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Climatic drivers of cork growth depend on site aridity

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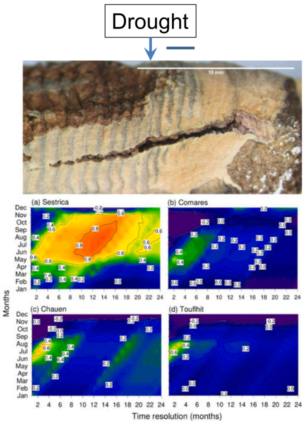
GRAPHICAL ABSTRACT



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ABSTRACT

Cork is one of the main non-timber forest products in the world. Most of its production is concentrated in the Iberian Peninsula, a climate change hotspot. Climate warming may lead to increased aridification and reduce cork production in that region. However, we still lack assessments of climate-cork relationships across ample geographical and climatic gradients explicitly considering site aridity. We quantified cork growth by measuring cork ring width and related it to climate variables and a drought index using dendrochronology. Four cork oak (*Quercus suber*) forests located from north eastern Spain to south western Morocco (31.5–41.5° N) and subjected to different aridity levels were sampled. Warm conditions in spring to early summer, when cork is formed, reduced cork width, whereas high precipitation in winter and spring enhanced it. The response of cork to increased water availability in summer peaked ($r = 0.89$, $p = 0.00002$) in the most arid and continental site considering 14-month long droughts. A severe drought caused a disproportionate loss of cork production in this site, where for every five-fold decrease in the drought index, the cork-width index declined by a factor of thirteen. Therefore, site aridity determines the responses of cork growth to the soil water availability resulting from accumulated precipitation during winter and spring previous to cork growth and until summer. In general, this cumulative water balance, which is very dependent on temperature and evapotranspiration rate, is critical

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for cork production, especially in continental, dry sites. The precipitation during the hydrological year can be used as a proxy of cork production in similar sites. Assessments of climate-cork relationships in the western Mediterranean basin could be used as analogues to forecast the impacts of aridification on future cork production.

1. Introduction

The cork oak (*Quercus suber* L.) is an evergreen tree species with diffuse-porous wood widely distributed in areas characterized by acid, often nutrient-poor soils in the western Mediterranean basin, where it is usually managed for cork production (Pereira, 2007). Given its numerous adaptive traits, such as leaf osmotic adjustments, stomata closure, deep root system, reduction of xylem vessel diameter, which confer cork oak a high resilience to summer drought, it is considered a drought-avoiding species (Aranda et al., 2005; David et al., 2007). Cork is traditionally stripped from the trunks of mature trees, typically older than 25 years, at intervals from 8 to 14 years (Pereira, 2007).

The sustainability of cork production may be menaced by climate warming and increased aridification because severe, hot and prolonged droughts threaten some cork oak stands by reducing growth and increasing mortality rate due to water shortage or amplifying pest incidence (Brasier, 1992; David et al., 1992; Costa et al., 2010; Gentilesca et al., 2017; Touhami et al., 2020). It has also been forecasted that if the current management of cork oak forests is maintained, climate change may result in a 20 % decrease in cork production by 2100 (Palma et al., 2015). In addition, climate warming can also impact cork quality, which depends on factors such as cork oak growth, cork thickness and porosity, and defects related to insect galleries or wood inclusions (Montero and Cañellas, 1999; Sánchez-Cuesta et al., 2021; Sánchez-González et al., 2023). Nonetheless, drought does not seem to alter the cork chemical composition, particularly the suberin concentration (Leite et al., 2020). However, we still lack comprehensive assessments of the impacts of drought severity on cork production across wide geographical and climatic gradients, which could represent analogues to the aridification forecasted for the western Mediterranean basin. Currently, Portugal and Spain are the world's largest cork producers, accounting for 58.3 % and 19.8 % of total exports, respectively, followed by North African countries (e.g., Morocco, 2 %), which show high relative increases in production (ITC, 2023).

The phellogen of cork oak remains active from early April up to November, usually with peak activity typically occurring around June, and low growth rates during summer (Pereira et al., 1987; Graça and Pereira, 2004; Pereira, 2007). This seasonal growth pattern results in the formation of annual cork rings, allowing the use of dendrochronology to quantify climate-cork relationships (e.g., Caritat et al., 2000). In general, cork production is reduced under warm and dry summer conditions (Caritat et al., 1996, 2000; Ferreira et al., 1998; Costa et al., 2016; Oliveira et al., 2016; Ghalem et al., 2018; Leite et al., 2018, 2019), and dry spring-summer conditions can also lead to lower xylem growth rates (Costa et al., 2002, 2003). Spring-to-summer warm and dry conditions increase cork density, probably by advancing cork cell-wall thickening and suberization (Costa et al., 2022). Cork growth and cork oak access to water depend on climate conditions, but they are also influenced by soil and geological features, as a decline in groundwater following drought has been shown to reduce cork yield (Mendes et al., 2016). Furthermore, some cork oak populations can be very sensitive to drought, particularly those occupying currently less suitable sites (characterized by xeric climate conditions and poor soils), which were favored by past management practices aimed to maximize cork production (Urbieta et al., 2008).

However, most of the previous studies analyzing cork growth responses to climate were conducted in a limited number of usually mesic sites, often overlooking sites along geographical and climatic gradients, including xeric locations. Here, our main objectives were: (i) to quantify cork radial growth using annually resolved measures of cork ring width and, (ii) to determine the main climatic constraints of cork radial growth in sites with contrasting climate conditions. We focused on characterizing how drought severity limits cork production considering different time scales and drought severity and comparing four cork oak forests subjected to different aridity intensity given the forecasted aridification trends over the Mediterranean Basin. We achieved those aims though: (i) cross-dating and measuring cork ring widths, and (ii) relating these measures of cork growth to climatic variables, including a drought index, along a 10°-wide latitudinal gradient spanning from NE Spain to SW Morocco. We sampled four stands where cork was not harvested for the past two decades. While it is well stated that cork rings tend to be narrower during dry years (Caritat et al., 2000; Oliveira et al., 2016), obtaining biogeographical information on climate-cork relationships could enhance adaptive management of cork oak in response to increasing aridity (Palma et al., 2015). This is especially critical when considering the xeric limits of the species distribution area, as the cork oak has been shown to be particularly vulnerable to drought stress there (Matías et al., 2019; Morillas et al., 2023). Furthermore, it is considered that cork with higher growth rates typically exhibits more and larger pores and lower compressive strength and Young's modulus than slow-growing cork (Natividade, 1950; Pereira et al., 1992). Therefore, cork growth rate significantly impacts its porosity and quality, since slow-growing cork of low porosity is highly appreciated. We hypothesize that the strongest response, here defined as the highest correlation, of cork-ring width to water availability (precipitation, cumulative water deficit measured using a drought index) will be observed in the most arid site along the studied climatic gradient, where the highest cork porosity should be also observed.

2. Material and methods

2.1. Study sites and climate data

We selected four sites where *Q. suber* is the dominant species located within the western Mediterranean basin, spanning a latitudinal gradient that extends from Northern (Sestrica) to Southern Spain (Comares), and from to Northern (Chaouen) to Southern Morocco (Toufliht) (Fig. 1).

These sites were located in natural areas with no evidence of human management at least during the last 20 years, and were selected due to their contrasting climate conditions, with a particular emphasis on their varying levels of aridity. Comares is located in a protected area ("Los Alcornocales Natural Park") in Andalusia, S. Spain, where the largest European cork oak forests are found. In contrast, Toufliht is situated in a severely degraded, xeric area near the southernmost distribution edge of the species (Fig. 1). Sestrica represents a relict cork oak population found in a privately-owned forest without recent management. Chaouen is located within the wet Rif area. The study sites encompass both pure and mixed cork oak forests, with tree densities ranging between 120 and 350 stems ha^{-1}.

Due to the lack of long-term and homogeneous climate series near the four study sites, we used monthly climate data (mean temperature, total precipitation; period 1950–2022) from the 0.5°-gridded CRU TS v. 4.07 dataset (Harris et al., 2020). According to these climate data, Comares is the warmest site (Table 1), followed by Chaouen, Sestrica, and Toufliht. All these sites are subjected to Mediterranean conditions and experience warm and dry summers, although with different intensities. The highest annual precipitations are recorded in Chaouen and Comares (Table 1), while Sestrica and Toufliht are the driest sites. Using temperature and precipitation data, we calculated the water balance following Willmott et al. (1985), who used the Thornthwaite method for calculating potential evapotranspiration (PET). The lowest annual water balances corresponded to Comares and Sestrica, followed by Chaouen and Toufliht (Table 1, Figs. S1 and S2). Both Sestrica and Toufliht have no water surplus, whereas water surplus was remarkable during February and March in Comares and Chaouen (Fig. S2). We also calculated the aridity index, representing the ratio between precipitation and PET (UNEP, 1997). Sestrica displayed the lowest aridity index (0.57), while Chaouen registered the highest one (0.84; Table 1).

To characterize the drought duration and intensity in each site, we obtained 0.5°-gridded data of the Standardized Precipitation Evapotranspiration Index (SPEI) at 1- to 24-month long scales from the webpage https://spei.csic.es/. Positive and negative SPEI values correspond

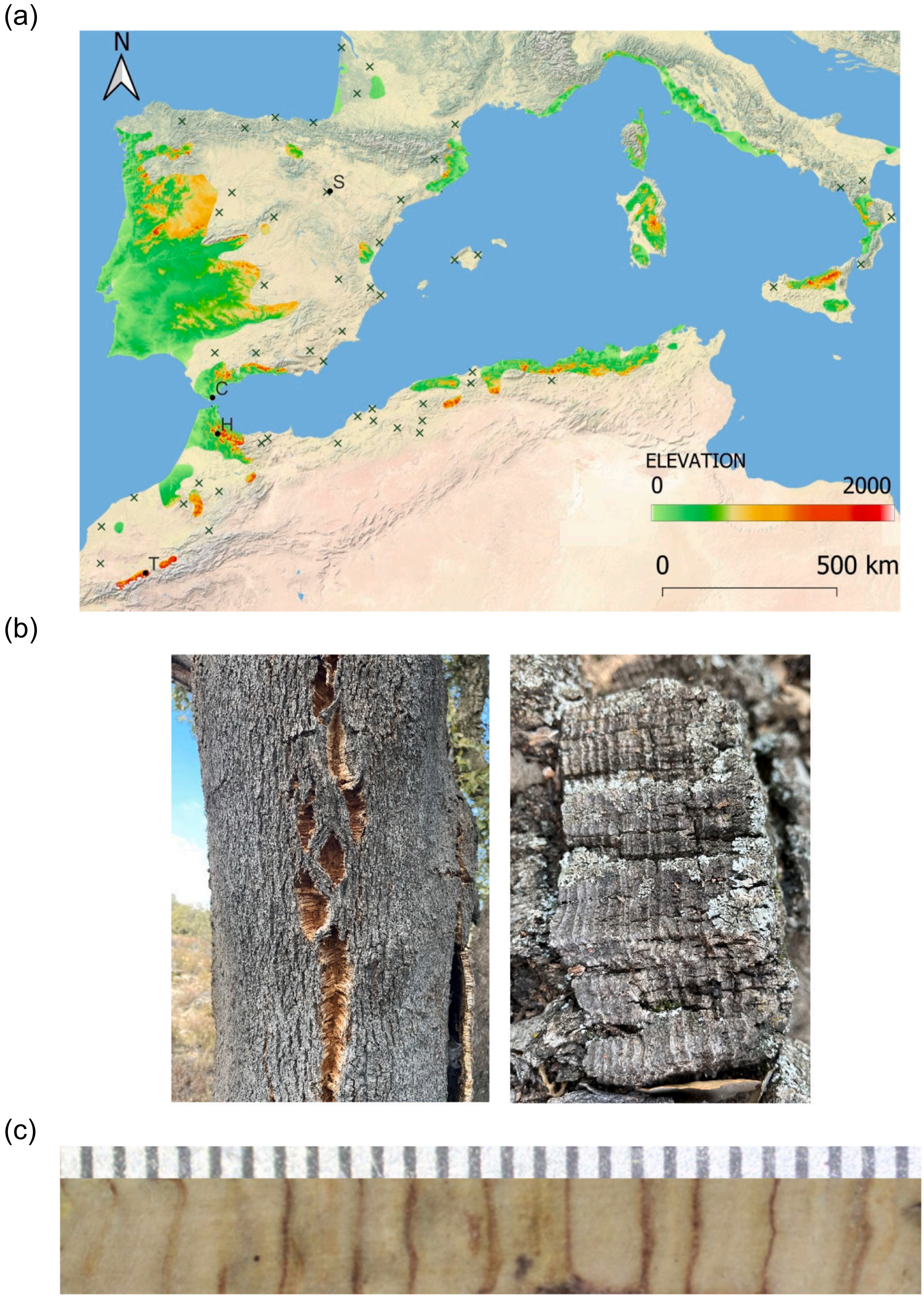

Fig. 1. (a) Map of the *Quercus suber* distribution area in the western Mediterranean Basin (colored patches corresponding to different elevations in m a.s.l.; crosses indicate native isolated populations) showing the location of the four study sites (S, Sestrica; C, Comares; H, Chaouen; and T, Toufliht). (b) Stem with cork from Sestrica site and view of rings in a cork piece. (c) Cross-section of cork showing conspicuous rings (the space between lines is 1 mm in the scale bar).

Table 1
Main features of the four study sites. Mean climatic variables are calculated for the period 1950–2022. AI is the aridity index with lower values indicating greater aridity. Dbh is the diameter measured at breast height. Values are means ± SD. Different letters indicate significant differences between sites (Tukey tests, $p < 0.05$).

Variables	Sestrica	Comares	Chaouen	Toufliht
Latitude N (°)	41.50	36.10	35.16	31.47
Longitude W (°)	1.63	5.51	5.32	7.42
Elevation (m a.s.l.)	859	410	532	1684
Aspect	SE	SE	SE	NE
Slope (%)	15	10	12	17
Soil type	Inceptisols	Cambisols	Luvisols	Luvisols
Annual precipitation (mm)	484	630	700	417
Spring precipitation (mm)	166	167	202	122
Mean (range) temperature (°C)	12.4 (4.1–21.9)	18.1 (12.3–24.9)	14.6 (9.5–21.3)	9.9 (3.2–17.6)
Annual water balance (mm)	−320	−386	−249	−218
AI	0.57	0.68	0.84	0.62
Dbh (cm)	31.4 ± 6.1	34.0 ± 9.1	38.1 ± 7.2	36.1 ± 8.7
Cork porosity (%)	4.4 ± 1.1a	8.0 ± 2.0b	9.2 ± 1.8b	7.2 ± 1.5b
No. sampled trees	14	15	16	15
Accompanying tree species	*Q. ilex*	*Q. canariensis*	None	*Q. ilex*
Q. suber dominance (% basal area)	72	67	98	82

to wet and dry conditions, respectively. The SPEI is calculated as a function of a cumulative water balance, i.e. the difference between precipitation and potential evapotranspiration (Vicente-Serrano et al., 2010).

Accompanying trees include *Quercus ilex* L., *Q. canariensis* Willd., and *Q. ilex* and *Pinus pinaster* Ait. in Toufliht, Comares and Sestrica, respectively. The Mediterranean tree *Arbutus unedo* L. is also found in Comares and Sestrica. Soils are acid in all sites, but developed on different geological substrates including quartzites (e.g., Sestrica) or sandstones (e.g., Comares).

2.2. Field sampling and processing cork samples

In the selected sites, cork had not been harvested at least since 2007, which allowed collecting relatively old cork samples. At each site, from 10 to 16 mature oaks with no evident deformations or scars were randomly selected within an area of ca. 1 ha for cork sampling. Their diameter at breast height (Dbh) was measured at 1.3 m to characterize the size structure of sampled trees (Table 1). One compact cork sample was obtained from each tree at 1.3 m using 10-mm Pressler increment borers (Table 2). Cork samples were air-dried, and cross-sections were cut using a sledge microtome (Gärtner et al., 2015). Then, they were visually cross-dated under the binocular scope and scanned at 1200 dpi (Epson Expression 10000XL). Cork widths were measured with a 0.001 mm resolution along two radii per sample using the CooRecorder software (Larsson and Larsson, 2018). The visual cross-dating was checked using the COFECHA software, which calculates moving correlations between individual series and the mean site series (Holmes, 1983). Robust site series were built for common, best-replicated period (2008–2021, $n = 14$ years; Table 2).

Table 2
Statistics of cork-ring width series. AR1 indicates the mean first-order autocorrelation of ring widths, MS represents the mean sensitivity among consecutive cork ring indices, and rbar the mean correlation among individual cork-width series. Different letters indicate significant differences between sites (Tukey tests, $p < 0.05$). Values are means ± SD.

Site	No. analyzed cork samples	Best-replicated period	Cork ring width (mm)	AR1	MS	rbar
Sestrica	14	2008–2021	3.06 ± 1.01bc	0.15	0.42	0.65
Comares	10	2008–2022	1.82 ± 0.48b	0.50	0.33	0.42
Chaouen	16	2008–2022	4.20 ± 1.20c	0.11	0.45	0.44
Toufliht	10	2008–2022	1.28 ± 0.30a	0.45	0.30	0.51

To illustrate how cork features were related to growth rate in the study sites we also measured the cork porosity. This measure quantifies the proportion of the transverse cork area occupied by pores (Pereira, 2007), and it was measured in the same measured cork cross-sections from each site along a 6-mm wide window. Cork images were analyzed using the ImageJ image analysis software (Schneider et al., 2012).

2.3. Processing cork width series using dendrochronological methods

To calculate climate-growth relationships, the individual cork-ring width series were converted into indexed ring-width series through standardization and detrending (Fritts, 1976). These procedures allow removing size-related trends in ring-width data and emphasize high-frequency growth variability. We fitted negative exponential functions to individual cork-ring width series and obtained cork-ring width indices by dividing observed by fitted values. Then, autoregressive models were fitted to remove most of the first-order autocorrelation in series of dimensionless ring-width indices. The residual or pre-whitened individual series were averaged using a bi-weight robust mean to obtain mean residual or pre-whitened cork-ring width series for each site (Fritts, 1976). These procedures were done using the dplR package (Bunn, 2010).

Lastly, we calculated several statistics for the common period 2008–2021. We characterized the mean site cork-width chronologies by calculating: the mean and standard cork-width values, the mean first-order autocorrelation of ring widths (AR1), which accounts for year-to-year persistence in cork growth, the mean sensitivity (MS), which measures relative changes in width among consecutive cork rings, and the mean correlation (rbar) among individual cork-width series (Fritts, 1976; Briffa and Jones, 1990).

2.4. Statistical analyses

Differences among sites in cork variables (width and porosity) were assessed using Tukey tests. The trends in cork-ring width were evaluated using the Kendall tau statistic (τ). A Principal Component Analysis (PCA) was calculated on the covariance matrix of the series or cork-ring width indices considering the common period of 2008–2021 using the ade4 package (Dray and Dufour, 2007). Then, a biplot showing the scores of the first (PC1) and second (PC2) principal components was drawn to compare relationships among sites. These two first principal components were kept after inspecting a scree plot (Peres-Neto et al., 2005).

To calculate climate-growth relationships, the site mean series or chronologies of cork-width indices were correlated with monthly climate data (mean temperature, total precipitation, SPEI) using the Treeclim package (Zang and Biondi, 2015). The analysis window for temperature and precipitation encompassed the period from October of the year previous to cork formation to October of the growth year. In the case of the SPEI, the window spanned from January to December of the growth year but considered 1- to 24-long SPEI temporal scales, i.e. months of accumulated water balance. These windows were selected following previous studies (e.g., Caritat et al., 2000). The slopes of linear regressions between SPEI and cork ring-width indices in the sites showing the highest correlations were compared using an analysis of covariance (ANCOVA). Statistical analyses were carried out using the R software (R Development Core Team, 2022).

3. Results

3.1. Cork width variability

The mean site Dbh of sampled oaks ranged from 31.4 to 38.1 cm, but did not differ among sites. In contrast, cork porosity was lower in Sestrica than in the other three sites (Table 1). The mean (±1SD) cork-ring width of all samples was 2.58 ± 1.42 mm (Fig. 2). However, significant differences appeared among sites, with Toufliht and Chaouen showing narrower (1.28 mm) and wider (4.20 mm) cork rings than the other two sites (Comares, 1.82 mm; Sestrica, 3.06 mm; Table 2). The highest AR1 was found in Comares, and the highest MS was detected in Chaouen. Sestrica presented the highest rbar, indicative of the strongest coherence among individual series of cork-width indices.

All cork-ring width series, excepting Toufliht, showed negative trends (Sestrica, $\tau = -0.56$, $p = 0.005$; Comares, $\tau = -0.49$, $p = 0.01$; Chaouen, $\tau = -0.27$, $p = 0.16$; Fig. 2a). Sestrica presented the highest variability in cork-width indices (SD = 0.31), with a very low value (0.18) observed in the year 2012, coinciding with a reduced cork production in the other sites. The Sestrica and Comares series of cork-width indices presented the highest positive correlation, although it was not significant ($r = 0.35$, $p = 0.22$). Similarly, the series from the two Moroccan sites were positively but not significantly correlated ($r = 0.27$, $p = 0.32$).

The first and second principal components (PC1 and PC2) collectively accounted for 56.3 % and 21.1 % of the total variability in cork width-indices, respectively (Fig. 3). The PC1 scores were linked to Sestrica measures, whereas the PC2 scores corresponded to the two Moroccan series, with Comares positioned intermediate in the biplot. Again, the year 2012 showed the lowest PC1 scores, while the year 2020 exhibited the highest scores.

3.2. Relationships between climate variables and cork-width indices

Warmer conditions in June were associated to lower cork-width indices in all sites excepting Comares (Fig. 4). In Sestrica, warm August conditions also restricted cork production. Conversely, in Comares, warm and wet conditions in the previous December and warm February conditions led to enhanced cork production. In Sestrica and Toufliht, higher precipitation levels in May improved cork formation, while a similar positive correlation was observed in Chaouen in June and also in Sestrica in March. Comares, however, exhibited a negative correlation between cork-width indices and high precipitation in October, but a positive correlation with December precipitation of the previous year.

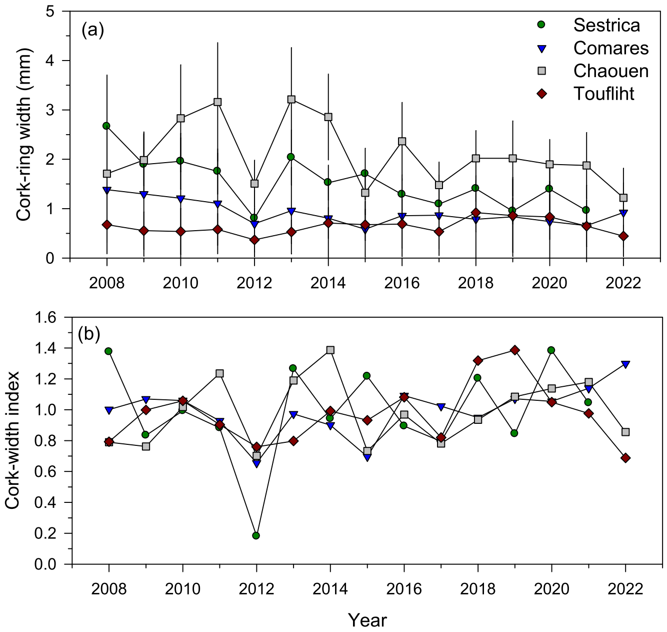

Fig. 2. Raw (a) and (b) detrended series of cork-ring widths and indices, respectively. Cork-ring width values are means ± SD.

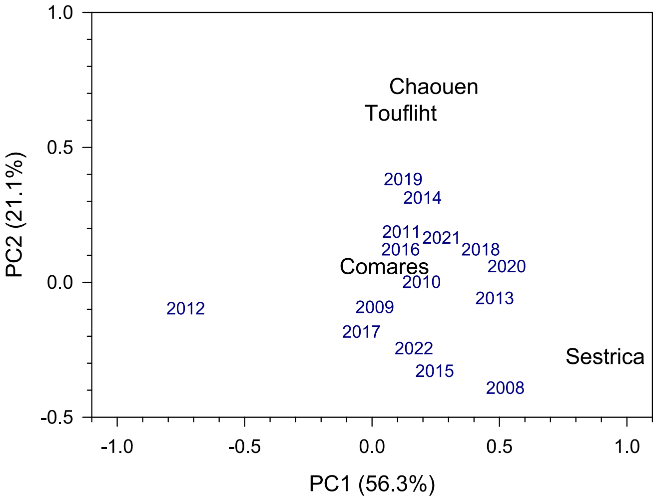

Fig. 3. Biplot showing the scores of the first (PC1) and second (PC2) principal components. Black symbols show the four study sites and blue symbols show the year of cork-ring width indices. The percentage of variance explained by each component is shown between parentheses.

3.3. Relationships between drought and cork-width indices

The highest correlation between the series of cork-width indices and the SPEI drought index ($r = 0.89$, $p = 0.00002$; slope = 0.35, 95 % bootstrapped confidence intervals: 0.24, 0.50) was found in Sestrica and correspond to the 14-month August SPEI (Fig. 5). In this site, strong correlations between cork and summer drought indices were observed at 1- to 24-month scales. In Comares, only the 2-month May SPEI showed a significant ($p < 0.05$) correlation with the cork indices ($r = 0.56$). Meanwhile, at the Moroccan sites, such positive and significant correlations between the series of cork-width indices and the SPEI were detected from June to August considering short SPEI time scales (1–4 months) in Chaouen ($r = 0.80$, slope = 0.28, 95 % bootstrapped confidence intervals: 0.18, 0.39) and Toufliht ($r = 0.67$). Interestingly, the slopes of linear regressions between SPEI and cork ring-width indices in the two sites showing the highest correlations (Sestrica and Chaouen) did not differ ($F = 0.79$, $p = 0.38$) suggesting a similar responsiveness of cork growth to water availability.

4. Discussion

Cork growth was mainly enhanced by wet-cool spring conditions, particularly in the driest sites (Sestrica, Toufliht). We found positive responses of cork ring width to wet conditions from the previous winter to summer, and also to warm conditions in the prior winter. Elevated summer temperatures and warm autumn conditions were associated to low cork growth indices, in agreement with previous studies (Caritat et al., 1996, 2000). High maximum summer temperatures tend to restrict cork formation, probably by increasing evapotranspiration rates and leading to drought stress, a phenomenon commonly observed among Mediterranean oak species (Corcuera et al., 2004; Alla and Camarero, 2012; Granda et al., 2014). These findings concur with irrigation experiments showing an increase in cork ring width and porosity (Poeiras et al., 2021). Conversely, in contrast to warm and dry summers, warm temperatures in the previous winter are associated to wider cork

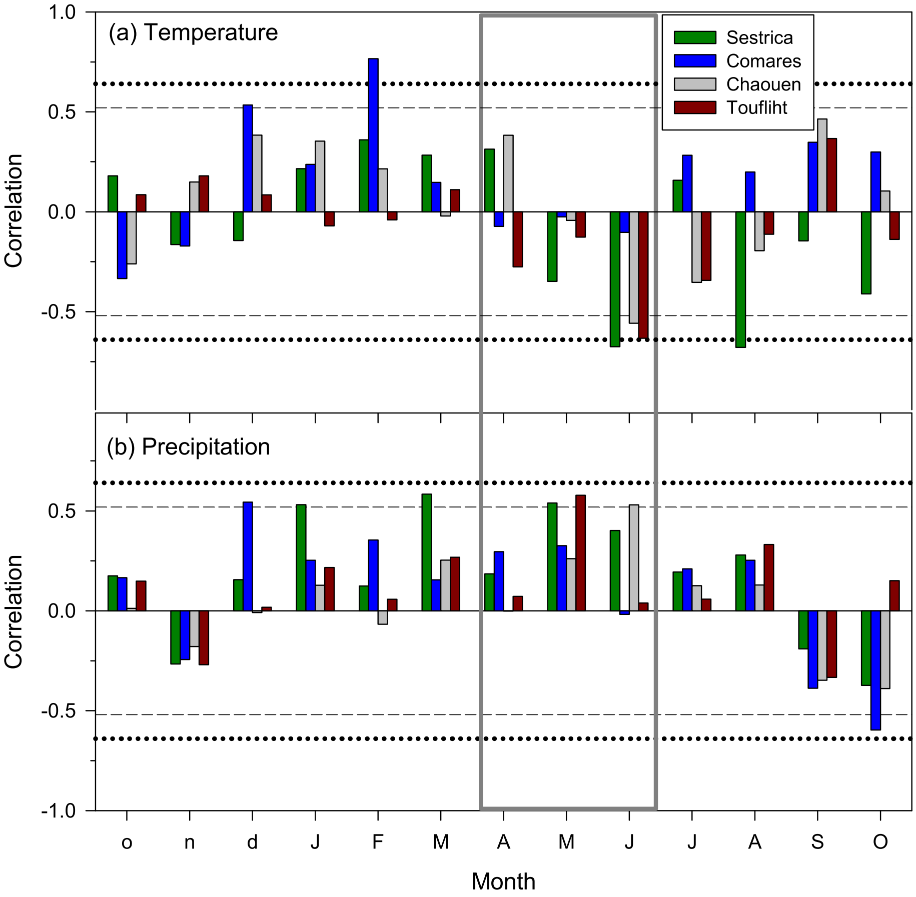

Fig. 4. Relationships (Pearson correlation) between monthly climate variables (a, mean temperature; b, total precipitation) and mean site series of indexed cork ring width. The dashed and dotted horizontal lines show the 0.05 and 0.01 significance levels, respectively. Correlations were calculated from the prior October (months of the previous year are abbreviated by lowercase letters) to the current October (months of the current year are abbreviated by uppercase letters). Cork growth mainly occurs from April to June (grey box).

rings (Ferreira et al., 1998; Oliveira et al., 2016), a response we found in the warm and wet Comares site, where an earlier onset of cork development can be expected. Overall, these findings show contrasting responses of cork growth to climate variables and drought severity as a function of site aridity.

As occur with the radial growth of cork oak (Costa et al., 2002), winter and spring precipitation enhance cork production, likely by recharging soil water reserves exhausted in summer (Pasho et al., 2011). Conversely, short- to long-term (2–16 months) summer droughts reduce cork growth (Oliveira et al., 2016). Therefore, the cumulative water balance in summer, heavily dependent on summer temperature and evapotranspiration rate but also on previous winter-spring precipitation, is critical for cork production. Thus, elevated summer maximum temperatures reduce cork production, as we found in both dry (Sestrica, Toufliht) and wet (Chaouen) sites. The negative impact of summer temperatures on cork production extended until August in the continental site (Sestrica). There, the onset of cork production might be delayed by cold winter conditions and then be negatively affected by early to late summer temperatures, inducing water loss and reducing phloem activity. This could explain the tight coupling we found in this site between cork-width indices and summer SPEI values, considering 10- to 16-month droughts as Oliveira et al. (2016) found. In contrast, these correlations peaked at shorter scales (1–4 months) in the other sites. This suggests that an accumulated negative water deficit is detrimental to cork production in continental, seasonally dry sites. Therefore, the precipitation during the hydrological year may serve as a suitable proxy for cork production in similar sites. Seasonal variations in cork growth between sites should be further investigated.

Overall, the high variability in cork-width indices and the strong negative responses of cork production to summer SPEI indicate that the relict Sestrica population was the most responsive to aridity in terms of cork production. For instance, in 2012, the cork-width index in this site was significantly lower than the 95 % confidence interval, and the 14-month August SPEI of that year recorded a value of −2.41, indicating an extreme or severe drought (cf. Vicente-Serrano et al., 2010). In Spain, the severe drought of 2012 negatively impacted the productivity of many forests, leading to the formation of narrow or even missing wood rings (Camarero et al., 2015; Zemrani et al., 2023), but probably also reducing cork production in sites with climate conditions similar to Sestrica. In fact, the 14-month August SPEI explained 79 % of the year-to-year variability of cork-width indices. Remarkably, cork porosity was the lowest in this arid site, suggesting that drought impairs cork production but not necessarily cork quality. Further research could analyze changes in cork porosity through time and relate it to changes in cork width and aridity in several sites given the remarkable cork quality found in the dry, isolated Sestrica site.

Despite the sensitivity of cork production to summer drought, cork growth also shows a rapid recovery after exceptionally dry years (Kurz-Besson et al., 2014; Oliveira et al., 2016). Similar to other oak species, cork oak can adapt by switching between a dominant use of shallow soil water sources to deep groundwater sources during the dry summer to maintain growth, also displaying hydraulic lift (Kurz-Besson et al., 2006; Otieno et al., 2006; David et al., 2007, 2013; Mendes et al., 2016). This resilience of cork oak could explain why the responsiveness of cork growth to drought severity, measured as the slope of SPEI-cork ring-width indices regressions, did not differ between the driest (Sestrica)

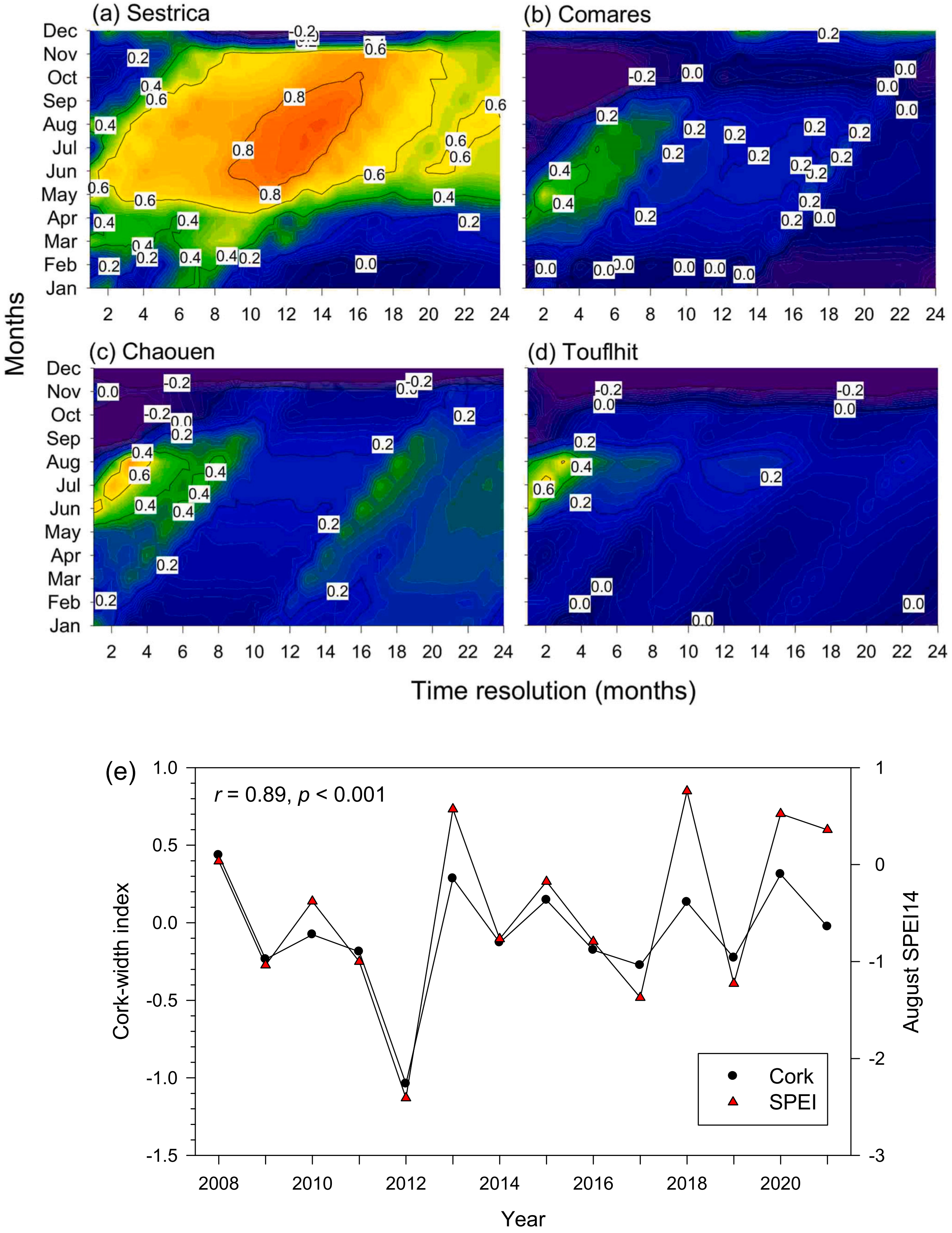

Fig. 5. Relationships (r, Pearson correlations) between monthly SPEI values, calculated at 1- to 24-month resolutions (x axes), and mean site series of indexed cork ring width in the study sites (plots a–d). Correlation coefficients higher than 0.52 are significant at the 0.05 level. The maximum correlation was obtained in Sestrica considering the 14-month SPEI in August (square in (a)) and it is shown in plot (e).

and wettest (Chaouen) sites. Nevertheless, prolonged and more severe droughts could reduce the cork resistance and negatively impact cork growth, particularly in recently debarked trees (Leite et al., 2019). Future studies could consider factors such as tree and cork ages, soil type, stand structure, past uses, and masting events due to resources allocation to reproduction.

The high within-site correlations among individual cork ring width series indicate we obtained robust site series of cork growth which contained climatic signal. The measured cork widths (ranging from 1.28 to 4.20 mm) are lower than those (2.60–3.67 mm) measured by Leite et al. (2019) in savanna-type “montados” in central-west Portugal. Several site-specific factors such as soil water holding capacity and tree-to-tree competition may explain these differences. Agroforestry cork oak systems are actively managed for cork production through cork harvesting and thinning. In general, mean values of cork ring width vary between 1.6 mm and 4.6 mm with an overall mean of 3.3 mm (Pereira, 2007; Lauw et al., 2018). Nevertheless, we sampled stands which have not been actively managed (coppiced, thinned, cork harvesting) for the past two decades. The lack of management could make them more responsive to changes in water availability if there is a strong competition among trees for soil water in spring and summer as climate shifts towards drier conditions (Kurz-Besson et al., 2014). Genetic differences among cork oak populations and hybridization with other oak species such as *Q. ilex* could also lead to different climate-cork relationships in Iberian and African sites (Lumaret et al., 2005). The E–W phylogeographic differences across the cork oak distribution area may explain the high drought-cork correlations found in Sestrica (Magri et al., 2007), but genetic analyses are needed to determine if this relict population is more similar to eastern (e.g. Italy, E. Spain) or western (e.g. Portugal, W. Spain) haplotypes.

Climate models forecast warmer and drier scenarios across the Iberian Peninsula in the late 21st century (Jacob et al., 2014). Warmer and drier spring and summers are expected to reduce cork harvests, and probably cork oak growth, in some areas of the main producing countries, particularly in continental, seasonally dry sites. A decrease in cork thickness would negatively impact cork stoppers production. Thus, adaptive management strategies aimed at enhancing the resilience of cork oak stands to climate warming should be implemented, including measures related to cork exploitation, such as reducing debarking intensity and extending the interval between debarking cycles (Palma et al., 2015). Considering new mesic areas for cork oak establishment and monitoring the responses to climate extremes of sensitive populations (e.g., Sestrica) to climate extremes should be also priorities. In addition, including information on cork-ring width variability and calculating long-term responses of cork production to climate would greatly improve regional assessments of cork quality and production (cf. Sánchez-González et al., 2023).

5. Conclusions

A negative summer water balance, driven by elevated temperatures and high evapotranspiration rates, is detrimental for cork production. This negative impact of dry-warm summers and long-term droughts on cork growth is more marked in continental, seasonally dry cork oak stands compared to wet, cooler sites. Such sensitive sites are not necessarily located near the southernmost distribution limit of cork oak in north western Africa. The precipitation during the hydrological year emerges as a suitable proxy for cork production in dry, continental sites. Further research is essential to better characterize cork growth responses to climate across different sites and to understand the underlying mechanisms behind these patterns. These assessments could be used as analogues for forecasting the impacts of increased aridification on cork production in the western Mediterranean basin.

CRediT authorship contribution statement

J. Julio Camarero: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ángela Sánchez-Miranda:** Writing – review & editing, Visualization, Software, Resources, Methodology, Investigation, Data curation. **Michele Colangelo:** Writing – review & editing, Visualization, Software, Resources, Methodology, Investigation, Data curation. **Luis Matías:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

Authors declare no conflict of interest.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.169574.

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