located in Southern Portugal. The climate is of the Mediterranean type, with the highest temperature in summer when precipitation is lowest, smoothed by the proximity of the Atlantic Ocean, particularly at Grândola (BS), the area closest to the ocean (Fig. 1).

The study areas are within the natural potential area of *Asparago Aphylli-Querco suberis* S. (vegetation series), corresponding to the thermomediterranean to low-mesomediterranean thermotypes and to sub-humid to humid onbrotypes (Capelo et al., 2007), where cork oak woodlands are dominant features in the landscape mosaic, interspersed with open farmland and shrubland areas (Costa et al., 2011).

HL and CL are flat to gentle undulating areas located in the alluvial area of the Tagus basin (with HL a more inland area than CL), and BS is a steeply undulating coastal area, in Grândola's mountain area (Fig. 1). The predominant soils in the study areas are mostly related to the nature of the geological formations (Table 1). At HL and CL, the Haplic Arenosols (dominant soils) are deep sandy soils, poor in nutrient and organic matter, and with low water storage capacity. These sandy soils, however, allow an easy deep root development and tree access to groundwater, the main reliable water source for the maintenance of their physiologic activity during summer season. The Haplic (and Endoleptic) Regosols, also present in HL and CL, are developed in consolidated material (sandstones), which can be close to the surface, inhibiting the tree's deep-rooting development pattern. This limiting factor, together with low nutrient and moisture supplies, may constrain cork oak growth (Costa et al., 2008).

At BS, on the schist formations, soils are mostly Haplic Leptposols, characterized by low nutrient and organic matter, with a reduced soil depth (less than 25 cm). In these soils, the occurrence of the schist vertical fracturation favored the tree's deep-root devel-

Table 1
Biophysical characteristics of the study areas: Montargil (HL), Samora Correia (CL) and Grândola (BS).

Study area	Montargil (HL)	Samora Correia (CL)	Grândola (BS)
Mean annual temperature	16.1 °C	15.3 °C	15.6 °C
Mean minimum temperature (January)	9.5 °C	9.6 °C	10.0 °C
Mean maximum temperature (July)	23.3 °C	21.2 °C	22.3 °C
Annual rainfall	600–700 mm	500–600 mm	700–800 mm
Air humidity	70–75%	70–75%	75–80%
Lithology	Pliocenic and Miocenic sedimentary formations	Pliocenic and Miocenic sedimentary formations	Carbonic schist formations
Soils	Haplic Arenosols and Haplic Regosols	Haplic Arenosols and Haplic Regosols	Haplic Leptosols
Slope	Flat and gentle undulating	Flat and gentle undulating	Steeply undulating
Cork quality region[1]	7	5	9
Cork productivity[1]	8–10 kg m^2	8–10 kg m^2	>10 kg m^2
Harvesting coefficient[1]	≈3	<2.5	<2.5
Stand density (trees per ha)	83	98	96
Tree diameter at breast height (cm)	35–45	28–41	25–40
Cork age	9	9	10
Cork-production cycles	2001–**2010**	2001–**2010**	2000–**2010**
Half-years	2001, 2010	2001, 2010	2000, 2010

[1] (Sousa, 1997).

opment and access to groundwater, mainly on the prevailing steep slopes (Costa et al., 2009).

The study areas have similar cork harvesting coefficient (Table 1), defined as the ratio between tree maximum harvesting height and stem perimeter at 1.30 m above the ground (Oliveira and Costa, 2012). In the hilly mountain of Grândola (BS) cork production in mature cork oak woodlands provides the economic cornerstone of local farming systems, as cork production, in quality – cork quality (region 9, high quality) – and in quantity – the weight of cork for each m^2 of stripped surface is superior to 10 kg m^2 – remains sufficiently attractive. HL and CL show the same productivity, between 8 and 10 kg m^2, but are located in distinct cork quality regions, respectively, 7 and 5 (Medium quality) (Table 1). These cork quality regions were established based primarily on econometric studies (see Sousa, 1997).

Typically, the Mediterranean climate type has a dry period (when precipitation values, in mm are lower than the double of the temperature values, in °C), from May to September. Since the year 2000 at BS, and the year 2001 at HL and CL, until 2010, successive annual dry periods have occurred (Fig. 2). The hydrological year 2004/05 was classified as an extremely dry year (IPMA, 2015), and in all study areas this disturbance of the precipitation regime was noticed (Fig. 2). The correspondent climatic diagrams showed the under-average monthly precipitation from November–January to early spring and to summer, mostly noted in all the study areas (Fig. 2).

2.2. Cork ring measurements

During the cork harvesting season, in July 2010, a total of 55 cork samples were randomly selected from harvested trees: 19 in HL (from 11 trees), 24 in CL (from 12 trees) and 12 in BS (from 10 trees). The selected trees were healthy trees, harvested for reproduction cork (3rd cork harvest onward), and under cork full production, with diameter at breast height (over cork) ranging between 25 and 45 cm, as defined by Natividade (1950). At HL and CL, the cork production cycle was nine years (from July 2001 to July 2010) with an eight year cork ring series, while at BS it was ten years (from July 2000 to July 2010) with a nine year cork ring series (Table 1).

The cork samples (of approximately $10 \times 10\,\text{cm}^2$) were boiled for one hour in water at 100 °C, and dried in open air until equilibrium. The two transversal sections were then sanded to allow image acquisition. Image acquisition of the transversal sections was made through snapshot images scanned at a resolution of 300 dpi and stored in TIF graphic format. Images were then analyzed using ImageProPlus® image-processing software.

Measurements of cork ring widths were made after an orthogonal position correction. Cork ring widths were measured along three transects in the radial direction, from cork back to cork belly, within an accuracy of 0.01 mm, in both the transversal sections of the cork sample. The six cork ring width measurement series were averaged as one mean annual cork growth time series (mm yr^{-1}), per cork sample with an estimated cork age, depending on the cork production cycle of the study area. For each study area, the cork production cycle had a total of *t* years (9 years at CL and HL and 10 years at BS), with *t-1* complete years and two half years, one half year corresponding to autumn cork growth in the cork harvest year, and the other half year corresponding to the spring cork growth of the current harvest, as defined by Oliveira and Costa (2012).

Selected dendrochronological statistics were defined in and calculated by COFECHA (Holmes, 1983) in the raw cork- ring chronologies from each study area. These included mean sensitivity (MS), which is an indicator of the variance of the trees at a study area and it was calculated as the absolute difference between consecutive cork ring widths divided by their mean value; and, mean series intercorrelation (SI), which is an indicator of the strength of the climate signal, common to all trees at the study area and it was calculated by adapting the "Regional Curve Standardization" method and standardize the cork ring widths by an horizontal line of their mean values thus, generating a chronology representing changing cork growth over time. We also calculated the expressed populations signal (EPS), based on the equation presented by Wigley et al. (1984), using mean interseries correlation and the number of chronologies. The EPS value of 0.85 is considered a threshold to be reached by a given chronology to be considered a reliable, consistent (climate) signal.

2.3. Climate indices

A total of 8 indices of precipitation were calculated for the period 2000–2010. Daily precipitation was obtained from the SNIRH database for the period from September previous to the year of growth to May. These indices were selected to assess the interannual variability in their intensity; frequency and the proportion of total precipitation and to reveal their seasonal synchronism with cork growth rates.

A wet day was considered a day with an accumulated precipitation of at least 1.0 mm. The total number of wet days was counted (COUNT, #) and the total amount of precipitation was measured (PRCPTOT, mm). The selected indices were the following: (i) spell indices, consecutive dry days (CDD, days) and consecutive wet days (CWD, days), defined as the maximum number of con-

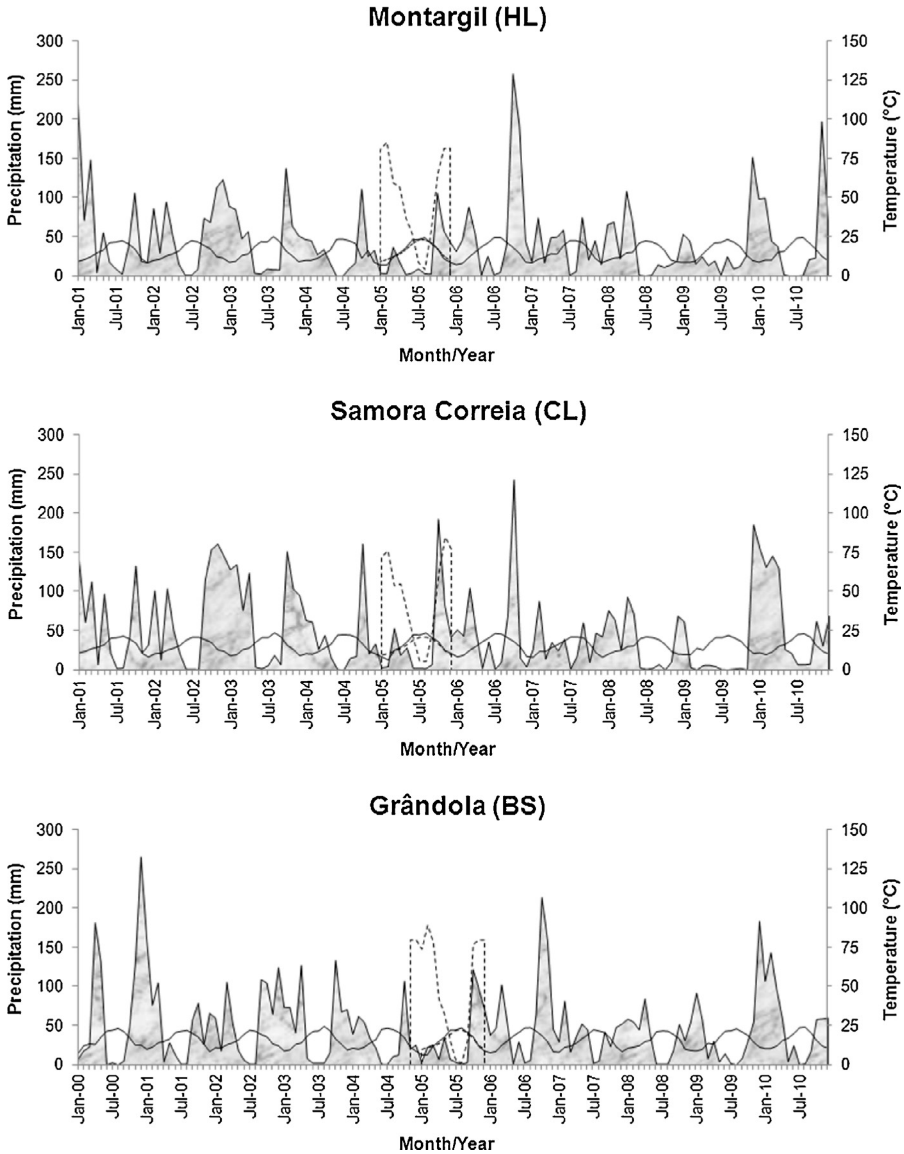

Fig. 2. Precipitation (full grey) and temperature (black line) curves for the study periods: beginning in 2001 and ending at 2010, at the study areas of Montargil (HL) and Samora Correia (CL); and beginning in 2000 and ending at 2010, at Grândola (BS). Dotted lines are for the climatic diagram of meteorological stations (MS) close to the study areas: at Montargil (HL) – MS of Mora for the period 1961–1990; at Samora Correia (CL) – MS of Salvaterra de Magos for the period 1961–1986; and for Grândola (BS) – MS of Grândola for the period 1961–1986. Climate data sets from SNIRH, INAG, Portugal.

secutive days with precipitation below/above 1 mm, respectively; (ii) absolute (fixed) thresholds, defined as the number of days on which a precipitation value fell above a fixed threshold: number of heavy precipitation days >10 mm (R10, days), number of very heavy precipitation days >20 mm (R20, days) and number of extremely heavy precipitation days >25 mm (R25, days) and; (iii) maxima of multi-day rainfall event indices defined by the annual maximum precipitation on one day (RX1D, mm).

2.4. Climate-cork growth relationships

In each study area, the mean cork growth curve within each cork production cycle was standardised to maximize inter-annual fluctuations due to climate using an empirical exponential negative function (Caritat et al., 2000), where $\hat{y}_t$ is the estimated annual cork growth (in mm) at the cork age t (in years). The estimated residual, $\frac{y_t}{\hat{y}_t}$, (defined as the ratio between observed and estimated cork ring widths) is the cork growth (or cork ring) index, at the time t (in years), representing the unpredictable part of the cork ring width variation (see Costa et al., 2015).

The mean series of annual cork growth indices over the *t-1* (complete) years of the cork production cycle were then calculated for the three regions to be compared to synchronous series of climatic indices. The higher or lower significant correlation coefficient (Pearson correlation coefficient, r, which reflects the degree of linear dependency between the two datasets), either a positive or negative correlation, indicates the degree of relationship between cork growth and climate. Response functions were calculated using the master chronology of cork growth indexes for each study area and the 24 series of monthly precipitation calculated for the Mediterranean climate within the "biological" year, from September of the year previous to growth (*t-1*) till May of the year of growth (t) considering the following decisive periods: autumn previous to the growth year (from September$_{(t\text{-}1)}$ till November$_{(t\text{-}1)}$); winter previous to the growth year (from December$_{(t\text{-}1)}$ till February); and spring of the growth year (from March till May). Pearson's correlation coefficients, between cork

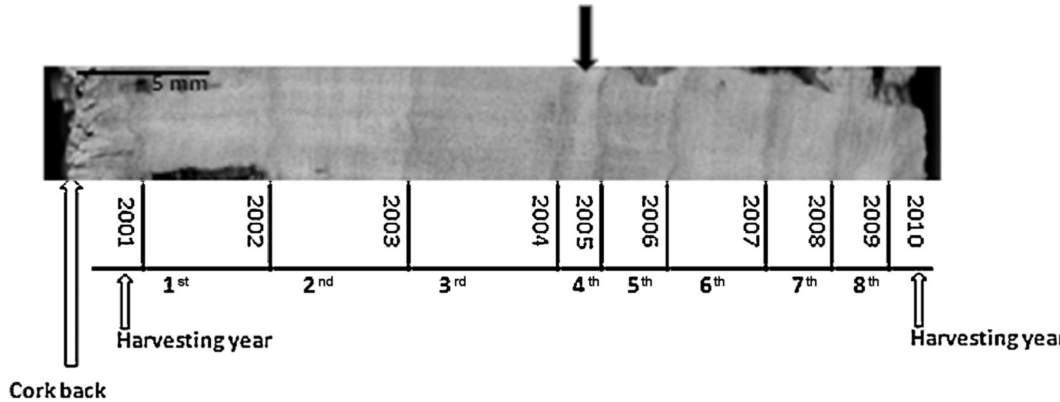

Fig. 3. Cork rings on a transversal section of a cork plank at Samora Correia (CL). Annual banding with earlycork cells (clearer tones) and latecork cells (darker tones) within a cork production cycle with 9-years (8-complete years and 2-half years, corresponding to harvesting years). A narrow cork ring was detected (black arrow), corresponding to the growth year of 2005.

Table 2
Cork ring widths in mm (mean ± std) and cork ring index (mean ± std) for all the cork samples (n) of the study areas, Montargil (HL), Samora Correia (CL) and Grândola (BS). In grey is the drought year of 2005.

Year	Montargil (**HL**) (n = 19)		Samora Correia (**CL**) (n = 24)		Grândola (**BS**) (n = 12)	
	Width (mm)	Index	Width (mm)	Index	Width (mm)	Index
2001					2.8 ± 0.67	0.89 ± 0.13
2002	4.1 ± 1.55	0.94 ± 0.23	3.9 ± 1.14	0.92 ± 0.14	3.6 ± 0.99	1.20 ± 0.18
2003	4.7 ± 1.53	1.17 ± 0.31	4.9 ± 1.63	1.26 ± 0.14	3.2 ± 1.09	1.08 ± 0.15
2004	4.2 ± 1.54	1.09 ± 0.27	4.1 ± 1.49	1.16 ± 0.15	2.8 ± 0.74	1.00 ± 0.16
2005	2.7 ± 0.83	0.75 ± 0.20	1.9 ± 0.65	0.60 ± 0.12	2.1 ± 0.40	0.79 ± 0.09
2006	3.4 ± 1.03	1.00 ± 0.24	3.1 ± 0.90	1.10 ± 0.19	2.7 ± 0.54	1.04 ± 0.12
2007	3.6 ± 1.11	1.15 ± 0.31	3.0 ± 0.86	1.22 ± 0.15	3.0 ± 0.60	1.18 ± 0.12
2008	3.2 ± 0.94	1.10 ± 0.27	2.5 ± 0.73	1.10 ± 0.13	2.6 ± 0.45	1.08 ± 0.11
2009	2.6 ± 1.08	0.92 ± 0.23	1.9 ± 0.60	0.91 ± 0.09	2.1 ± 0.35	0.88 ± 0.08

growth index and precipitation indices were analyzed. The higher significant correlation coefficient may indicate potential optimal predictors.

3. Results

3.1. Cork growth

The average thickness of the cork planks ranged between 30.8 ± 8.8 mm at Montargil (HL) and 28.2 ± 7.3 mm at Samora Correia (CL), both with a cork production cycle of 9 years, and 28.0 ± 5.0 mm at Grândola (BS), with a cork production cycle of 10 years. Maximum values for cork thickness were found at HL, 45.0 mm, followed by CL with 43.4 mm and BS with 36.1 mm. The average cork ring width for the 8-complete years of the cork production cycle was greater than 3 mm at HL and CL, respectively 3.6 mm and 3.1 mm, and inferior to 3.0 mm at BS (2.8 mm for the 9 complete years of the cork production cycle) (Table 2).

In each cork production cycle, the cork ring widths were larger in the years immediately following the cork harvest. In all the study areas, the largest cork ring width was found in the second complete year of growth of the cork production cycle (in 2003, at Montargil (HL) and Samora Correia (CL), and in 2002, at Grândola (BS). At CL and HL, the second cork ring width was larger than 4.0 mm measuring on average 4.9 mm and 4.7 mm, respectively, and at BS, was 3.6 mm. In all the study areas, the narrowest average cork ring width was found in the last complete year of the cork production cycle, at HL and CL, in the eighth year of the cork production cycle, 2.6 mm and 1.9 mm, respectively, and at the BS, it was found in the ninth year of the cork production cycle, 2.1 mm (Table 2).

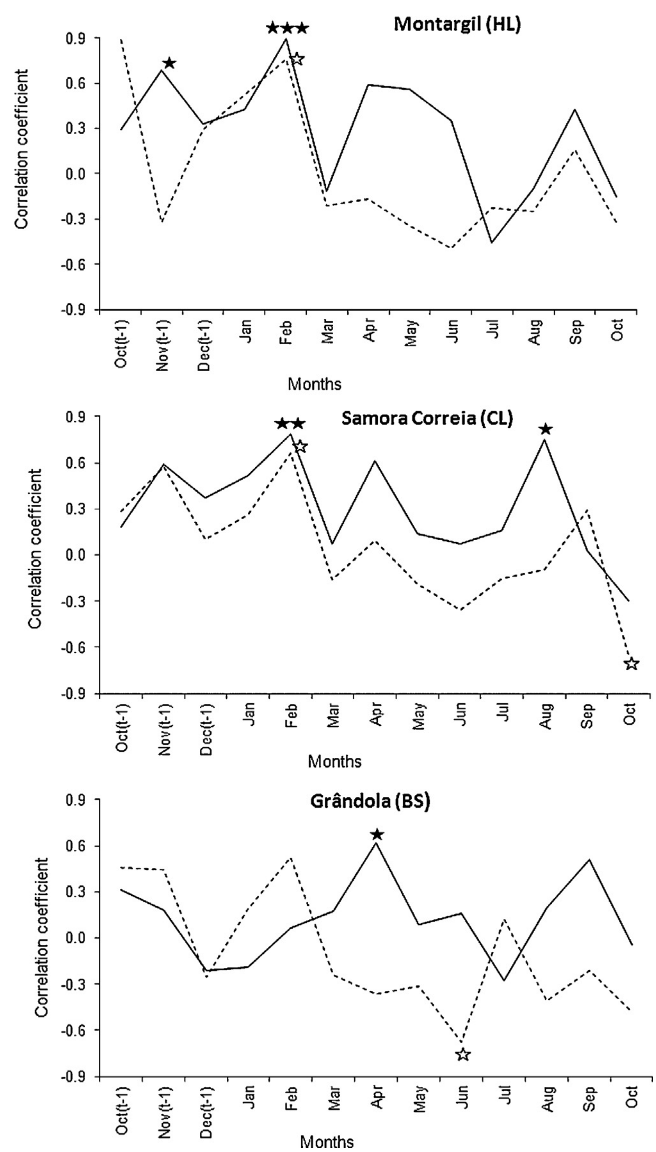

Fig. 4. Pearson rank order correlation coefficient between the master chronology of cork ring index and monthly precipitation (solid black line) and mean monthly temperature (dotted black line) at the study areas: Montargil (HL), Samora Correia (CL) and Grândola (BS). Significant correlation coefficients are higlighted with asterisks; *, ** and ***, respectively for significant at 95%, 99% and 99.9%.

Table 3
Descriptive statistics for raw cork rings chronologies of cork samples in the study areas, Montargil (HL), Samora Correia (CL) and Grândola (BS): Mean Sensitivity (MS); Mean series intercorrelation (SI); Expressed Population Signal (EPS).

Descriptive statistics	Montargil (**HL**)	Samora Correia (**CL**)	Grândola (**BS**)
Number of trees (#)	11	12	10
Number of cork samples (#)	19	24	12
MS	0.311	0.317	0.241
SI	0.676	0.765	0.436
EPS[1]	0.975	0.987	0.903

[1] EPS = (t x SI)/(t x SI + (1 − SI)), where t is number of cork samples and SI is the mean series intercorrelation (Wigley et al., 1984).

Cork ring chronologies showed a relatively high mean sensitivity (MS), ranging between 0.311 and 0.317, at Montargil (HL) and Samora Correia (CL), respectively, and a lower value at Grândola (BS), of 0.241 (Table 3). These former high values of MS, at Montargil and Samora Correia, corresponded to higher values of mean series intercorrelation (SI), ranging between 0.765 and 0.676, respectively at Samora Correia (CL) and Montargil (HL). Grândola (BS) showed the lowest value of SI equal to 0.436.

The mean values of MS and SI found in the study areas are within the acceptable range for these statistics and suggested that, in each study area the cork growth was sensitive to (environmental) climate and showed a coherent climate signal at study area-level. Grândola (BS) showed the lowest climate signal while Samora Correia (CL) showed the high climate signal. The values found for Expressed Population Signal (EPS), ranging between 0.903 at Grândola (BS) and 0.987 at Samora Correia (CL), were high and above the minimum standard value of 0.85, meaning that cork ring chronologies were reliable indicators of a coherent population climate signal in each study area.

An abnormal narrow cork ring width was found in the cork samples, synchronized with the year of 2005 (Table 2). At Samora Correia (CL) the sensitivity of the cork growth was high (high MS) (Table 3) and it was clearly visible a narrow cork ring (correspondent to year 2005), in relation to the adjacent, previous and consecutive, cork rings (Fig. 3).

3.2. Climate-cork growth relationships

The results of Pearson rank correlation tests on monthly precipitation and mean monthly temperature showed contrasting patterns between Montargil (HL), Samora Correia (CL) and Grândola (BS) (Fig. 4). In relation to monthly precipitation, at Montargil (HL) and Samora Correia (CL), precipitation in the winter previous to the growth year (in November, previous to the growth year and February, at HL and, in February, at CL) had a significant positive influence on cork growth. Precipitation in summer (August) also showed a significant positive influence on cork growth index at Samora Correia (CL). On the other hand, at Grândola (BS), only the precipitation in spring (April), at the onset of the growing season showed positive influence on cork growth.

In relation to mean temperature, significant positive correlations were found in February at Montargil (HL) and at Samora Correia (CL) and negative correlations were found with mean June temperature at Grândola (BS). At Samora Correia (CL) was also found a significant negative correlation between mean temperature in October and cork growth index (Fig. 4).

The correlation coefficients between the cumulative precipitation and mean temperature for the established periods, along the growth year and the master chronologies for cork growth index showed some variability in the seasonal climate variables between the study areas (Fig. 5).

At Montargil (HL), the cork growth index showed higher (significant) correlations with total (cumulative) precipitation from November$_{(t-1)}$ previous to the growth year until February, a longer period, when compared to Samora Correia (CL). At Montargil (HL), the spring precipitation, starting in March, showed also positive but non-significant correlations, and precipitation in the summer (in July to August) was non-significant. In this region, mean temperatures from the winter previous to the growth year, from October$_{(t-1)}$ till summer, in July, had significant positive correlations (Fig. 5).

The correlation coefficient patterns for cumulated precipitation and mean temperature at Samora Correia (CL) were somewhat similar to those found for Montargil (HL). At CL, the cumulative precipitation in the winter previous to the growth year, since January, was significantly correlated with cork growth index. The spring precipitation starting in March and the summer precipitation (June to August) showed always positive but non-significant correlations with the cork growth. Similarly to Montargil (HL), at Samora Correia (CL) the average temperatures from the winter previous to the growth year, from October$_{(t-1)}$ till early summer, in June, had highly significant correlations with the cork growth index. In both regions, Montargil (HL) and Samora Correia (CL), consistent negative but non-significant correlation coefficients were found with average mean temperatures in spring (starting in March) and summer (June till August) (Fig. 5).

At Grândola (BS), the strongest signal of positive correlation came from the cumulative precipitation starting in February–April and extended until September. Precipitation from May to September (i.e., from late spring to summer) was positively correlated with cork growth but was not statistically significant. In this region, in relation to mean temperature, the high correlation coefficients (negative) were found with spring (March–April) to summer (June–August) (Fig. 5).

Noticeably, at Grândola (BS), from March-April to July-August, cork growth was significantly and positively correlated with cumulative precipitation and simultaneously was significantly and negatively correlated with mean temperature, which may suggest a potential period of drought stress (Fig. 5).

3.3. Precipitation indices

The correlation coefficients found between the cork growth index and the seasonal precipitation indices, from September$_{(t-1)}$ to May (Table 4), were consistent to previous correlations found with monthly precipitation.

From September$_{(t-1)}$ to May, PRCPTOT was positively correlated with cork growth in all the study areas but statistically significant only at Montargil (HL) and Samora Correia (CL). At both study areas, HL and CL, PRCPTOT in September$_{(t-1)}$ − November$_{(t-1)}$ and in December$_{(t-1)}$ − February, was highly correlated with the cork growth index when compared to the spring precipitation. At Grândola (BS), in accordance to previous results on correlation with monthly precipitation, it was the spring (March–May) PRCPTOT that showed a significant correlation (Table 4). Also at Grândola, it is noticeable the found positive correlation (despite non significant) with the duration of continuous periods with significant rainfall (CWD) in this period (March–May).

At Montargil (HL) and Samora Correia (CL), between autumn previous to the growth year, September$_{(t-1)}$ and spring of the growth year, May, the dry spells (CDD) had significant negative correlation coefficients with cork growth index (between December$_{(t-1)}$ and February, for both regions, HL and CL, and between September$_{(t-1)}$ and May, only for HL), in contrast with wet spells (CWD). Only at Montargil (HL), the heavy precipitation events were significant for a threshold of 10 mm (R10), 20 mm (R20) and 25 mm (R25), while at Samora Correia (CL) they were significant only for a threshold of 25 mm (R25). At Grândola (BS), neither dry nor wet spells were significant, and only a threshold of 25 mm

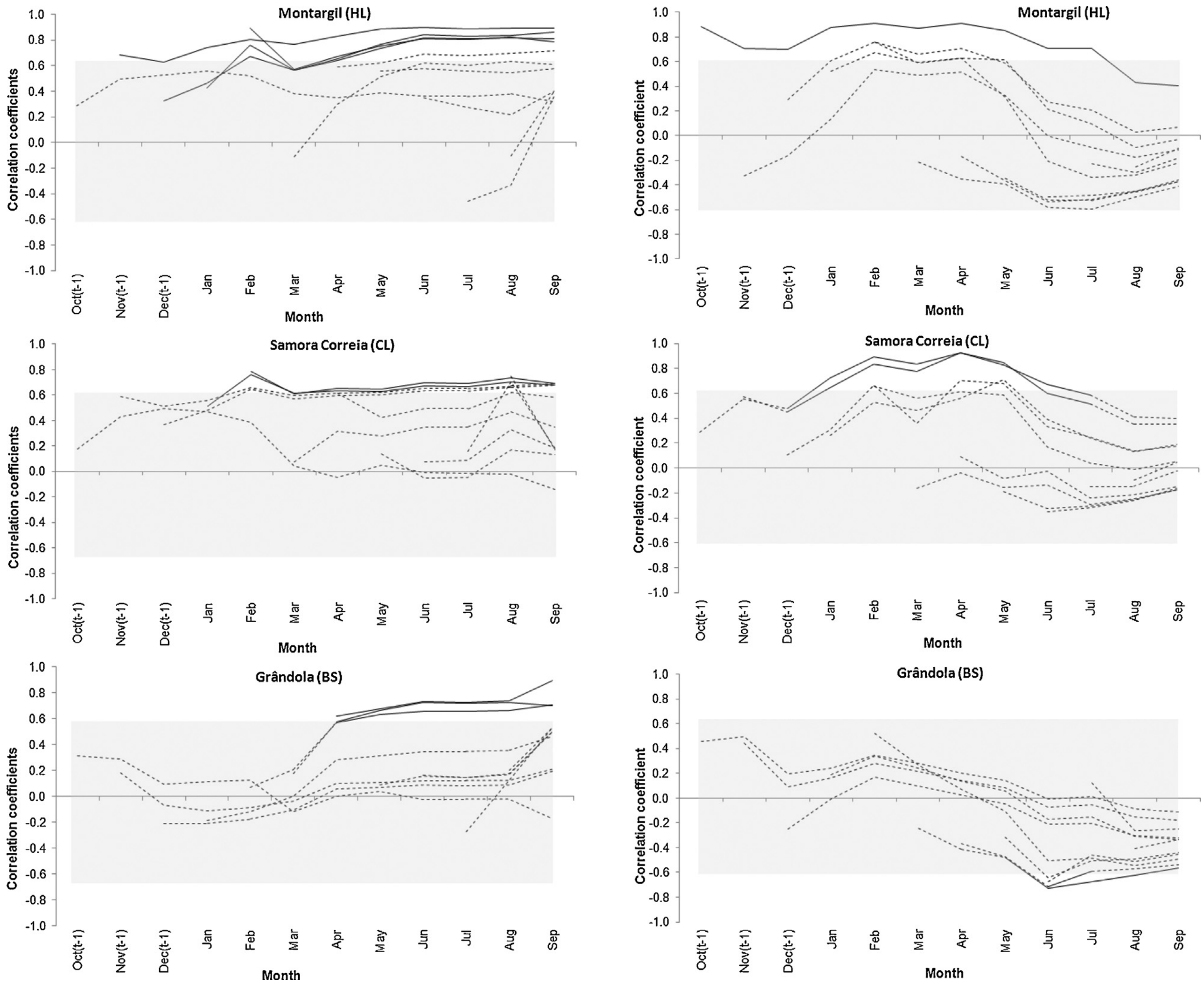

Fig. 5. Pearson rank order correlation coefficient between the master chronology of cork ring index and cumulated precipitation (left column) and mean monthly temperature (right column) at the study areas: Montargil (HL), Samora Correia (CL) and Grândola (BS). Significant correlation coefficients ($p < 0.05$) are located outside the grey shaded area. Solid black lines are for large periods with significant correlation.

Table 4
Summary of the correlation coefficients expressing the effects of precipitation indices on cork growth index chronologies of the study areas: Montargil (HL), Samora Correia (CL) and Grândola (BS). The signal of the correlation are presented and the significant correlation coefficients are higlighted with asterisks; *, ** and ***, respectively for significant at 95%, 99% and 99.9%. PRCPTOT, total precipitation in wet days, R ≥ 1 mm; CDD, maximum number of consecutive dry days, R < 1 mm; CWD, maximum number of consecutive wet days, R ≥ 1 mm; COUNT, total number of wet days; R10, 20, 25, total number of days when R ≥ 10, 20 or 25 mm, respectively; and RX1D, maximum 1-day precipitation.

Study area	Biological year	PRCPTOT (mm)	CDD (#)	CWD (#)	Count (#)	R10 (#)	R20 (#)	R25 (#)	RX1D (mm)
Montargil (**HL**)	**Sep$_{(-1)}$–May**	+***	–*	+	+*	+*	+**	+**	+
	Sep$_{(-1)}$–Nov$_{(-1)}$	+*	–	+	+	+	+**	+*	+
	Dec$_{(-1)}$–Feb	+	–*	+	+	+	+	+	+
	Mar–May	+	–	–	+	+*	+	+	+
Samora Correia (**CL**)	**Sep$_{(-1)}$–May**	+*	-	+	+*	+	+	+*	+
	Sep$_{(-1)}$–Nov$_{(-1)}$	+	-	+	+	+	+	+	+
	Dec$_{(-1)}$–Feb	+*	-*	+	+*	+	+	+*	+*
	Mar–May	+	-	-	+	+	+	n.a.	+
Grândola (**BS**)	**Sep$_{(-1)}$ –May**	+	–	+	+	+	+	+	+
	Sep$_{(-1)}$–Nov$_{(-1)}$	+	–	+	+	+	+	+*	+
	Dec$_{(-1)}$–Feb	–	–	+	–	+	–	–	–
	Mar–May	+*	–	+	+	+	+	+	+

(R25) in the previous autumn (September$_{(t-1)}$–November$_{(t-1)}$) was significantly and positively correlated with cork growth (Table 4).

For cork growth responses, at Montargil (HL) and Samora Correia (CL), the precipitation indices in autumn previous to the growth year, including the total amount of precipitation, the duration of the dry spells or the number of heavily precipitation days (>25 mm) were the best predictors (Table 4). At Grândola (BS), the number of heavy precipitation days (>25 mm, R25) in the autumn previous to the growth year (September$_{(t-1)}$–November$_{(t-1)}$) and total amount of precipitation strictly in the onset within the growing season (March – May) were the best predictors. The later, markedly more influential at Grândola (BS) than at Montargil (HL) or at Samora Correia (CL) (Table 4).

The cork growth index was lower in the year 2005, when trees have been subjected to a moderate-severe drought during the autumn-winter months previous to the growth year and in spring months, in the onset of the growth year, corresponding to 0.75, 0.60 and 0.79 (Table 2), respectively for Montargil (HL), Samora Correia (CL) and Grândola (BS). However, trees recover in the following 1–2 years, when no drought occurred, at Samora Correia (CL) the plasticity of cork ring widths was higher than at Montargil (HL) and at Grândola (BS). At Grândola (BS), the response function was somewhat more stable, with a less drastic reaction to the drought event (Table 2), also in accordance to its lower mean sensitivity (Table 3).

4. Discussion

4.1. Cork ring width

The cork ring widths found in this study are within the range of mean annual cork growth (cork rings) reported at national level, between 2.2 and 4.8 mm yr^{-1} (Ferreira et al., 2000) and in the range of cork ring widths reported for southwestern Spain (at Caceres and Badajoz) between 1.85 and 5.25 mm yr^{-1} (Caritat et al., 2000).

The decreasing trend in cork ring widths along the cork production cycles found for the cork samples at the three study areas is in accordance with the adjusted mean annual cork growth curve in harvest cork oaks previously reported (Natividade, 1950; Caritat et al., 1996; Ferreira et al., 2000; Costa et al., 2002, 2015; Oliveira and Costa, 2012). Cork growth is enhanced at the beginning of the cork production cycle (in the first 2–4 years), in response to traumatic cork harvest and afterwards the current cork ring widths tend to decrease (Caritat et al., 1996; Costa et al., 2002).

Trees grown at Montargil (HL) and Samora Correia (CL) had larger cork ring widths in relation to those at Grândola (BS). This is consistent with a previous study which reported similar discrepancies in mean annual values of cork growth for the study sites: ranging between 1.9 and 3.5 mm yr^{-1} at Grândola; between 2.3 and 3.7 mm yr^{-1} at Montargil and between 2.2 and 3.7 mm yr^{-1} at Samora Correia (Sousa, 1997).

The lowest cork growth values found at Grândola (BS) are in accordance with typical relatively lower tree growth reported for the Grândola's mountain area (Costa et al., 2009), possibly due to prominent geomorphic conditions such as soil type and depth, slope and aspect, which decisively constrain the soil water availability, and the access of the tree roots to deep ground water, mainly in the summer dry season. Moreover, the lower cork growth rates found at this study area should represent proportional lower tree respiration rates during water stress periods, and less carbon is diverted for the cork growth, similarly to the strategies used by other species to cope with drought periods, such as Q. ilex (Cherubini et al., 2003; Gea-Yzquierdo et al., 2009; Pasho et al., 2011), *P. sylvestris* (Martínez-Vilalta et al., 2012) and P. nigra (Martín-Benito et al., 2008).

The relatively high values of mean sensitivity (MS) and mean interseries correlation (SI) found for all the study areas confirms our first hypothesis on that climate is likely the dominant signal affecting cork growth at the three study areas. Values of Q. suber mean sensitivity (MS) (ranging between 0.241–0.317) and mean interseries correlation (SI) (ranging between 0.436–0.765) for the three study areas were similar but slightly superior to those found for Q. ilex (tree-rings) in Central Spain (Gea-Izquierdo et al., 2009), respectively ranging between 0.208–0.257 (MS) and between 0.223–0.441 (SI).

At Grândola (BS), the cork growth chronologies showed the lowest values of mean sensitivity (MS), mean interseries correlation (SI) and expressed population signal (EPS), when compared to Montargil (HL) and Samora Correia (CL). The explanation for this may be related to the fact that, at Grândola (BS), trees are growing in more heterogeneous biophysical conditions (soil/slope/aspect) which likely contribute to high variability in trees' adaptive capacity to water stress periods. Moreover, between Samora Correia (CL) and Grândola (BS), the cork growth climate response variability can be affected by contrasting environmental conditions, confirming our hypothesis that environmental stress may affect the climate signal in cork growth. This is in accordance to previous conclusion of Cherubini et al. (2003) of trees' climate response across Mediterranean environments as a function of water availability, the major limiting factor for growth.

4.2. Climate-cork growth relationship

Climate responses of cork growth under Mediterranean environments also confirm our third hypothesis on that cork ring widths can be used for dendroclimatological studies. At Grândola (BS) is noticeable that cork growth had two limiting factors: a statistically significant positive cork growth response to precipitation in April (spring) and a statistically significant negative cork growth response to temperature in June (summer) (Fig. 4). These climate signals were encoded in the cork growth and indicated that *Q. suber* profited from spring precipitation which should trigger phenological events and the cambium and phellogen reactivation post dormancy (Oliveira and Costa, 2012). At this study area, the strong dependency of cork growth on spring cumulative water deficit should markedly affect the onset of tree growth by June (Fig. 5), when maximum cambial activity should occur (*data not published*). This is in accordance with the responses of species such as Q. ilex, at more xeric sites, which showed maximum radial growth between May and June (Gea-Yzquierdo et al., 2009; Pasho et al., 2011).

At Montargil (HL) and Samora Correia (CL), in contrast to Grândola (BS), the cork growth index is significantly positively related to precipitation in the winter previous to the growing season, in February (Fig. 4). These results are in accordance with studies showing higher cork growth in years following very wet winters (Caritat et al., 2000; Costa et al., 2002, 2003). Rainfall and warmer temperatures in late winter (February) previous to growing season generally stimulate cork ring formation (Figs. 4 and 5), similarly to tree-ring formation in deciduous oaks and Q. ilex (Tessier et al., 1994; Gea-Izquierdo et al., 2009).

At Samora Correia (CL), the late summer precipitation (August) is positively correlated with cork growth which is in accordance with the reported absence of the summer dormancy period and pause of phellogen activity (Costa et al., 2003), similarly to other reports in relation to cambial activity and radial growth for deciduous oaks (Tessier et al., 1994) and Q. ilex (Corcuera et al., 2004; Gea-Izquierdo et al., 2009). Moreover, at Samora Correia (CL), August rainfall allows the prolongation of the growing season into late autumn, producing larger cork ring widths (see Fig. 3), as it was previously reported by Rozas (2005) for the formation of larger tree-rings in Q. robur.

The extended growing season at Samora Correia (CL) is only constrained by October (early autumn) temperatures (see Fig. 4) which indicates an increase in drought stress, starting in late summer and extending throughout autumn. This is in accordance with the negative correlation between summer temperatures and radial growth (tree-ring widths) in other *Quercus* spp. (Tessier et al., 1994), as in Q. ilex (Gea-Izquierdo et al., 2009).

At Montargil (HL) and Samora Correia (CL), trees cope with drought by continuing their growth (Costa et al., 2003). It seems that *Q. suber* may become more drought tolerant in some Mediterranean environments, where soil and geomorphology avoid severe and extended water deficits. At Samora Correia (CL), however, the potential low soil water holding capacity of Haplic Arenosols (Table 1) (Costa et al., 2008), may proportionally amplify the effect of drought, when compared to Montargil (HL) and, consequently, the trees have higher mean sensitivity and responds to drought with a more drastic reduction in cork growth when compared to Montargil (HL), where carbon resources should be less sharply diverted from cork growth in response to drought. These results agree with previous studies showing the physiological trees mechanisms underlying drought vulnerability affecting the carbon balance, and the portioning of carbon resources used for cambial activity and tree-rings growth (Campelo et al., 2007; Martín-Benito et al., 2008; Gea-Izquierdo et al., 2009; Martínez-Vilalta et al., 2012). On the other hand, the climate-cork growth relationship at Grândola (BS) also somewhat reflect the adaptation of cork oaks to the Mediterranean-summer drought. At this study area, trees seems to cope with drought by avoiding it (Cherubini et al., 2003) and this adaptation strategy to cope with the summer-drought periods is to effectively reduce photosynthetic carbon uptake via stomatal closure (Vaz et al., 2010), and stop their radial growth (*data non published*).

4.3. Response to a drought event

Under the recent climate projections for the Mediterranean basin, which agree in forecasting longer and more frequent drought events, cork oak trees are likely to decrease their cork growth. At Samora Correia (CL) and Montargil (HL), cork growth is higher sensitive to climate as trees react proportionally to both unfavorable and favorable conditions, by drastically decreasing and increasing cork growth, respectively. Moreover, in contrast to Grândola (BS), at Samora Correia (CL) and Montargil (HL), it is the length of the dry spells beginning in the winter prior to growth year that is decisive for cork growth. Climate change predictions for the period 2021–2050 (López-Franca et al., 2013) suggest an increase of 25% in the length of the consecutive dry days within this period, and these trends would probably cause a reduction in the cork yield, at Montargil (HL) and at Samora Correia (CL).

At Grândola, the lower cork growth rates and lower mean sensitivity are adaptations of the trees. The limiting climate conditions for cork growth are related to the amount of precipitation in early spring (March-May), in the onset of the growing season (Table 4). Climate change scenarios forecasted at regional level for the period 2021–2050 (Barrera-Escoda et al., 2014) suggested a reduction of 3–4 days of consecutive wet days and, in this scenario, trees will probably reduce their cork growth and yield at Grândola region. Enlarged periods of rainfall and days with heavy rainfall are particularly needed for water stress-free and normal cork growth at Grândola (BS).

Assuming cork growth as a proxy for the cork oak growth, these changes in trees' growing conditions would force cork oaks to grown under increasing stress which may lead to forest health decline and an increase by the incidence of forest pathogens, reducing its buffering against drought events (Martín-Benito et al., 2008; Allen et al., 2010). In accordance, Grândola's region has been recently classified as an endangered region regarding cork oak decline (Costa et al., 2009), and this decline has been mainly related to local environmental stresses induced by a highly seasonal and uncertain rainfall (Costa et al., 2010, 2011; Costa and Madeira, 2011).

5. Conclusions

In conclusion, our results indicate that dendroclimatological studies using cork ring chronologies are possible. This approach allow assessing the variability of climate responses of *Q. suber* at the regional level, under distinct Mediterranean environments, and show that climate is likely the dominant signal affecting cork growth in mature trees under cork exploitation. However, similar direct effect of precipitation on cork growth across Mediterranean environments may not be straightforward, because limiting local environmental stresses, related to (soil) water availability, would affect the strength of climate signal on cork rings.

Assuming cork growth as a proxy for cork oak growth, our results show a range of tree strategies to cope locally with drought, from drought tolerance (at Montargil and Samora Correia) to drought avoidance (at Grândola). These strategies turn the trees more sensitive to specific climate variables to grown: while in Montargil and Samora Correia the dry spells in the previous winter wet season have a direct negative effect on the cork growth, on the contrary, in Grândola, is the amount of precipitation in early spring that have a positive effect on cork growth.

One constraint of the application of the climate variables on cork yield projections derives from the concepts of cork oak growth plasticity and variability, which depend also on the degree of naturalness of the woodland ecosystem. Our perception of climate change impacts on cork growth can be exacerbated by the fact that cork oak woodlands ecosystems, considered iconic examples of domesticated nature, are indeed among the ecosystems most intensively managed and highly disturbed by human activities in Europe.

This study reinforces knowledge of the climate-cork growth relationship, but also highlights the need for a better understanding of the climate-environment-growth dynamics. These uncertainties warrant further cork ring analysis, of a larger cork sampling, from more sites, and extending over a longer (cork ring) chronologies, to forecast climate response of cork yield, at local and regional levels.

Author contributions

Formulated the idea: AC. Conceived and designed the methodology and analysis: AC. Collaborated in imaging analysis: IB, CR, AC. Analyzed the data: AC, JG, HS. Wrote the paper: AC, JG, HS.

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