

Old oaks show increasing growth synchrony after pollarding cessation as climate becomes more arid

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ABSTRACT

Pollarded oak woodlands have been historically managed by people to produce firewood and timber. Pruning cessation and climate warming could contribute to their decline, especially in southern Europe under ongoing aridification. Widespread pollarding abandonment could make oaks more responsive to drought stress and increase between-site growth synchrony. To fill this research gap, we compared the basal area increment (BAI) trends and the responses of growth indices to climate variables and a drought index of formerly pollarded oak stands (five stands of *Quercus faginea*, one stand of *Q. humilis*) located in northern and eastern Spain. Radial growth indices were correlated with monthly climate variables (mean maximum and minimum temperatures, precipitation) and a multiscalar drought index. BAI was also projected based on recent trends to forecast stands viability in the 21st century. Major growth suppressions (MGS), which were attributed to pollarding, were reconstructed using dendrochronology. Wet-cool conditions from prior winter to current early summer improved oak growth. Year-to-year growth synchrony has increased since 1850 as summer conditions became more arid, but BAI did not significantly decline in four out of the six study sites. Synchrony among sites regarding MGS was low indicating a high spatial variability in oak pollarding. The strongest BAI decline was observed in La Guarguera site, where growth cessation was forecasted in the mid-21st century. In contrast, BAI data suggested strong growth improvement in sites Campillo de Dueñas and Valsalobre, which were pollarded in the 1960–1970s. These findings confirm that pollarding is a suitable management tool to keep vigorous old oak stands under more arid climate conditions.

1. Introduction

European forests and woodlands have been shaped by humans for centuries through logging, planting, coppicing, burning or pollarding (Rackham, 2008). Pollarded trees have longer lifespans than maiden trees and characteristic crown shapes creating unique landscape components which require appropriate conservation measures (Read, 2006; Camarero et al., 2022). Such monumental trees deliver unique ecological, social, cultural and economic values and provide habitats to many plant, lichen or animal species such as threatened saproxylic beetles (Ranius and Jansson, 2000).

In the case of Spain there is documentary evidence of pollarding in open oak woodlands (“dehesas”) since the 15th century (Guzmán-Álvarez, 2016). In such savanna-like “dehesas”, scattered trees were

pollarded or pruned by lopping branches at a certain height above the ground, out of the reach of livestock (Read, 2006, 2008). Harvested shoots were used for many purposes such as firewood, charcoal, timber and fodder, among others. Currently, there are about 3.5 million ha of oak woodlands in the Iberian Peninsula and they represent the largest agroforestry system in Europe (Eichhorn et al., 2006). They are dominated by oak species adapted to withstand summer drought and winter coldness (Montserrat-Martí et al., 2009), but also subjected to particular historical uses (Olano et al., 2023). For instance, pollarding was common in deciduous species such as *Q. faginea* Lam., whereas pruning was done in evergreen species such as *Q. ilex* L. (Camarero and Valeriano, 2023)

It is still unknown how pollarded oaks will respond to different components of global change including the abandonment of their

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traditional use (pollarding cessation) due to rural depopulation and recent climate warming (but see Camarero and Valeriano, 2023). Thus, a legacy-based, retrospective perspective is needed to gain a better understanding of climate–growth relationships in woodlands and forests facing changes in historical use and recent warming-triggered aridification (Mausolf et al., 2018; Vilà-Cabrera et al., 2023). Tree-ring data allow reconstructing changes in radial growth and pinpointing pollarding events (Rozas, 2004; Candel-Pérez et al., 2022) and how changes in pollarding frequency or intensity modify oak responses to climate (Rozas, 2005; Camarero and Valeriano, 2023; Olano et al., 2023). However, growth coherence among formerly pollarded oaks is still understudied, despite higher tree-to-tree and site-to-site growth synchrony being driven by stronger climate stress (Shestakova et al., 2016).

Forests show an increasing site-to-site growth synchrony in response to warmer and drier climate conditions as has been observed in Mediterranean pine stands (Sangüesa-Barreda et al., 2019). However, attributing changes in tree growth synchrony to particular environmental drivers such as drought stress is challenging because forests have been impacted by disturbances at different geographical scales (Shestakova et al., 2021). For instance, forests have shown higher growth synchrony in dry than in wet sites (Gazol et al., 2020) or as climate conditions become more arid at local to regional scales (Camarero et al., 2020). These authors suggested that climate warming may strengthen growth synchronization as climate aridification intensifies leading to growth decline. Nevertheless, disturbances can also uncouple growth from climate stress leading to changes in synchrony as found in frequently burned Siberian Scots pine (*Pinus sylvestris*) stands (González de Andrés et al., 2022). Therefore, historical forest uses such as pollarding could also uncouple growth from climate influences including drought stress.

Here, we test the hypothesis that pollarding abandonment and recent warmer and more arid conditions lead to higher growth synchrony among six oak stands from northern and eastern Spain. We address this question by fulfilling the following objectives: (a) to reconstruct growth suppressions in pollarded oak trees subjected to different pollarding history (severity, frequency) and aridity intensity, (b) to evaluate climate-growth relationships focusing on drought as the main climate stressor, and (c) to quantify changes in growth synchrony among the study stands. We expect a lower growth (hypothesis H1) and a higher growth synchrony (hypothesis H2) as climate becomes warmer and drier after widespread pollarding abandonment during the second half of the 20th century in rural Spanish areas.

2. Material and methods

2.1. Study sites and oak species

Six study sites located in northern and eastern Spain where formerly pollarded, apparently old oaks abound were selected (Table 1, Fig. 1). They are “dehesas” used in the past for grazing and where deciduous oaks were formerly pollarded to obtain firewood and timber. All sites are dominated by the Mediterranean Portuguese oak (*Q. faginea* Lam.), except the La Guarguera site (hereafter GU site), where the sub-Mediterranean *Quercus humilis* subsp. *subpyrenaica* (Villar) Rivas Mart. & C.Saenz, the hybrid between *Q. faginea* and *Q. humilis* Mill. (Himrane

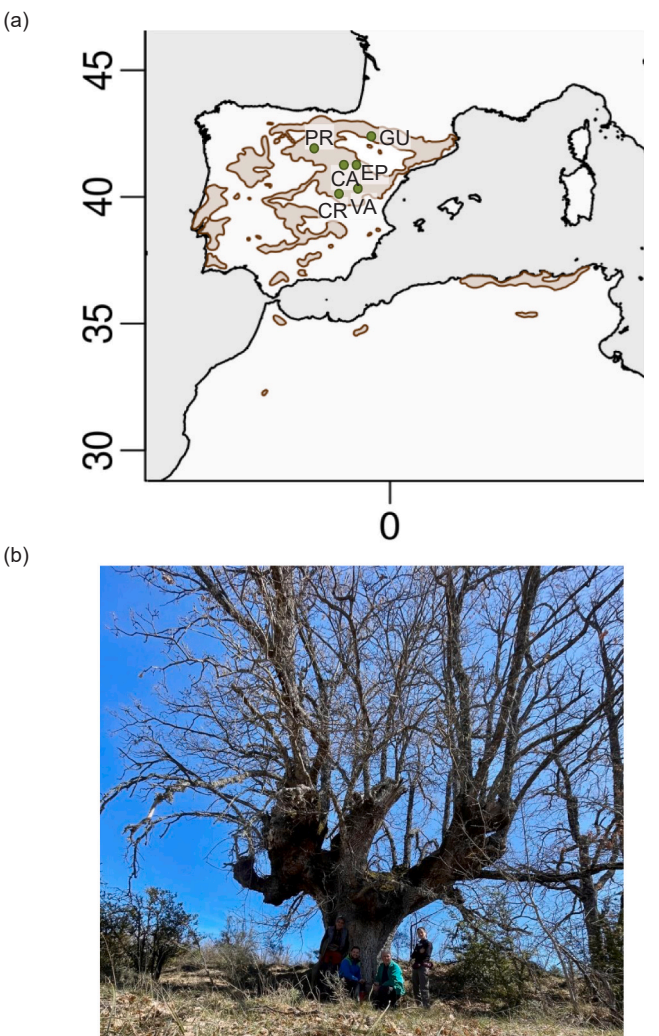


Fig. 1. (a) Location of sampled sites in northern and eastern Spain and distribution area (brown patches) of *Q. faginea* in the western Mediterranean Basin. (b) View of a formerly pollarded oak sampled in site GU with part of the research team and collaborators.

et al., 2004), was sampled. In this site and also in Pradillo (hereafter PR site) oaks are often found isolated or near villages, near formerly cultivated terraces. In site GU, oaks are surrounded by dense pine (*Pinus nigra* J.F. Arn.) plantations, and some show partial canopy dieback with abundant dead branches. In the other sites oaks are located in “dehesas” near croplands. In sites El Pedregal (hereafter EP site) and Campillo de Dueñas (hereafter CA site) *Q. ilex* and *Q. pyrenaica* trees grow near sampled *Q. faginea* individuals, respectively. In sites Carrascosa (hereafter CR site) and Valsalobre (hereafter VA site), oaks co-occur with big, formerly tapped *P. nigra* trees.

The study sites are subjected to Mediterranean and continental conditions. According to 4-km gridded climate data (Abatzoglou et al., 2018) and estimated values of the aridity index (ratio between annual

Table 1
Characteristics of the six study sites. AI is the aridity index.

Site (code)	Latitude °N	Longitude °W	Elevation (m a.s.l.)	Mean annual temperature (°C)	Total annual precipitation (mm)	AI
La Guarguera (GU)	42.408	0.280	845	12.1	790	0.96
Pradillo (PR)	42.180	2.637	925	10.7	698	1.10
El Pedregal (EP)	40.789	1.556	1230	10.2	615	1.04
Campillo de Dueñas (CA)	40.855	1.674	1145	10.3	620	1.03
Carrascosa (CR)	40.594	2.147	1303	11.3	581	0.86
Valsalobre (VA)	40.625	2.123	1355	11.2	565	0.84

precipitation and reference evapotranspiration; Zomer et al., 2022), PR is the wettest site and VA is the driest site. In all sites, there is a period of summer drought. This dry period is shorter at sites GU and PR (July) than at sites EP and CA (July, August), and CR and VA (mid June to September) (Fig. S1). Seasonal precipitation peaks in spring and late autumn. Winters are cold. Frosts are frequent and can occur from early October to early May with a frost-free period of just 150 days (García-Martín et al., 2021). To characterize site aridity, the aridity index (AI), i.e. the ratio between annual precipitation and reference evapotranspiration, was calculated (Zomer et al., 2022). Values of AI > 0.65 correspond to humid climate conditions as those found in sub-Mediterranean regions such as the study area (Table 1).

In the GU site, soils are acid and develop on shales with *Buxus sempervirens* L., *Genista scorpius* (L.) D.C., *Rhamnus* spp. and *Rosa canina* L. dominating the understory. In site PR, soils are basic and the main shrub species is *Juniperus communis* L. In sites EP, CA, CR and VA soils are also basic with clay texture and the most abundant shrubs are *Crataegus monogyna* Jacq., *G. scorpius* and *Cistus laurifolius* L.

There is historical evidence of oak pollarding in “dehesas” at least since the late 15th century in site EP (Cortés-Ruiz, 2000). In the study sites, the traditional pollarding of mature deciduous oaks was done every 10–20 years, but this use was mostly abandoned during the 1950s and 1960s when most rural population migrated to cities (Collantes and Pinilla, 2011). In those decades, timber extraction rapidly decayed and lost its role as the main bioenergy source being rapidly replaced by coal, gas, oil and other fossil fuels (Infante-Amate and Iriarte-Goñi, 2017).

2.2. Climate data and drought index

To assess climate-growth relationships, we obtained monthly climate data (mean maximum and minimum temperatures, total precipitation; period 1958–2020) from the 4-km gridded Terraclimate dataset (Abatzoglou et al., 2018). To assess drought-growth relationships, we obtained 0.5°-gridded monthly data of the multi-scalar Standardized Precipitation Evapotranspiration Index (SPEI) drought index (Vice-Serrano et al., 2010). The SPEI considers the effect of temperature and evapotranspiration on a cumulative water balance. It was calculated for 1- to 24-month-long scales with negative and positive values indicating dry and wet conditions, respectively. SPEI data were obtained from the SPEI Global Drought Monitor webpage (<https://spei.csic.es/>). Sites CA and EP and sites CR and VA were located in the same 0.5° grids.

To obtain a long-term (1500–2010) perspective of changes in drought severity a 0.5°-gridded reconstruction of summer (June to August) drought intensity based on the Palmer Drought Severity Index (PDSI) was obtained (Cook et al., 2015). The PDSI data were downloaded from the webpage <http://drought.memphis.edu/OWDA/>. A regional PDSI series was obtained by averaging the site PDSI series.

2.3. Field sampling and dendrochronological methods

Sampling was done during autumn or winter from October 2022 to March 2024, excepting site PR which was sampled in October 2015. Sampled trees were monumental, formerly pollarded trees. To characterize post-pollarding growth improvement, we also sampled 10 individuals recently pollarded in sites CA and VA. Trees were pollarded in the late 1960s and early 1970s. Two cores were extracted from each tree at 1.3 m above ground level using a 5-mm Pressler increment borer (Häglof, Sweden). We measured the diameter at breast height (dbh, measured at a height of 1.3 m) of each sampled tree using tapes. The total tree height was measured using a laser rangefinder (Nikon Forestry Pro 550 hypsometer). Bark thickness was also measured using a bark gauge to correct the estimates of basal area increment (BAI).

Cores were taken to the laboratory, air-dried, glued to wooden mounts and surfaced with progressively finer grades of sandpaper for detecting the ring boundaries (Fritts, 1976). Sanded cores were scanned at 2400 dpi resolution and visually cross-dated. Then, ring widths were

measured with a 0.001 mm resolution using scanned images and the CooRecorder-CDendro software (Larsson and Larsson, 2018). The quality of cross-dating was checked using the COFECHA software which calculates moving correlations between individual series of ring-width values and the mean sites series (Holmes, 1983).

2.4. Processing tree-ring width data: major growth suppressions

To estimate tree age at 1.3 m we used graphical methods in most cores since they presented innermost, curved rings, but did not reach the pith which was often rotten. The length of the missing radius was estimated as the difference between the geometric radius, after removing bark thickness, and the total core length (Norton et al., 1987). Then, the number of inner missing rings was estimated by extrapolating the mean radial growth rate from the innermost ten rings. In the case of very hollow stems (20 % of samples), the length of the missing radius was calculated by considering the bark thickness, the trunk diameter and the sum of all measured rings in the longest core.

To assess growth trends, tree-ring width data were converted into BAI assuming concentric radial growth. In addition, 3rd-order polynomials were fitted to BAI data to forecast BAI in the 21st century as a preliminary evaluation of long-term growth trends. To calculate climate- and drought-growth correlations tree-ring width series were first detrended. Each series was detrended by fitting x-year cubic smoothing splines with a 50 % frequency response cut-off to individual ring-width series, where x was 2/3 of the mean series length (Cook, 1985). Observed ring-width values were divided by fitted values. The resulting series of dimensionless ring-width indices (RWIs) were pre-whitened by fitting autoregressive models, and bi-weight robust means were computed to obtain residual site series chronologies preserving annual to decadal variability. We calculated the first-order autocorrelation (AC1) and the mean sensitivity (MS) to characterize the persistence of raw ring-width series and the year-to-year variability of RWI series, respectively. The rbar (mean correlation between series) was also obtained. Calculated over the common 1850–2022 period (1930–2015 in site PR; Table 2), an Expressed Population Signal (EPS) over 0.85 indicates a high common signal in all study sites (cf. Wigley et al., 1984).

To estimate periods of growth suppression, negative growth changes (NGC) were calculated following Nowacki and Abrams (1997):

$$NGC = [(M1 - M2)/M2] \times 100 \quad (1)$$

where M1 and M2 are previous and subsequent 10-year ring-width medians calculated on individual series and shifted every year. We focused on major growth suppressions (MGS) calculated for each stand. MGSs were defined considering a 50 % threshold in NGCs observed in at least 50 % of trees in each stand (Camarero et al., 2022; Camarero and Valeriano, 2023). The NGC series were obtained for periods with at least 10 sampled trees. Since the annual frequencies (f) of MGSs change as annual sample size (number of measured trees, n) does, corrected MGS frequencies (f_c) were obtained following Osborn et al. (1997):

$$f_c = f \times n^{0.5} \quad (2)$$

To detect periods of abrupt growth reductions and to characterize their temporal variability, we calculated several statistics related to MGSs for the common period 1790–2022 such as the mean, standard deviation, coefficient of variation (CV), maximum, trend and periods with the highest MGS (frequency of trees showing MGS > 10 %).

To assess changes in between-site similarity of the series of major growth suppressions, correlations (r_s, Spearman coefficients) were calculated considering 20-year-long intervals. Then, a regional average series of correlations of major growth suppressions site series was obtained.

Table 2

Tree size and tree-ring width data with related statistics. The dbh is the diameter at breast height, BAI is the basal area increment, AC1 is the first-order autocorrelation, MS is the mean sensitivity, and rbar is the mean correlation between series. Values are means $\pm$ SE. Different letters indicate significant ($p < 0.05$) differences in size or growth rates between sites.

Site	dbh (cm)	Height (m)	No. trees/ cores	Timespan	Tree-ring width (mm) ^a	BAI ^a (cm ² yr ⁻¹)	BAI trend ^b (p)	AC1	MS	rbar ^b	EPS $\geq$ 0.85 (period)
GU	126.4 $\pm$ 11.0c	13.5 $\pm$ 2.0b	18/30	1712–2022	1.09 $\pm$ 0.53b	8.21 $\pm$ 0.17c	– 0.36 (< 0.001)	0.76	0.23	0.30	0.88 (1850–2022)
PR	62.0 $\pm$ 8.1b	8.7 $\pm$ 1.6a	11/21	1752–2015	1.15 $\pm$ 0.70b	16.25 $\pm$ 0.36d	– 0.11 (0.035)	0.80	0.23	0.27	0.85 (1930–2015)
EP	51.7 $\pm$ 7.0a	8.8 $\pm$ 1.5a	25/43	1748–2022	0.83 $\pm$ 0.47a	5.30 $\pm$ 0.22b	0.23 (< 0.001)	0.64	0.30	0.36	0.89 (1850–2022)
CA	59.9 $\pm$ 8.0a	8.2 $\pm$ 1.7a	16/29	1710–2022	0.78 $\pm$ 0.46a	4.81 $\pm$ 0.27a	0.78 (< 0.001)	0.71	0.28	0.35	0.90 (1850–2022)
CR	63.8 $\pm$ 4.9b	8.5 $\pm$ 1.3a	11/17	1742–2023	0.90 $\pm$ 0.42b	5.69 $\pm$ 0.19b	0.36 (< 0.001)	0.72	0.22	0.28	0.86 (1830–2023)
VA	68.6 $\pm$ 4.8b	8.4 $\pm$ 1.4a	12/23	1745–2023	0.98 $\pm$ 0.45b	6.78 $\pm$ 0.31c	0.58 (< 0.001)	0.71	0.24	0.26	0.85 (1850–2023)

^a Mean $\pm$ SD calculated for the period 1750–2015.

^b Calculated for the period with EPS $\geq$ 0.85.

2.5. Statistical analyses and synchrony

To compare the two growth variables (ring width, BAI) or tree diameters between sites we used non-parametric Mann-Whitney tests. Trends in MGS and moving climate- and SPEI-correlations were assessed using the Kendall τ statistic.

Synchrony among site chronologies was calculated using 20-year moving correlations (rbar₂₀) and compared to Euclidean distances between sites (Shestakova et al., 2016). To account for changes in annual sample size (number of measured trees), an estimate of relative synchrony (α) was calculated for each site (Cronbach, 1951):

$$\alpha = n \text{ rbar}_{20} / (1 + (\text{rbar}_{20} (n - 1))) \quad (3)$$

where n is the maximum number of measured trees in every 20-year interval. Cronbach's α values above the 0.70 threshold are considered to indicate good internal consistency (Cho and Kim, 2015).

To summarize changes in relationships among site series of growth indices through time, we calculated Principal Component Analyses (PCAs) on the variance-covariance matrix of residual chronologies considering three periods (1850–1899, 1900–1949 and 1950–2015). We also obtained the standard deviation of the first principal component (PC1), years with the lowest and highest PC1 scores and sites with the highest loadings on the PC1 and second principal component (PC2).

Finally, climate-growth relationships were calculated by relating site residual chronologies and monthly climate variables (mean maximum and minimum temperatures, precipitation) using Pearson correlations and from prior to current September. To evaluate if climate-growth associations were unstable through time, moving correlations between sites chronologies and climate variables or drought indices (SPEI, PDSI) were calculated along 20-year moving intervals.

All analyses were carried out using the R statistical package (R Development Core Team, 2023). The dplR package was used to process dendrochronological data including detrending and the calculation of statistics (Bunn, 2008, 2010, Bunn et al., 2023). The NGCs were calculated using the TRADER package (Altman et al., 2014). The vegan package was used to calculate the PCA (Oksanen et al., 2024). The “dcc” function from the treeclim package was used to calculate correlations between climate variables or SPEI and series of ring-width indices (Zang and Biondi, 2015).

3. Results

3.1. Growth patterns of pollarded oaks

Sampled oak trees showed the widest and narrowest diameters in sites GU and EP, respectively (Table 2). The tallest trees were also found in site GU. The highest growth rates were measured in sites GU and PR, which also showed high first-order autocorrelation (AC1) values. The sites EP and CA showed the lowest mean BAI values, but the highest

mean sensitivity (MS) and rbar values indicating a high responsiveness to climate and high internal coherence, respectively. All sites presented EPS $\geq$ 0.85 since 1850, excepting PR which showed it after 1930.

The mean diameter and age values of all sampled oaks were 68 cm and 206 years, respectively (Fig. S2). The maximum diameter and age values were 170 cm and 313 years, respectively. Age at 1.3 m was predicted based on diameter (dbh) data using a logarithm function (age = $-53.38 + 62.86 \ln(\text{dbh})$, $r = 0.56$, $p < 0.001$), albeit the fit did not capture well some trees from sites EP and CA which showed small diameters (50–70 cm) but elevated ages (250–300 years).

All sites showed significant positive BAI trends since 1850, reaching a maximum value in site CA ($\tau = 0.78$), excepting GU and PR (Table 2). Site PR showed the highest BAI values until a general BAI reduction in the 1950s (Fig. 2a). Site GU also showed high BAI values until the early 20th century, when it started a long-term BAI decline. Sites VA and CR showed intermediated BAI values with CR presenting BAI increases from ca. 1900–1970. Sites EP and CA showed the lowest BAI values until the 1970s. There was a noticeable increase of BAI in the recently pollarded CA site. Regarding ring-width indices, there were periods of high (e.g., 1910s, 1970s, 2000s) and low (e.g., late 19th century, 1920s, 1930s) year-to-year variability (Fig. 2b).

3.2. Growth synchrony

We found a higher similarity or shared common variance (PC1) among indexed sites growth series in 1950–2015 (53.9 %) than in 1850–1899 (36.2 %) (Table 3). In the most recent period, there was also a higher standard deviation of PC1 scores indicating higher growth variability which was linked to sites EP and CA showing the highest PC1 and PC2 loadings, respectively. The highest and lowest correlations among chronologies in 1950–2015 corresponded to sites VA–CR and GU–CA, respectively (Table S1).

The regional series (average) correlation among site series significantly increased ($\tau = 0.63$, $p < 0.001$) since 1850, whereas the summer PDSI decreased ($\tau = -0.31$, $p < 0.001$) (Fig. 3a). Therefore, these two variables showed a significant and negative ($r_s = -0.30$, $p = 0.0003$) correlation. This negative relationship was not stable through time, being significant from 1885 to 1958 (results not presented). In addition, the regional correlation and RWI means, both calculated for 20-year running periods, were positively related ($r_s = 0.20$, $p = 0.01$). Considering site-to-site correlations, all showed significant ($p < 0.001$) positive trends, excepting the pairs GU–CR and VA–CR. Maximum and minimum regional correlations were found in the 2010s and 1870s, respectively. Other remarkable decades with high and low regional correlations were the 1980s and 1920s, when the maximum ($r = 0.81$, sites CA–VA) and minimum correlations were found ($r = -0.40$, sites GU–PR), respectively.

The relationship between site-to-site correlations and distances peaked in the 1940s and 1950s indicating a stronger spatial

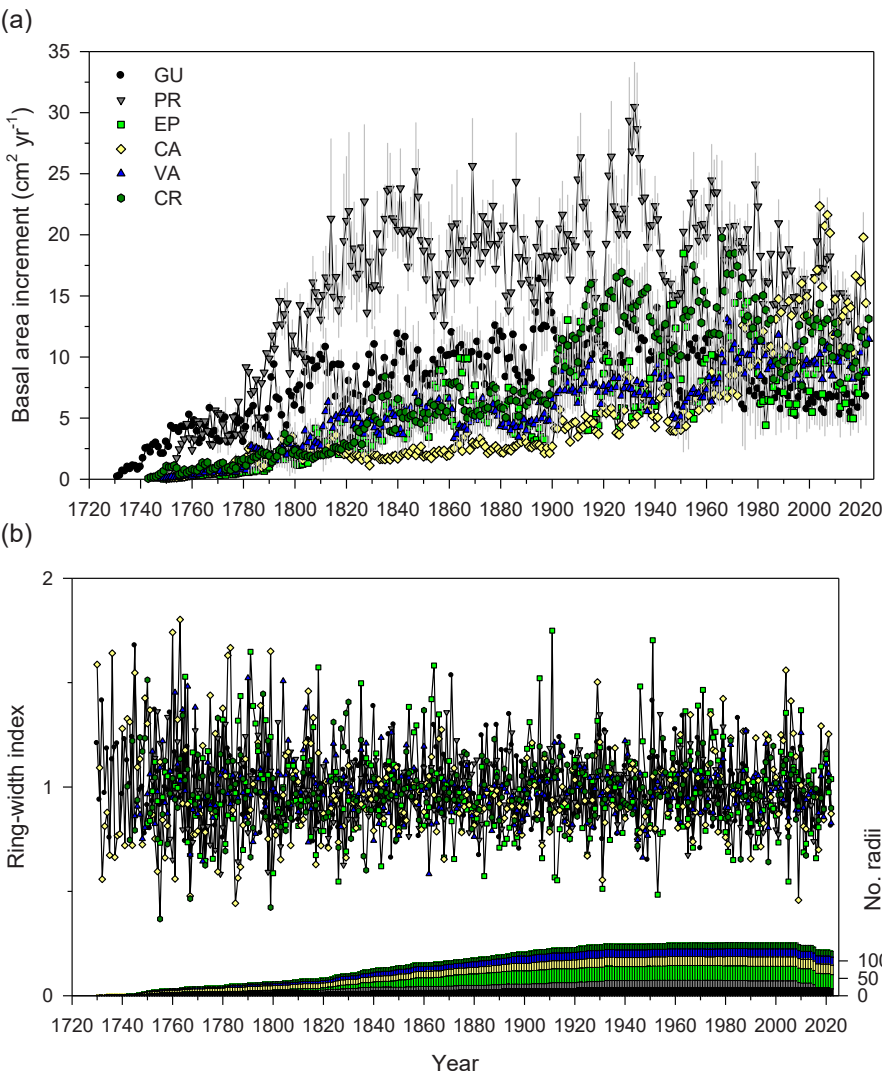


Fig. 2. (a) Basal area increment values measured in the six study sites. Values are means $\pm$ SD. (b) Series of ring-width indices and annual number of measured radii. Most sites showed reliable and well-replicated series since 1850.

Table 3
Variance explained by the first (PC1), and second (PC2) principal components of PCAs calculated on the variance-covariance matrix of residual ring-width chronologies considering three periods. The last two columns show sites and years with the highest or lowest loadings and scores along the PC1 and PC2 axes.

Period	PC1 (%)	PC2 (%)	Standard deviation of PC1 scores	Sites with highest PC1/PC2 loadings	Years with lowest/highest PC1 scores
1850–1899	36.2	26.8	0.22	EP/GU	1884/1864
1900–1949	48.6	17.9	0.28	EP/CA	1931/1946
1950–2015	53.9	15.7	0.31	EP/CA	2005/1951

configuration of growth synchrony, whilst minimum values were found in the late 19th century (Fig. 3b). The relationships between correlations and site-to-site distances were negative since the 1970s indicating negative spatial autocorrelation, i.e. closer sites showed dissimilar growth variability.

3.3. Major growth suppressions

The sites with the highest and lowest MGS mean frequencies were EP (20.2 %) and VA (8.6 %), respectively (Table 4). Consequently, they also

showed the highest and lowest SD and maximum MGS values, but the highest CV of MGSs corresponded to site CA (140.2 %) and the lowest one to site GU (78.1 %). All sites presented significant ($p < 0.05$) negative trends in MGS, excepting sites EP and GU. In sites PR, CA and VA, MGSs peaked in the 1810s and 1820s, whereas in sites GU and EP they did it in the 1870s. In site CR, MGSs reached a maximum value in the 1930s.

Several decades presented high frequencies of MGSs such as the 1810s, 1820s, 1840s, 1870s, 1910s, 1930s, 1940s and 1980s (Fig. 4a). Overall, synchrony among sites regarding MGS was low and peaked in the 1990s (Fig. 4b). Synchrony among MGSs site series was very low in the 1840s and 1930s. There were three decades with both high mean values of MGSs and high correlations between sites series of MGSs: 1820s, 1910s and 1980s.

3.4. Responses of growth indices to climate and drought

Warm conditions in prior winter (sites GU and CR), spring (sites PR, EP and VA) and summer (sites GU and CR) constrained growth (Fig. 5). High maximum and minimum January temperatures improved growth in site CA. In sites PR and CR, growth also decreased as spring, summer and early autumn minimum temperatures increased. High precipitation from the prior winter to summer enhanced growth, particularly in site

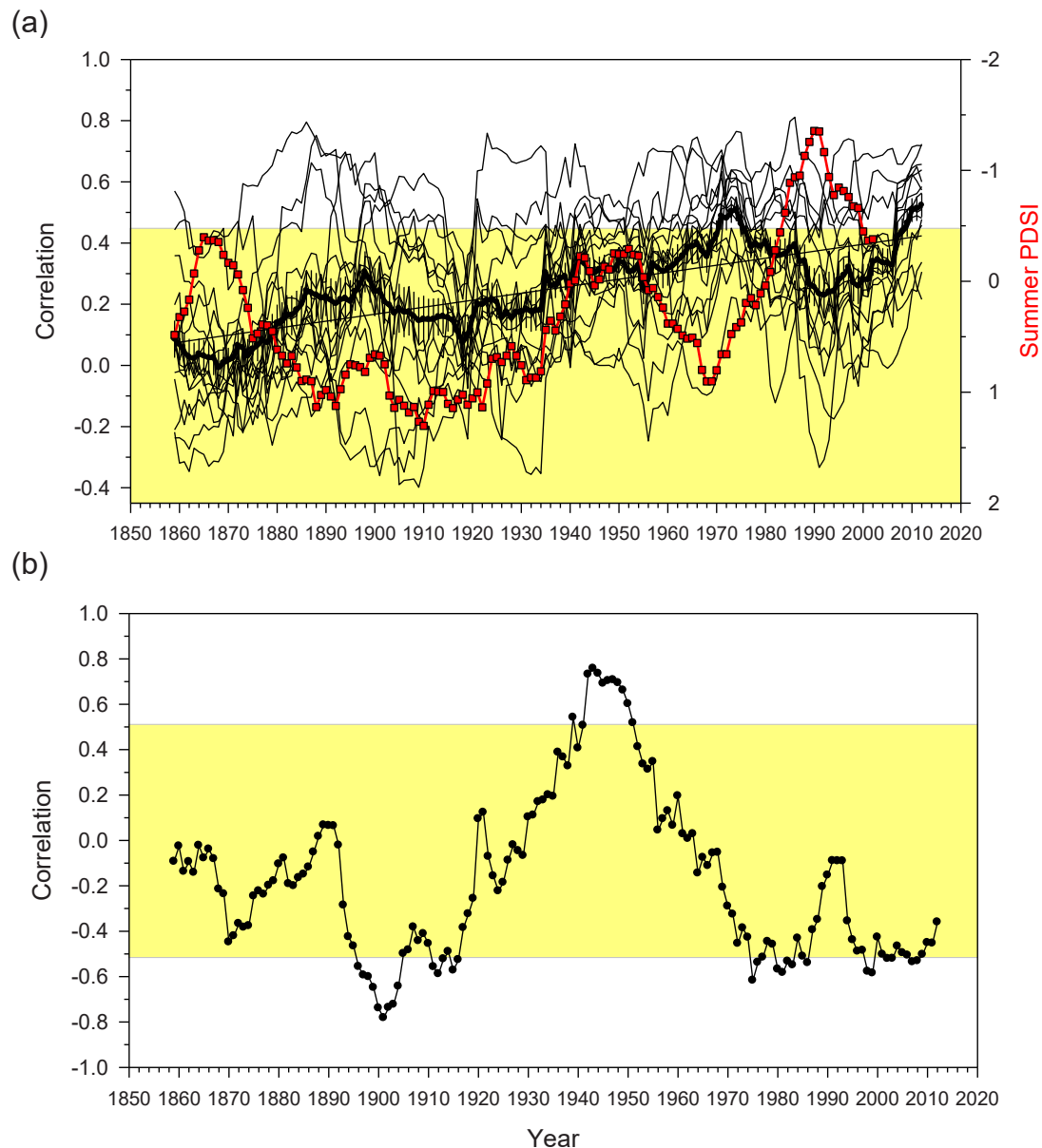


Fig. 3. (a) Paired correlations between sites chronologies (thin black lines) and regional correlation (black line with symbols, mean $\pm$ SE) and summer PDSI (red line with symbols). In both variables, linear regressions are fitted to indicate their trends. (b) Correlations between the vectors of site-to-site growth correlations and Euclidean distances (in km). Correlations (Pearson coefficients) were calculated for 20-year long intervals lagged year by year and using residual tree-ring chronologies. Values located outside the yellow stripes are significant ($p < 0.05$).

EP.

Sites EP and CA showed the highest correlations of growth indices with the June SPEI values for 6- ($r = 0.57$) and 7-month ($r = 0.54$) scales, respectively (Fig. 6). Sites VA and PR showed similar highest correlations ($r = 0.48$ and $r = 0.47$), but at very different scales (11-month October and 5-month June SPEIs, in that order), whilst sites CR and GU showed the lower maximum correlations ($r = 0.41$).

Since 1950, correlations between growth indices and April to June summed precipitation or SPEI changed through time (Fig. S3). The precipitation-growth correlation strengthened in site CA, but weakened in sites PR and CR. The SPEI showed an increasingly stronger influence on growth in sites CA and VA, but correlations decreased in site CR. In a longer temporal context and considering the summer PDSI, growth was more constrained by summer drought since the dry 1980s and 1990s in sites EP and CA (Fig. S4).

Regarding long-term changes in growth synchrony, sites EP and CA

and sites VA and CR presented the highest and lowest r_{bar} or α values, respectively, with GU and PR showing intermediate values (Fig. S5). Synchrony and summer PDSI were not significantly related excepting in sites VA, CR and PR, where negative correlations were found since the 1980s (Fig. S6).

3.5. BAI projections for the 21st century

Cubic functions were fitted to site BAI series (see also Table S2 and Fig. S7). The derived BAI projections for the 21st century suggested that site GU would show the most negative BAI, whereas forecasts for site CA indicate increasing BAI (Fig. 7). Sites CR-EP and VA showed negative and positive BAI projections, respectively, whereas in site PR, BAI projections were relatively stable.

Table 4

Summary of statistics related to major growth suppressions (MGS) detected in each site. Values correspond to the common period 1790–2022. In the last column, the character in bold shows the year with the highest MGS (frequency of trees showing MGS > 10 %). Significance levels of trends: $p < 0.05^*$, $p < 0.01^{**}$, and $p < 0.001^{***}$.

Site	Mean (%)	SD (%)	CV (%)	Maximum (%)	Trend, Kendall τ	Years with MGS peaks
GU	11.14	8.70	78.07	38.89	−0.01	1816, 1852, 1875 , 1901, 1965, 1992
PR	13.74	13.50	98.28	50.00	−0.30*	1819 , 1851, 1915, 1942, 1980
EP	20.17	21.40	106.09	73.81	−0.05	1871 , 1910, 1953, 1980
CA	10.59	14.84	140.17	66.67	−0.12*	1822 , 1872, 1922, 1944, 2008
CR	8.81	10.89	123.61	37.50	0.14**	1838, 1924, 1938 , 1961
VA	8.64	8.15	94.37	28.57	−0.42***	1828 , 1855, 1919, 1979

4. Discussion

The presented findings shed light on long-term interactions between historical forest use and growth responses to climate variability. The observed increase in growth synchrony among pollarded oak woodlands in Spain following pollarding abandonment during the mid-20th century underscores the profound impact of past human activities on current forest structure and dynamics. Pollarding left a legacy effect on growth synchrony influencing responses to climate and drought stress.

We found that site-so-site or regional growth synchrony of the study pollarded oak stands strengthened as climate became more arid apparently supporting hypothesis H2. However, this did not lead to growth decline. So, hypothesis H1 was not supported. In fact, growth indices and synchrony were positively related suggesting that the long-term negative relationship between aridity and synchrony was not stable through time. Therefore, H2 was not fully supported because the negative association between summer aridity and synchrony lasted from the late 19th century up to the 1960s, but relaxed afterwards. This could be explained because other climate drivers became more important and improved oak growth in some sites after pollarding cessation, such as warmer January temperatures in site CA. In addition, the spatial uncoupling of regional growth synchrony after the 1970s could be related to wet-cool conditions during that decade and the local

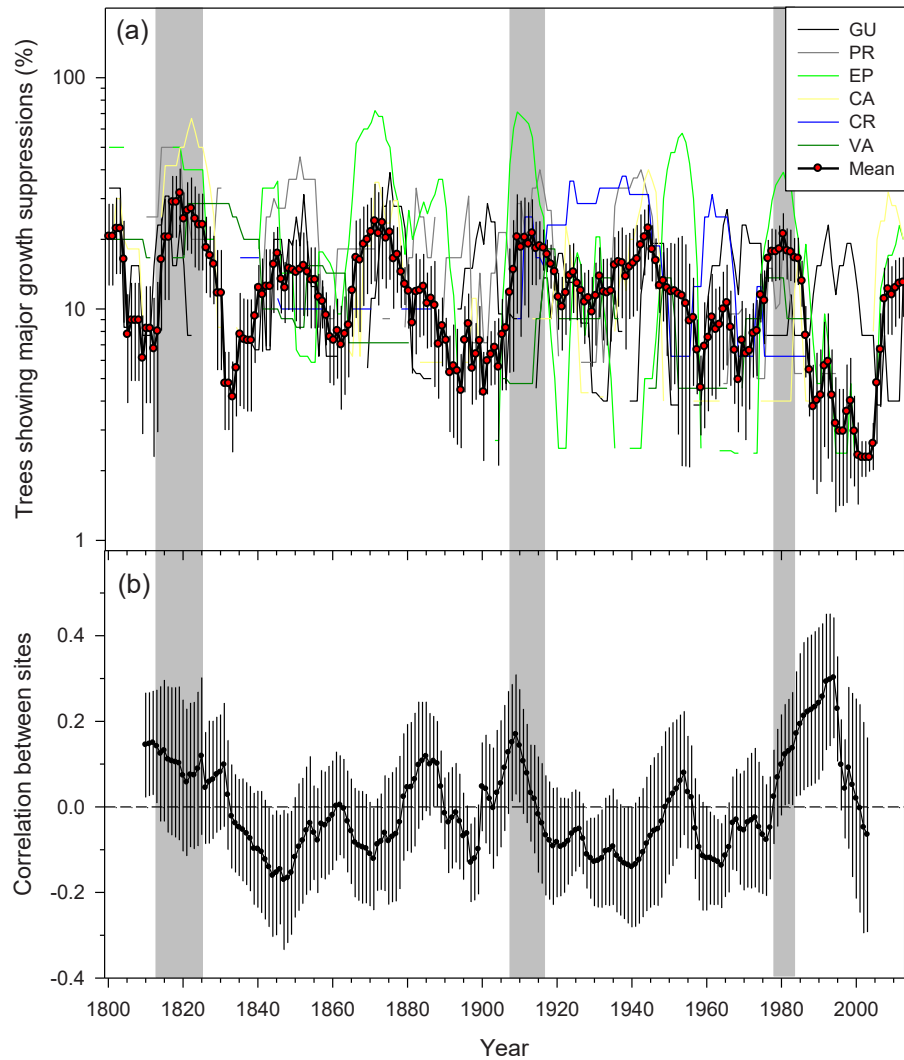


Fig. 4. Patterns of major growth suppressions (MGSS) and correlation calculated among sites. (a) Site and regional series (line with red symbols) of MGSS. (b) Mean correlation (Spearman coefficients, mean $\pm$ SE) calculated between site series of MGSS. Grey areas highlight periods with high values of both mean MGS and correlations between sites series of MGSS.

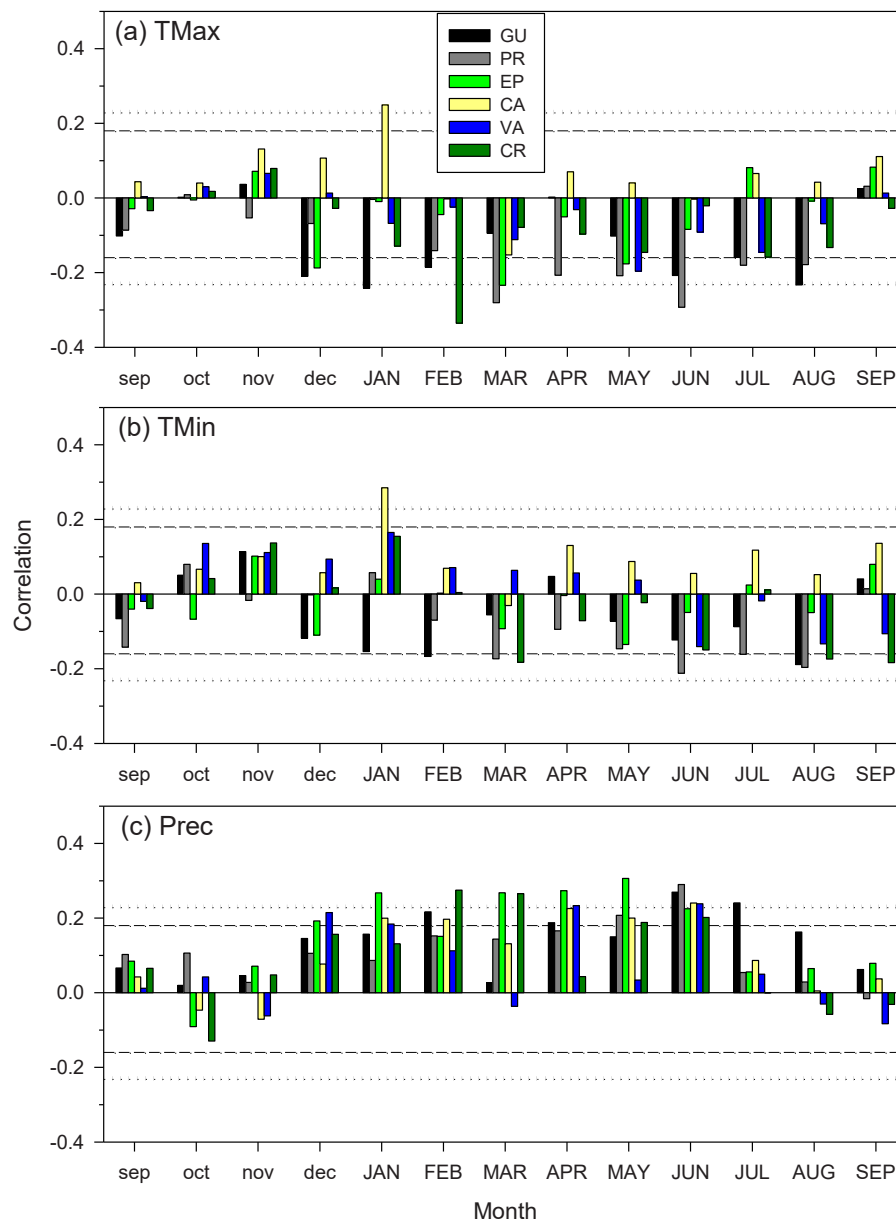


Fig. 5. Climate-growth relationships (Pearson correlations) obtained by relating monthly climate variables (a, TMax, mean maximum temperature; b, TMin, mean minimum temperature; c, Prec, precipitation) and mean series of ring-width indices. The window of analyses goes from the previous September to the current September with months of the current year being abbreviated by uppercase letters. The horizontal dashed and dotted lines show the 0.05 and 0.01 significance levels, respectively.

pollarding performed in some sites (CA, VA).

The BAI trends since 1850 and the fitted 3rd-order polynomial functions indicate that sites GU and CA showed the worst and best growth scenarios. In site GU, canopy dieback is apparent in several trees which grow near dense pine stands. These plantations may reduce soil moisture during summer when growth in GU depends on precipitation. In contrast, the improved growth of the recently pollarded site CA could explain why its growth positively responded to winter temperature, which could be related to a better transport or transformation of non-structural carbohydrates prior to cambium resumption in spring (Alla and Camarero, 2012). Interestingly, the positive growth response to growing-season precipitation strengthened in site CA, indicating that pollarding not only enhanced growth but could have coupled growth with precipitation variability in the mid-term. The positive correlation between April to June precipitation or SPEI and growth indices has been found before in the study Mediterranean oak species (Alla and

Camarero, 2012; Vieira et al., 2022; Tonelli et al., 2023). Severe winter-to-spring droughts reduce oak growth and can trigger canopy dieback in *Q. faginea* (Corcuera et al., 2004; Camarero et al., 2016). Pollarding could partially alleviate this drought stress in the case of the study old oaks and this could be tested by analyzing C isotope ratios ($^{13}\text{C}/^{12}\text{C}$) in tree-ring wood.

Among the oak stands with moderately pessimistic growth scenarios for the 21st century, sites EP and CR illustrate contrasting patterns. First, growth in site EP was increasingly synchronized and showed a higher dependence on summer drought in agreement with hypothesis H2. Sites GU and PR also presented higher synchrony driven by increasing drought severity. Second, growth in site CR showed moderate synchrony and a weakening of its relationship with spring precipitation and drought, but its synchrony was negatively influenced by drought as in sites VA and PR. Therefore, growth synchrony within each oak stand does not only depend on climate, but could also be driven by alternating

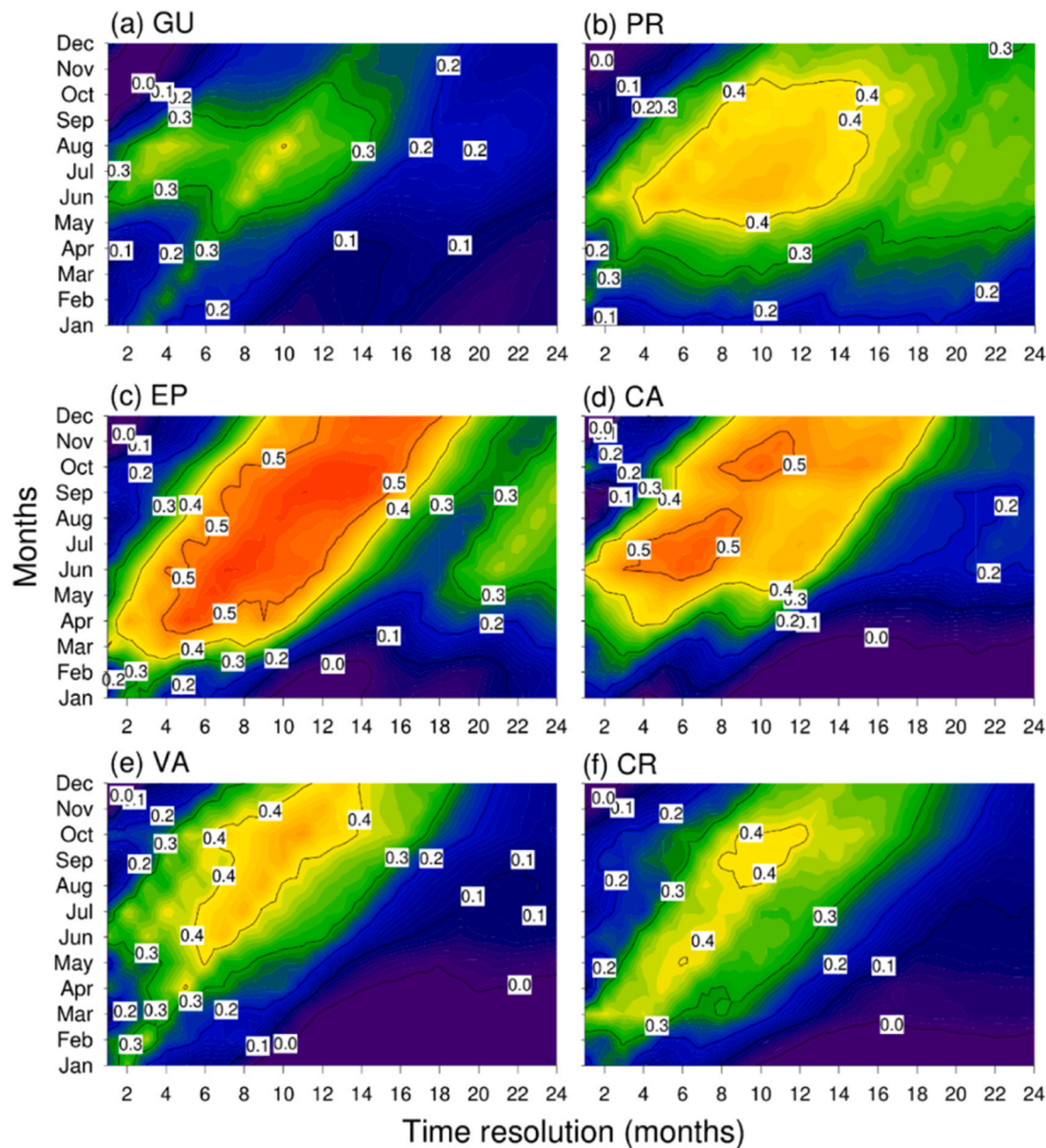


Fig. 6. SPEI-growth relationships (Pearson correlation coefficients) were calculated for 1- to 24-long-month long SPEIs (x axes) and from January to December (y axes). Significant correlations ($p < 0.05$) correspond to $r > 0.44$.

phases of pollarding being more or less synchronized or frequent in different stands (Olano et al., 2023). This should be further investigated and linked to site growing conditions including soil depth or competition of nearby pine plantations in the case of site GU.

This study case illustrates how past historical use condition recent tree growth dynamics, in agreement with previous studies. For instance, trees growing in ancient European beech (*Fagus sylvatica* L.) forests showed lower growth reductions in response to summer drought than trees growing in young fragmented forests (Mausolf et al., 2018). Our results provide a strong temporal perspective by showing that old pollarded oaks maintain relatively high growth rates in most sites even after pruning cessation and increasing summer drought severity. Growth synchrony has increased as climate dried and warmed, but such increase also depended on past pollarding which strengthened the spatial signal of the regional growth synchrony in the 1940–1950s. However, the limitations of historical reconstructions of pollarding severity based on tree-ring data should be also acknowledged. Tree-ring analyses allow reconstructing disturbance impacts on radial growth with annual to seasonal resolution, but these historical inferences should be

complemented with other proxies (e.g., wood anatomy, C and O isotopes) and validated with field data to account for differences in pollarding frequency and intensity. In this sense, gathering information from recently pollarded stands, such as sites CA and VA, could be helpful. Furthermore, comparing tree-ring data with other historical data of forest use is a promising avenue of research.

The changes in growth synchrony of pollarded oaks and in MGSs can be linked to historical phases of firewood extraction in Spain, a proxy of the past use of these stands (Infante-Amate and Iriarte-Goñi, 2017). First, during the coal phase (1860–1910) firewood consumption was slowly replaced by coal as the main fuel (Fig. 8). In this period MGSs were frequent (e.g., 1810s, 1870s) and synchrony increased during the dry late 19th century. Second, during the firewood phase (1910–1950) the increase in coal price because of conflicts (e.g., Spanish Civil War) triggered the consumption of firewood by rural population. This corresponded to abundant MGSs in the 1930s and 1940s found in most stands, explaining the spatial signature of synchrony and its strengthening. Third, during the oil phase (1950s–1980) firewood consumption declined by ca. – 50 % as energy demand increased thanks to the use of

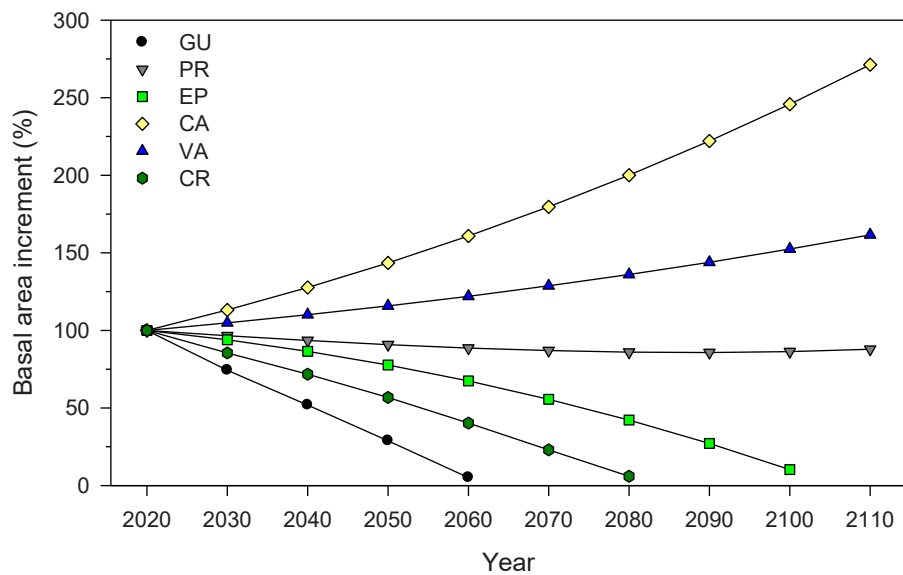


Fig. 7. Decadal projections of basal area increment for the study pollard oak stands based on the fitted 3rd-order polynomial functions.

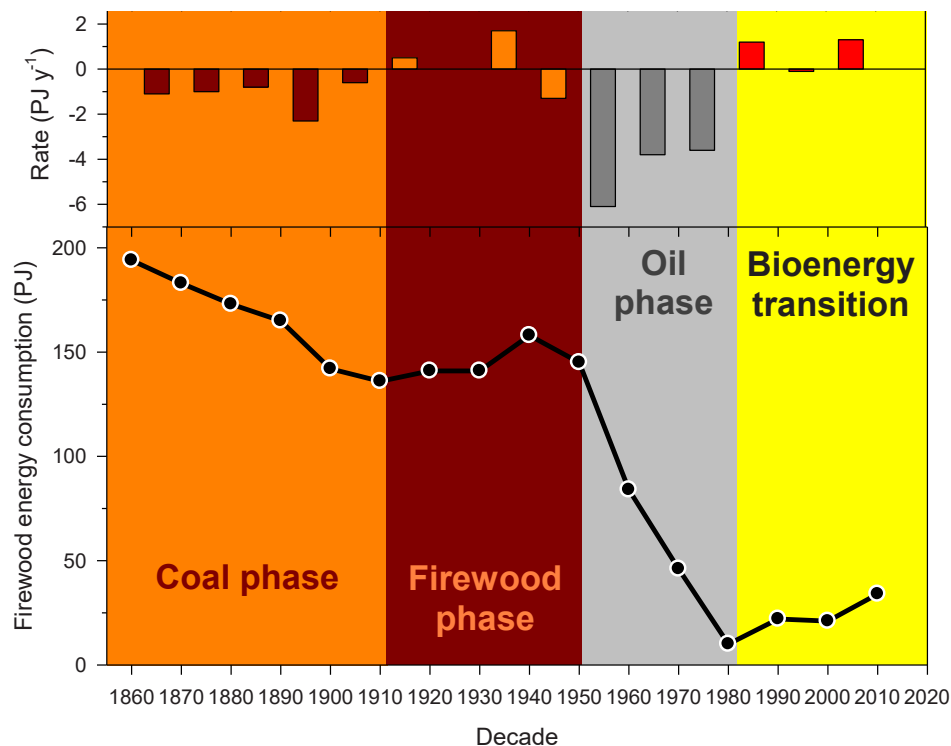


Fig. 8. Historical changes in firewood energy consumption in Spain from the 19th to the 21st centuries expressed in relative (annual rate, upper plot) or absolute terms (PJ, petajoules; lower plot). The data on firewood consumption were extracted from Infante-Amate and Iriarte-Goni (2017).

oil, gas and electricity. This was accompanied by industrialization and migration to cities leading to pollarding cessation in most rural Spain and corresponded to MGSs in 1980s, related to warm and dry conditions, and an increase in growth synchrony. Fourth, during the bioenergy transition (1989–2010), characterized by biomass use, there was a reduction of synchrony during the dry and warm 1990s. It is possible that too stressful conditions in the 1990s lead to low growth rates during dry periods making trees less responsive to changes in soil moisture deficit and lowering synchrony. Alternatively, the impacts of 1990s droughts may have been local. This question could be disentangled by sampling more pollarded oak stands considering climatically contrasting

sites and different oak species. Lastly, synchrony increased during the warm and dry early 21st century.

The recent increase in firewood consumption because of biomass demand observed in Spain was linked to increasing prices of fossil fuels and electricity (Infante-Amate and Iriarte-Goni, 2017). This biomass was mainly obtained from plantations and croplands but point out future bioenergy sources including pollarded oak stands which could complement other green energy sources. A sustainable pollarding of these abandoned stands could increase their growth rates, improve their vigor and shape, increase their lifespan and represent an additional economic input for small municipalities if pruned branches and shoots are

transformed into biomass. Furthermore, pollarding different stands in different periods and taking into account climate conditions could also desynchronize their growth trajectories and make them more resilient to drought stress. In extreme cases (e.g., site GU), watering and carefully pollarding declining trees could alleviate their drought stress and lengthen their lifespan.

5. Conclusions

To conclude, our tree-ring data confirm that pollarding is a suitable management tool to keep vigorous and healthy old oak stands under more arid climate conditions. Growth synchrony among sites and trees increased as climate warmed and dried, but this did not translate into growth decline in most sites. Further multidisciplinary research combining forestry, ecology and economy could investigate if pruned branches and shoots are profitable sources of biomass and timber. In sites with recent growth loss and projected reduction such as GU, pollarding is urgent and should be accompanied by other measures to alleviate drought stress such as thinning of nearby dense pine plantations, watering and soil preservation. Growth suppression and increased synchrony reflected historical pollarding events, albeit reconstructions involve uncertainty. Growth suppression and between- and within-site synchrony could be also used as early-warning signals of impending drought-induced dieback in old pollarded oak stands.

CRedit authorship contribution statement

Cristina Valeriano: Writing – review & editing, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Alvaro Rubio-Cuadrado:** Writing – review & editing, Resources, Methodology, Investigation, Conceptualization. **J. Julio Camarero:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.foreco.2024.122189](https://doi.org/10.1016/j.foreco.2024.122189).

References

Abatzoglou, J., Dobrowski, S., Parks, S., Hegewisch, K.C., 2018. TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958 to 2015. *Sci. Data* 5, 170191. <https://doi.org/10.1038/sdata.2017.191>.

- Alla, A.Q., Camarero, J.J., 2012. Contrasting responses of radial growth and wood anatomy to climate in a Mediterranean ring-porous oak: implications for its future persistence or why the variance matters more than the mean. *Eur. J. For. Res.* 131, 1537–1550.
- Altman, J., Fibich, P., Dolezal, J., Aakala, T., 2014. TRADER: a package for tree ring analysis of disturbance events in R. *Dendrochronologia* 32, 107–112.
- Bunn, A.G., 2008. A dendrochronology program library in R (dplR). *Dendrochronologia* 26, 115–124.
- Bunn, A.G., 2010. Statistical and visual crossdating in R using the dplR library. *Dendrochronologia* 28, 251–258.
- Bunn, A.G., Korpela, M., Biondi, F., Campelo, F., Mérian, P., Qeadan, F., Zang, C., 2023. dplR: Dendrochronology Program Library in R. R package version 1.7.6. (<https://CRAN.R-project.org/package=dplR>).
- Camarero, J.J., González de Andrés, E., Colangelo, M., De Jaime Loren, Ch., 2022. Growth history of pollarded black poplars in a continental Mediterranean region: a paradigm of vanishing landscapes. *For. Ecol. Manag.* 517, 120268.
- Camarero, J.J., Sánchez-Salguero, R., Sangüesa-Barreda, G., Lechuga, V., Viñegla, B., Seco, J.I., Taiqui, L., Carreira, J.A., Linares, J.C., 2020. Drought, axe and goats. More variable and synchronized growth forecasts worsening dieback in Moroccan Atlas cedar forests. *Sci. Total Environ.* 765, 142752.
- Camarero, J.J., Sangüesa-Barreda, G., Vergarechea, M., 2016. Prior height, growth, and wood anatomy differently predispose to drought-induced dieback in two Mediterranean oak species. *Ann. For. Sci.* 73, 341–351.
- Camarero, J.J., Valeriano, C., 2023. Responses of ancient pollarded and pruned oaks to climate and drought: chronicles from threatened cultural woodlands. *Sci. Total Environ.* 883, 163680.
- Candel-Pérez, D., Hernández-Alonso, H., Castro, F., Sangüesa-Barreda, G., Mutke, S., García-Hidalgo, M., Rozas, V., Olano, J.M., 2022. 250-year reconstruction of pollarding events reveals sharp management changes in Iberian ash woodlands. *Trees Struct. Funct.* 36, 1909–1921. <https://doi.org/10.1007/s00468-022-02343-8>.
- Cho, E., Kim, S., 2015. Cronbach's coefficient alpha: well known but poorly understood. *Organ. Res. Methods* 18, 207–230. <https://doi.org/10.1177/1094428114555994>.
- Collantes, F., Pinilla, V., 2011. Peaceful Surrender: The Depopulation of Rural Spain in the Twentieth Century. Cambridge Scholars Publishing.
- Cook, E.R., 1985. A Time Series Analysis Approach to Tree Ring Standardization. University of Arizona, School of Renewable Natural Resources. Tucson, USA.
- Cook, E.R., Seager, R., Kushnir, Y., Briffa, K.R., Büntgen, U., Frank, D., Krusic, P.J., et al., 2015. Old world megadroughts and pluvials during the common era. *Sci. Adv.* 1 (10) <https://doi.org/10.1126/sciadv.1500561>.
- Corcuera, L., Camarero, J.J., Gil-Pelegrín, E., 2004. Effects of a severe drought on growth and wood-anatomical properties of *Quercus faginea*. *IAWA J.* 25, 185–204.
- Cortés-Ruiz, M.P., 2000. Articulación jurisdiccional y estructura socioeconómica en la comarca de Molina de Aragón a lo largo de la Baja Edad Media (PhD thesis). Univ. Complutense de Madrid, Spain.
- Cronbach, L.J., 1951. Coefficient alpha and the internal structure of tests. *Psychometrika* 16, 297–334. <https://doi.org/10.1007/bf02310555>.
- Eichhorn, M.P., Paris, P., Herzog, F., Incoll, L.D., Liagre, F., Mantzanas, K., Mayus, M., Moreno, G., Papanastasis, V.P., Pilbeam, D.J., Pisanelli, A., Dupraz, C., 2006. Silvoarable systems in Europe—past, present and future prospects. *Agroforest. Syst.* vol. 67, pp. 29–50.
- Fritts, H.C., 1976. Tree Rings and Climate. Academic Press, London, UK.
- García-Martín, A., Paniagua, L.L., Moral, F.J., Rebollo, F.J., Rozas, M.A., 2021. Spatiotemporal analysis of the frost regime in the Iberian Peninsula in the context of climate change (1975–2018). *Sustainability* 13, 8491. <https://doi.org/10.3390/su13158491>.
- Gazol, A., Camarero, J.J., Sangüesa-Barreda, G., Serra-Maluquer, X., Sánchez-Salguero, R., Coll, L., Casals, P., 2020. Tree species are differently impacted by cumulative drought stress and present higher growth synchrony in dry places. *Front. For. Glob. Change* 3. (<https://www.frontiersin.org/articles/10.3389/fgc.2020.573346>).
- González de Andrés, E., Shestakova, T.A., Scholten, R.C., Delcourt, C.J.F., Gorina, N.V., Camarero, J.J., 2022. Changes in tree growth synchrony and resilience in Siberian *Pinus sylvestris* forests are modulated by fire dynamics and ecophysiological conditions. *Agric. For. Meteorol.* 312, 108712.
- Guzmán-Álvarez, J.R., 2016. The image of a tamed landscape: dehesa through history in Spain. *Cult. Hist. Digit. J.* 5, e003 <https://doi.org/10.3989/chdj.2016.003>.
- Himrane, H., Camarero, J.J., Gil-Pelegrín, E., 2004. Morphological and ecophysiological variation of the hybrid oak *Quercus subpyrenaica* (*Q. faginea* × *Q. pubescens*). *Trees - Struct. Funct.* 18, 566–575. <https://doi.org/10.1007/s00468-004-0340-0>.
- Holmes, R., 1983. Computer-assisted quality control in tree-ring dating and measurement. *Tree Ring Bull.* 43, 69–78.
- Infante-Amate, J., Iriarte-Goni, I., 2017. Las bioenergías en España. Una serie de producción, consumo y stocks entre 1860 y 2010. (No. 1702). Documentos de Trabajo de la Sociedad Española de Historia Agraria. Sociedad Española de Historia Agraria. (Available at (<https://ideas.repec.org/p/seh/wpaper/1702.html>), Accessed 22 March 2022).
- Larsson, L.A., Larsson, P.O., 2018. CDendro and Coorecorder (v. 9.3.1) [software]. Cybis Elektronik and Data AB, Saltsjöbaden, Sweden. Available from (<http://www.cybis.se>).
- Mausolf, K., Härdtle, W., Jansen, K., Delory, B.M., Hertel, D., Leuschner, C., Temperton, V.M., von Oheimb, G., Fichtner, A., 2018. Legacy effects of land-use modulate tree growth responses to climate extremes. *Oecologia* 187, 825–837. <https://doi.org/10.1007/s00442-018-4156-9>.
- Montserrat-Martí, G., Camarero, J.J., Palacio, S., Pérez-Rontomé, C., Milla, R., Albuixech, J., Maestro, M., 2009. Summer-drought constrains the phenology and growth of two co-existing Mediterranean oaks with contrasting leaf habit:

- implications for their persistence and reproduction. *Trees Struct. Funct.* 23, 787–799.
- Norton, D.A., Palmer, J.G., Ogden, J., 1987. Dendroecological studies in New Zealand. 1. An evaluation of age estimates based on increment cores. *N. Z. J. Bot.* 25, 373–383.
- Nowacki, G.J., Abrams, M.D., 1997. Radial-growth averaging criteria for reconstructing disturbance histories from presettlement-origin oaks. *Ecol. Monogr.* 67, 225–249.
- Oksanen, J., Simpson, G., Blanchet, F., Kindt, R., Legendre, P., et al., 2024. *vegan*: Community Ecology Package. R package version 2.6-5, (<https://github.com/vegandevs/vegan>).
- Olano, J.M., García-López, M.A., Sangüesa-Barreda, G., Coca, M.E., García-Hidalgo, M., Houdas, H., Rozas, V., Hernández-Alonso, H., 2023. Forgotten giants: robust climate signal in pollarded trees. *Sci. Total Environ.* 903, 166591.
- Osborn, T.J., Briffa, K.R., Jones, P.D., 1997. Adjusting variance for sample-size in tree-ring chronologies and other regional mean timeseries. *Dendrochronologia* 15, 89–99.
- R Development Core Team, 2023. *R: A Language and Environment for Statistical Computing*. Vienna, Austria.
- Rackham, G., 2008. Ancient woodlands: modern threats. *New Phytol.* 180, 571–586.
- Ranius, T., Jansson, N., 2000. The influence of forest regrowth, original canopy cover and tree size on saproxylic beetles associated with old oaks. *Biol. Conserv.* 95, 85–94.
- Read, H., 2006. A Brief Review of Pollards and Pollarding in Europe. 1er Colloque Européen sur les Trognés. Vendôme, France.
- Read, H., 2008. Pollards and pollarding in Europe. *Br. Wildl.*, pp. 250–9.
- Rozas, V., 2004. A dendroecological reconstruction of age structure and past management in an old-growth pollarded parkland in northern Spain. *For. Ecol. Manag.* 195, 205–219.
- Rozas, V., 2005. Dendrochronology of pedunculate oak (*Quercus robur* L.) in an old-growth pollarded woodland in northern Spain: tree-ring growth responses to climate. *Ann. Sci.* 62, 209–218.
- Sangüesa-Barreda, G., Camarero, J.J., Sánchez-Salguero, R., Gutiérrez, E., Linares, J.C., Génova, M., Ribas, M., Tísar, P.A., López-Sáez, J.A., 2019. Droughts and climate warming desynchronize Black pine growth across the Mediterranean Basin. *Sci. Total Environ.* 697, 133989.
- Shestakova, T.A., Camarero, J.J., Voltas, J., 2021. Are global forests performing in sync? The need to account for spatiotemporal biases in tree-ring records. *J. Biogeogr.* 48, 2961–2965.
- Shestakova, T.A., Gutiérrez, E., Kirdyanov, A.V., Camarero, J.J., Génova, M., Knorre, A.A., Linares, J.C., Resco de Dios, V., Sánchez-Salguero, R., Voltas, J., 2016. Forests synchronize their growth in contrasting Eurasian regions in response to climate warming. *Proc. Natl. Acad. Sci. USA* 113, 662–667. <https://doi.org/10.1073/pnas.1514717113>.
- Tonelli, E., Vitali, A., Brega, F., Gazol, A., Colangelo, M., Urbinati, C., Camarero, J.J., 2023. Thinning improves growth and resilience after severe droughts in *Quercus subpyrenaica* coppice forests in the Spanish Pre-Pyrenees. *Dendrochronologia* 77, 126042.
- Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., 2010. A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. *J. Clim.* 23, 1696–1718.
- Vieira, S., Campelo, F., Nabais, C., 2022. Environment controls seasonal and daily cycles of stem diameter variations in Portuguese Oak (*Quercus faginea* Lambert). *Forests* 13, 170.
- Vilà-Cabrera, A., Astigarraga, J., Jump, A.S., Zavala, M.A., Seijo, F., Sperlich, D., Ruiz-Benito, P., 2023. Anthropogenic land-use legacies underpin climate change-related risks to forest ecosystems. *Trends Plant Sci.* 28, 1132–1143. <https://doi.org/10.1016/j.tplants.2023.04.014>.
- Wigley, T.M.L., Briffa, K.R., Jones, P.D., 1984. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *J. Clim. Appl. Meteorol.* 23, 201–213.
- Zang, C., Biondi, F., 2015. treeclim: an R package for the numerical calibration of proxy-climate relationships. *Ecography* 38, 431–436.
- Zomer, R.J., Xu, J., Trabucco, A., 2022. Version 3 of the global aridity index and potential evapotranspiration database. *Sci. Data* 9, 409. (<https://www.nature.com/articles/s41597-022-01493-1>).