Contents lists available at ScienceDirect

Science of the Total Environment

Forgotten giants: Robust climate signal in pollarded trees

J.M. Olano [a,*], M.A. García-López [a], G. Sangüesa-Barreda [a], M.E. Coca [a], M. García-Hidalgo [a], H. Houdas [a], V. Rozas [a], H. Hernández-Alonso [a,b]

[a] iuFOR, EiFAB, Campus de Soria, Universidad de Valladolid, E-42004 Soria, Spain
[b] Area of Ecology, Faculty of Biology, University of Salamanca, E-37007 Salamanca, Spain

HIGHLIGHTS

- Pollarded trees are not used for climate reconstructions due to recurrent management.
- Pollarded oaks can live >500 years in intensively managed territories.
- Pollarded oaks secondary growth encapsulates valuable climate information.
- We have few decades left to retrieve pollarded trees environmental information.

GRAPHICAL ABSTRACT
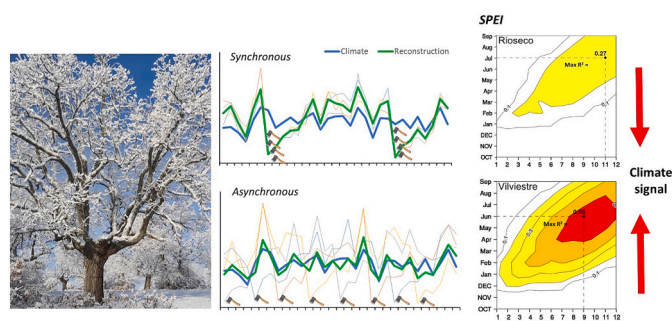
Pollarded trees have a strong potential to reconstruct climate

ARTICLE INFO

Editor: Manuel Esteban Lucas-Borja

ABSTRACT

Tree ring records are among the most valuable resources to create high-resolution climate reconstructions. Most climate reconstructions are based on old trees growing in inaccessible mountainous areas with low human activity. Therefore, reconstruction of climate conditions in lowlands is usually based on data from distant mountains. Albeit old trees can be common in humanized areas, they are not used for climate reconstructions. Pollarding was a common traditional management in Europe that enabled trees to maintain great vitality for periods exceeding the longevity of unmanaged trees. We evaluate the potential of pollarded deciduous oaks to record past climate signal. We sampled four pollarded woodlands in Central Spain under continental Mediterranean climate. We hypothesized that pollarded trees have a strong response to water availability during current period without pollarding management, but also in the period under traditional management if pruning was asynchronous among trees. Moreover, we hypothesized that if climate is a regional driver of oak secondary growth, chronologies from different woodlands will be correlated. Pollard oaks age exceeded 500 years with a strong response to Standardized Precipitation-Evapotranspiration Index (SPEI) from 9 to 11 months. Climate signal was exceptionally high in three of the sites (r^2 = 0.443–0.655) during low management period (1962–2022). The largest fraction of this climate signal (≈70 %) could be retrieved during the traditional management period (1902–1961) in the three sites where pollarding was asynchronous. Chronologies were significantly correlated since the 19th century for all the studied period, highlighting a shared climate forcing. We identified critical points to optimize pollard tree sampling schema. Our results show the enormous potential

* Corresponding author.
  E-mail address: josemiguel.olano@uva.es (J.M. Olano).

of pollarded woodlands to reconstruct hydroclimate conditions in the Mediterranean with a fine spatial grain. Studying pollarded trees is an urgent task, since the temporal window to retrieve the valuable information in pollarded trees is closing as these giants collapse and their wood rots.

1. Introduction

Reconstructing climate variability from tree rings is one of the most conspicuous applications of dendrochronology (Speer, 2010). Dendroclimatology has changed our understanding of past climate conditions by allowing us to reconstruct environmental patterns far beyond climatic observations (Friedrich et al., 2004; Esper et al., 2018; Coulthard et al., 2020). This information is critical to contextualize current climate change within a wider temporal context (Esper et al., 2018), to improve the forecasts of climate models (Beniston, 2002), as well as to understand the impact of climate on human history (Schmid et al., 2015; Sangüesa-Barreda et al., 2020). The historical relevance of climate reconstruction in dendrochronology has been such that the largest dendrochronological database (ITRDB) is biased towards trees and environments with characteristics that maximize climate signal (Babst et al., 2017).

Not surprisingly, old and isolated trees growing under stressful conditions have received considerable attention, being intensely searched and cored to obtain long and robust climate signals. However, such ancient trees are very scarce and typically restricted to inaccessible mountainous areas with low human activity (Sangüesa-Barreda et al., 2022), producing global-scale spatial aggregation that makes climatic reconstructions to be concentrated in specific areas/environments. Thus, climate condition reconstruction in lowland regions and areas under intense human pressure, *i.e.* places where human population thrives, is usually based on data from mountain sites. This is not a major issue for temperature reconstructions, since temperature exhibits a strong correlation at large spatial scales but might be problematic for precipitation reconstructions since precipitation varies strongly at small scales (Ljungqvist et al., 2020). Moreover, precipitation is the most limiting climatic factor along large areas of the world, particularly in Mediterranean climate, determining historical variation in primary production, river flow levels and crops success (Vicente-Serrano et al., 2006, 2012), and therefore denser precipitation reconstructions are required.

Historically, the scarcity of tree-ring chronologies of sufficient length has been the primary hurdle in producing climate reconstructions for lowland areas. Nevertheless, some traditional management practices, like tree pollarding, have maintained old trees populations in areas under high historical human pressure. Pollarding leads to periodic growth reductions that predispose trees to a longer lifespan (Brienen et al., 2020). Tree pollarding was one of the most important tree and landscape management practices in Europe until the middle of the 20th century (Read, 2008). Pollarding involved the regular cutting of branches at certain height to obtain a product (fodder, timber, firewood…), while keeping trees at a low density to maintain open woodlands for livestock pasture. Despite the aggressiveness of this technique, pollarding enables trees to maintain great vitality for periods that far exceed the longevity of unmanaged trees (Camarero et al., 2022; Candel-Pérez et al., 2022). The combination of longevity and low inter-tree competition would make pollards candidates to record and reconstruct past climate signal. However, pollards have been under-prospected for climate reconstruction since the climate signal of tree rings is disrupted by recurrent management disturbances associated to branch pruning, as well as by the formation of typical cavities within these trees that hinder the extraction of high-quality wood cores. Nevertheless, although pollarding aimed at fodder production involved high frequency pruning like ash, holly, or poplar, pollarded management for wood production as in oaks or beech have a lower cutting frequency (Read, 2000; Rozas, 2004; Haneca, 2009), that might be compatible with retaining a high proportion of the climate signal.

Understanding to what extent pollarded trees xylem retains climate signal has become an urgent issue. Albeit wide areas of pollarded perennial oak woodlands (*dehesas*) are maintained in Western Iberian Peninsula (Costa et al., 1997), pollarding of deciduous oaks was almost abandoned along the second half of 20th century. Ceasing pollarding results in the pollarded trees' branches growing to large dimensions, compromising their stability and eventually leading to breakages or even tree collapse (Read, 2000). Despite the strong interest in pollard trees maintenance due to their high cultural and environmental values (Read, 2008), the current large economic costs limit these practices to certain conservation schemes usually at small scales and reliant on financial support (*vg.* Mugarza, 2012; Read et al., 2013) or to a few dehesas where mechanization is feasible, keeping management costs at bay. Unfortunately, most deciduous oak woodlands will vanish during this century, becoming either closed forests or grasslands, with ancient trees being lost as it has already occurred in most Europe. Thus, the temporal window to retrieve the valuable climatic and management information contained in their tree rings is closing as trees collapse and internal wood rots.

The aim of this study is to evaluate the potential of pollarded trees to reconstruct climate signal in deciduous oaks. To do this, we sampled four deciduous oak woodlands in north-central Spain under different historical management units. These woodlands were typically pruned with a 15–30 years' frequency before the second half of 20th century (JM Olano unpublished data). In a first step, we evaluated the climate signal for the last 61 years (1962–2022) where pollard management was very low or absent. We expected that radial growth of these deciduous oaks would respond mainly to water availability as congeneric individuals growing in dense forest and that this signal would be stronger due to the low tree-to-tree competition. In a second step, we evaluated climate signal in the tree rings of these pollarded trees during a period of traditional pollarding management (1902–1961), with the end of this period matching the rural exodus of inner Spain and traditional activities abandonment (Lasanta et al., 2021), leading to rapid ecosystemic changes (DeSoto et al., 2010). We expected that the climate signal would be lower in traditional management period compared to the current low management period due to the confounding effect of sharp growth decrease after pollarding. However, the intensity of this signal will depend on pollarding synchrony. If pollarding were synchronous among all the trees within one woodland, inter tree correlation will increase, but climate signal will decrease due to non-climate sharp secondary growth reduction after pollarding events. In contrast, if management was asynchronous within one woodland, inter trees correlation would decline, but climate signal would remain strong due to the compensation of pollarding growth decreases between different trees. We also hypothesize that common climate forcing would drive correlation between residual chronologies from the four woodlands. So, we evaluated correlation among tree ring chronologies among the four forests for two distinct periods: the recent period (1962–2022) with low or no management when climate signal would be the only driver of correlation, and traditional management period (1800–1961) when pollarding could disrupt the common climate signal. A significant correlation between sites for the period with traditional management would imply the existence of a common climate forcing in tree rings from pollarded trees and therefore a potential for climate reconstruction. Finally, we also evaluated the sampling depth required to retrieve the maximum climate signal.
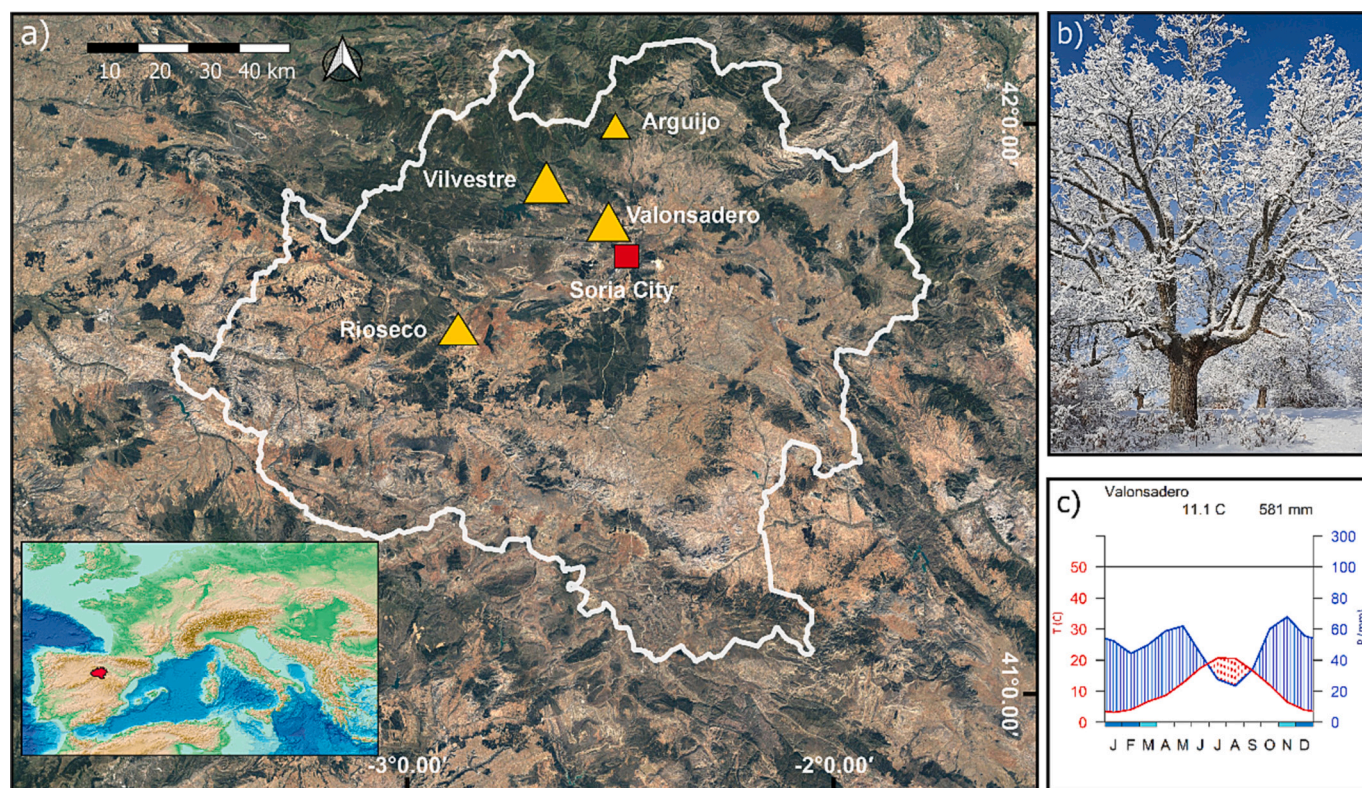
Fig. 1. Location of study sites with inset maps showing the ubication of the study area in the context of Western Mediterranean, the size of the triangles is proportional to the R² of the growth-SPEI relationship (A), an image of pollarded *Quercus pyrenaica* oaks in Valonsadero (B) and the 30-year Walter & Lieth climatic diagram of Soria (CRU TS v4.07, 1993–2022 period) to represent regional context (C).

Table 1
Location of the study sites and dendrochronological features of the residual tree-ring chronologies. Latitude (Lat), longitude (Long) and altitude of the sites, number of sampled trees, time span, mean series length, characteristics of the tree-rings measured (mean ring width ± standard deviation (mm)), first order autocorrelacion (AC1), series intercorrelation (IC), mean sensitivity (msx), as well as Expressed Population Signal (EPS).

Site	Lat (°N)	Long (°W)	Altitude (m a.s.l.)	# trees	Time span	Mean series length (yr)	Ring width ± SD (mm)	AC1	Series IC	msx	EPS
Vilviestre	41.88	−2.65	1069	50	1520–2022	307	0.64 ± 0.28	0.72	0.326	0.156	0.962
Valonsadero	41.81	−2.53	1040	51	1718–2022	181.7	0.93 ± 0.33	0.77	0.336	0.167	0.966
Arguijo	41.99	−2.51	1290	47	1646–2022	188.1	0.92 ± 0.23	0.73	0.252	0.156	0.944
Rioseco	41.63	−2.87	1003	53	1855–2022	149.6	1.31 ± 0.41	0.72	0.481	0.199	0.978

2. Material and methods

### 2.1. Study sites and sampling design

We selected four woodlands dominated by pollarded deciduous oaks in the northern Soria province, Central Spain (Fig. 1; Table 1) under a subhumid climate with summer drought. Yearly accumulated precipitation has a strong interannual variability, whereas temperature shows an increasing trend that becomes steeper since 1975 (Fig. S1). Arguijo is the smallest (43 ha), highest (1290 m) and northernmost site, including *Quercus pyrenaica* Willd. and scattered *Q. petraea* (Matt.) Liebl. trees that grew with European beech (*Fagus sylvatica* L.) over Jurassic sandstone on moderate slopes and flat areas intersected by temporary water channels. Valonsadero is the largest site with 2793 ha, where trees grew over Lower Cretaceous sandstone materials, in an open woodland dominated by *Quercus pyrenaica,* but with frequent hybridization with *Q. faginea* Lam. and more seldomly with *Q. petraea*. Vilviestre is a medium sized woodland of 270 ha with a mean altitude of 1040 m over Lower Cretaceous sandstone. Woodland was dominated by *Q. faginea* with scattered *Q. pyrenaica* in flat areas. Finally, Rioseco is the lowest (1003 m) and southernmost locality, occupying a 100 ha area over a parent material dominated by a combination of sand, gravel and marls

of Neogen origin. Woodland was largely dominated by *Juniperus thurifera* L. with just a few hundred of *Quercus faginea* and scattered *Q. pyrenaica* present. Trees had been historically pollarded with its upper branches removed periodically during leafless period.

Sampling took place between October 2022 and April 2023. At each woodland, we sampled a minimum of 50 trees that were georeferenced using a submetric GPS. Since synchronous management would reduce the climatic signal, we took one core per tree with a Pressler increment borer to reduce this effect due to common management signal within both cores of one tree, while maximizing the number of individuals to reduce the effect of synchronous management signal between two cores of the same tree. Previous tests showed that cross-dating quality was not improved by using more than one core per tree.

2.2. Sample processing and chronologies calculation

Samples were mounted on wooden supports and sanded with sandpaper of progressively decreasing grit. Tree cores were digitized using the CaptuRING device (García-Hidalgo et al., 2022) with a Tokina Macro 100 F2.8 lens mounted in a Nikon D7500 camera with a resolution of 3.7 to 4.5 μm per pixel. Single images were stitched using PTGui (New House Internet Services BV, Netherland) to create a large image per tree
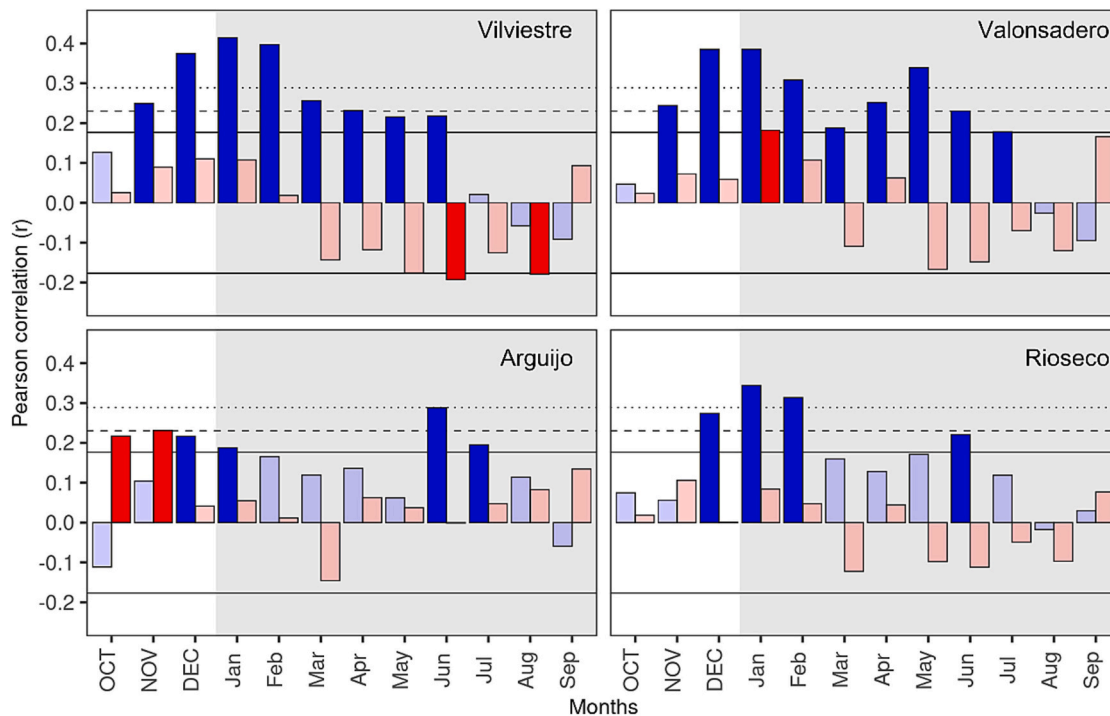
Fig. 2. Correlation between residual chronologies and monthly accumulated precipitation (blue bars) and mean temperature (red bars) for the period 1902–2022. Horizontal lines reflect P value thresholds: continuous indicates $P = 0.05$, dashed line $P = 0.01$ and dotted line $P = 0.001$. Months in capital letters correspond to previous year.

core. Digital cores were used to properly cross-date the tree-ring series using CooRecorder 9.6 (Cybis Elektronik & Data AB, Sweden). Cross-dating quality was verified using the xDateR shiny app and chronologies were generated using dplR software (Bunn, 2008, 2010).

We standardized ring width time series to obtain dimensionless ring-width chronologies without autocorrelation. We removed long term trends and tree age/size effects on annual ring width using a linear or negative exponential function. After this procedure, we applied a cubic smoothing spline with a 50 % frequency response cut-off of 0.67 of series length years. Finally, we removed temporal autocorrelation in the resulting series, obtaining a residual chronology using the "Ar" option of dplR *detrend* function (Bunn, 2008). We calculated the mean correlation value (r_{bt}) as well as Explained Population Signal (EPS) for each chronology to estimate chronology common signal (Table 1). These analyses were performed in R environment (R Core Team, 2022).

2.3. Statistical analysis

We downloaded monthly gridded data from the datasets of the Climate Research Unit, University of East Anglia (https://crudata.uea.ac.uk/; CRU TS 4.07, $0.5° \times 0.5°$; Harris et al., 2020), for monthly mean, minimum and maximum temperatures and total precipitation in the period 1901–2022. We used these data to calculate a modified version of Hargreaves potential evapotranspiration (Droogers and Allen, 2002) and the standardized precipitation-evapotranspiration index using the R SPEI package (SPEI; Beguería and Vicente-Serrano, 2023). SPEI is a multiscalar index that integrates precipitation and evapotranspirative demands, proving to be one of the measures to determine climate control of secondary growth in water limited environments (Vicente-Serrano et al., 2010). We calculated Pearson's correlations with monthly precipitation and temperature from previous year October to current year September when final ring width is reached (González-González et al., 2013) for the period with available climate data (1902–2022). We also calculated SPEI with a maximum window of 12 months from previous year October to growing year September to assess

for the effect since last growing season for the period (1902–2022). We identified the month and lag for each of the maximum climatic signal for each woodland. To estimate the decline in climate signal associated to traditional pollarding management, we divided each residual chronology into two periods: traditional management period, comprising the first half of the study period (1901–1961) and low or no management period (1962–2022). We calculated the correlation with for the month and lag with maximal SPEI signal for each period.

To assess the effect of sample size and management pattern on pollarded climate signal, we created chronologies of different sample size from 1 to 50 trees for 1902–1961 and 1962–2022 periods by resampling without repetition from the pool of individual chronologies of each site and calculated its Pearson correlation with the month and lag with maximal SPEI signal. This process was iterated 1000 times per sample size to calculate the mean Pearson correlation per aggregation level.

To assess whether different woodlands shared a common climate forcing we calculated Pearson correlation between residual chronologies for the low management period 1962–2022 and for the periods with traditional management since 1800 or the start of the chronology if later, and 1961.

We expected that climate will increase inter-tree synchrony in growth, since common climate limitations will drive common growth patterns. In contrast, the effect of pollarding will depend on its synchrony: a synchronous pollarding will have an additive effect to climate in inter-tree synchrony, whereas an asynchronous management will reduce inter-tree synchrony, reducing climate driven synchrony. During traditional management period both forces will interact, whereas under low management only climate effect will be apparent. To address shared growth patterns among trees, we computed synchrony using a network topology approach. Within this framework, each tree symbolizes a node and the growth relationships among them represents links, being the resulting connectivity a factual description of the tree's growth synchrony (Astigarraga et al., 2023). For this analysis, we employed detrended BAI series using a smoothing spline of frequency = 50 % and rigidity = 0.67 of series length. An established link between trees was
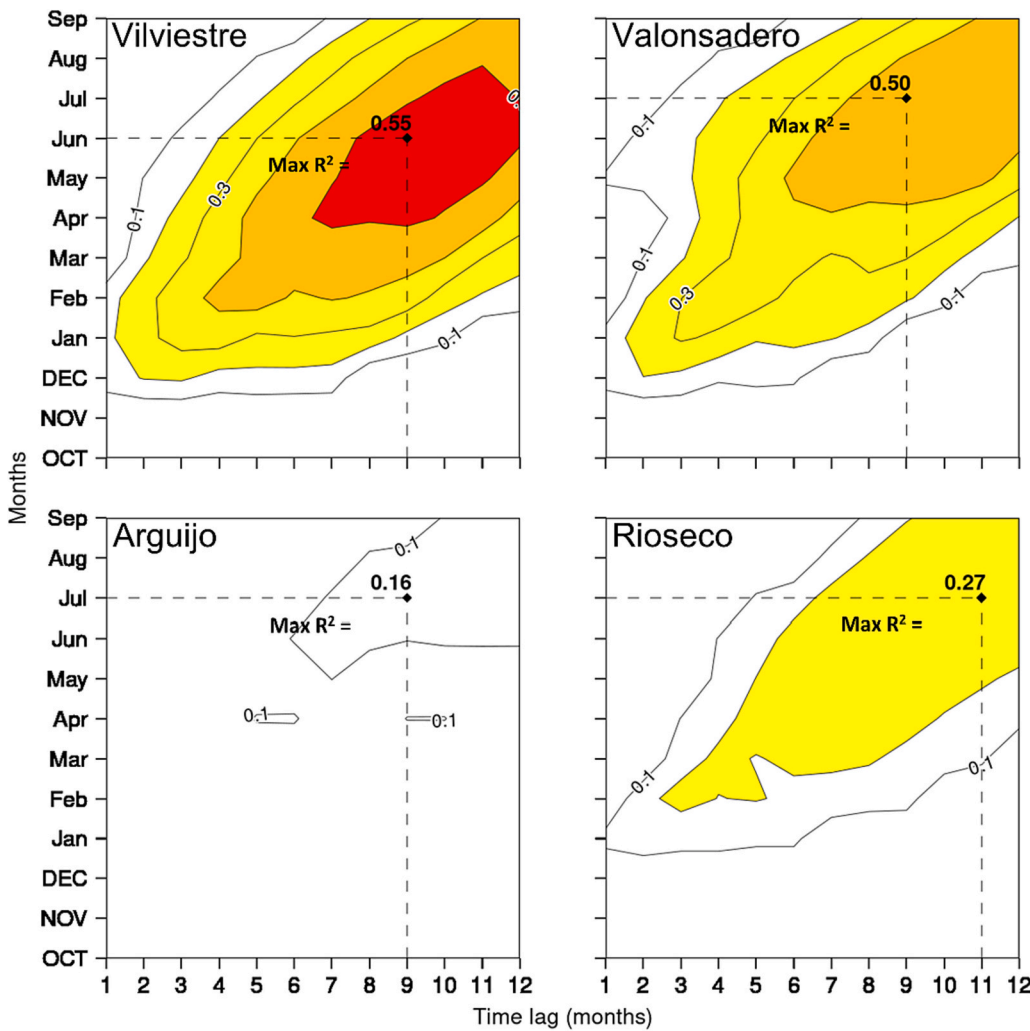
Fig. 3. Percentage of the variance (with sign) of residual ring-width chronology explained by monthly Standardized Precipitation–Evaporation index (SPEI) series at different time scales for the period 1902–2022. The correlations were calculated from September to previous year October. Inserts in the plots represent the month and temporal lag in which maximum appears and percentage of explained variance. Black dots indicate the maximum signal occurrence. Percentage of variance is calculated as the variance explained by the coefficient of determination (R^2) but retaining the sign of r to evaluate the direction of the effect.

considered whenever a pair of growth series showed a positive and significative ($P < 0.05$) Spearman's correlation. Growth correlations were assessed in 30-year moving correlation matrices of lag 1-year that fulfilled that all growth series must be free of missing values and the minimum sample size for a matrix were 20 trees. Finally, synchrony was computed as the proportion of established growth links from the total of unique and potential links.

3. Results

Pollarded trees reached considerable ages in three of the sites, with seven trees in Vilviestre reaching the 16th century (Table 1). In contrast, trees were in Rioseco, established coetaneously in the second half of 19th century. Annual mean growth rate ranged from 0.64 mm per year in the Vilviestre to nearly twice (1.31 mm) in Rioseco. Chronologies were robust in all cases with EPS > 0.94. Interseries correlation was moderate, being the highest at Rioseco. Mean sensitivity was low ranging between 0.15 and 0.2 (Table 1; Fig. S2).

Precipitation was the main driver of oak secondary growth (Fig. 2). Vilviestre and Valonsadero had significant precipitation signal in all months from November to June, extending to July in Valonsadero. The pattern was similar in Rioseco and Arguijo with the signal starting in December, but with no spring signal, but positive signal in June in Rioseco and in June–July in Arguijo. The effect of mean temperature was lower, being negative in spring and summer months in Vilviestre, positive in January in Valonsadero, positive in previous October and

Table 2
Pearson coefficient of correlation (R) between residual chronologies for the low or no traditional management period (1962–2022, upper triangle) and traditional management period (1800–1961, except for Rioseco, that starts in 1856 with $n = 105$, lower triangle). Cells include two-tailed P value.

	Vilviestre	Valonsadero	Arguijo	Rioseco	
Vilviestre		0.89 P < 10^{-4}	0.53 P < 10^{-4}	0.74 P < 10^{-4}	Low management 1962–2022
Valonsadero	0.62 P < 10^{-4}		0.58 P < 10^{-4}	0.74 P < 10^{-4}	
Arguijo	0.44 P < 10^{-4}	0.34 P < 10^{-4}		0.60 P < 10^{-4}	
Rioseco	0.30 P < 0.002	0.31 P < 0.002	0.21 P < 0.032		
	Traditional manag. 1800/first year-1961				

November in Arguijo and with no month with significant effect in Rioseco. Response to SPEI reflected this pattern with positive responses to SPEI since the end of last growing season to the onset of summer (Fig. 3). SPEI explained roughly 50 % of the residual chronology variability in Vilviestre and Valonsadero, whereas these values were lower for Rioseco (27.5 %, but as high as 44 % since 1962) and especially in Arguijo (16 %). The climate signal window was rather similar among sites, with 9-months lag in Valonsadero and Arguijo (11 months in the
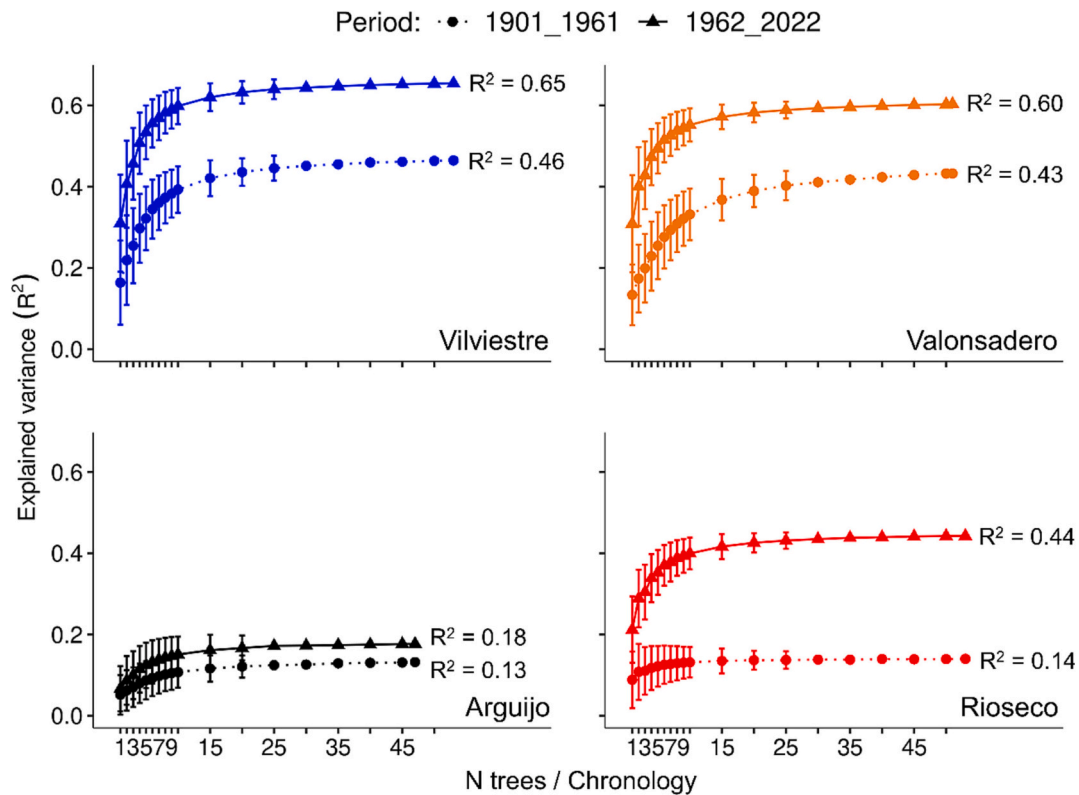
Fig. 4. Mean explained variance (R^2) of increasing sampling size residual chronologies with SPEI for the period with the maximum signal for each site (see Fig. 2). Continuous lines with triangles correspond to low or no management period (1962–2022) and dotted lines with circles to the traditional management period (1902–1961). Error bars indicate the standard deviation of climate correlations when a certain aggregation level is composed by >1 chronology (above 25 trees, all chronologies share trees and thus no standard deviation is presented).

southernmost site, Rioseco) since July (June in Vilviestre, 8 months), revealing very similar climate limitations.

Residual chronologies were strongly correlated between them during the low management period (Table 2), all paired correlations were significant at $P < 0.0001$ supporting the existence of a common climate forcing. Correlation levels between sites were lower during traditional management period (1800–1961), however all of them were still significantly correlated, and coefficient of determination explained a large variance proportion ($r^2 = 0.38$) between the two sites with strong climate signal (Valonsadero and Vilviestre), and still highly significant with Arguijo ($r^2 = 0.19$), where climate signal was lower, but management also asynchronous. Correlations between these sites with Rioseco residual chronology during the traditional management period were much lower due to the confounding effect of management, albeit P value was still significant.

Climate signal increased rapidly with sample size up to 10 trees (Fig. 4), with the increase in explained variance becoming almost flat after 20 trees. Nevertheless, the variance explained by climate was rather high, even with 20 trees, indicating that higher sample size may produce more stable estimates of climate signal. The slopes were similar for low management and traditional management period in all sites except Rioseco, where traditional management period showed a flatter slope. Climate signal was higher during low management period ($r^2 = 0.655$–0.177), retaining >70 % of the signal in Valonsadero, Vilviestre and Arguijo, but only 30 % in Rioseco (Fig. 4).

Synchrony reflected the balance between climate and management effects Climate forcing increased synchrony through a common growth response, whereas the effect of management was disparate: management increased synchrony when pruning was simultaneous for all the trees but decreased synchrony when pruning was not performed simultaneously in all the stand. During the traditional management period synchrony was relatively low (below 50 %) in all sites, except Rioseco,

which showed much higher values for synchrony (60–80 %). Higher synchrony in Rioseco could be attributed to a simultaneous pruning management in Rioseco (Fig. 5), a fact what was visually confirmed with sharp growth reductions (see 1895, 1913, 1927, 1944 …) (Fig. S2) as a consequence pruning events in most of the trees that could be traced in the wood. The sharp decrease in synchrony in Rioseco matches the last cutting that was scattered between 1977 and 1981 thus decreasing inter-trees synchrony. In the rest of the sites the lowest synchrony values during traditional management suggest that pollarding was asynchronous thus counteracting the positive effect on synchrony due to common climate forcing. Synchrony increased in the low management period, when no or very little pruning events occurred and common climate forcing was the dominant force. Interestingly, the site with the lowest climate signal (Arguijo, Fig. 3), also had the lowest synchrony and the driest site (Rioseco) had the highest synchrony (Fig. 5). A 30-year moving correlation in climate response supported the increase in climate signal during low management period for Rioseco (Fig. S3).

4. Discussion

Pollarded oaks reached up to 500 years. Pollards had a strong climate signal for the low management period (1962–2022), reaching exceptionally high values in three of the sites ($r^2 = 0.443$–0.655). A large fraction of this climate signal ($\approx$70 %) could be retrieved during the traditional management period (1902–1961) in woodlands with asynchronous pollarding but decreased drastically (only 30 % retained) in the only site with synchronous management. All chronologies were highly and significantly correlated not only during the low or null management period 1962–2022 period, but also for the traditional management period (1800–1961) in the sites with asynchronous management, pointing to a shared climate forcing. Overall, our results confirm our hypothesis that pollarded trees with asynchronous
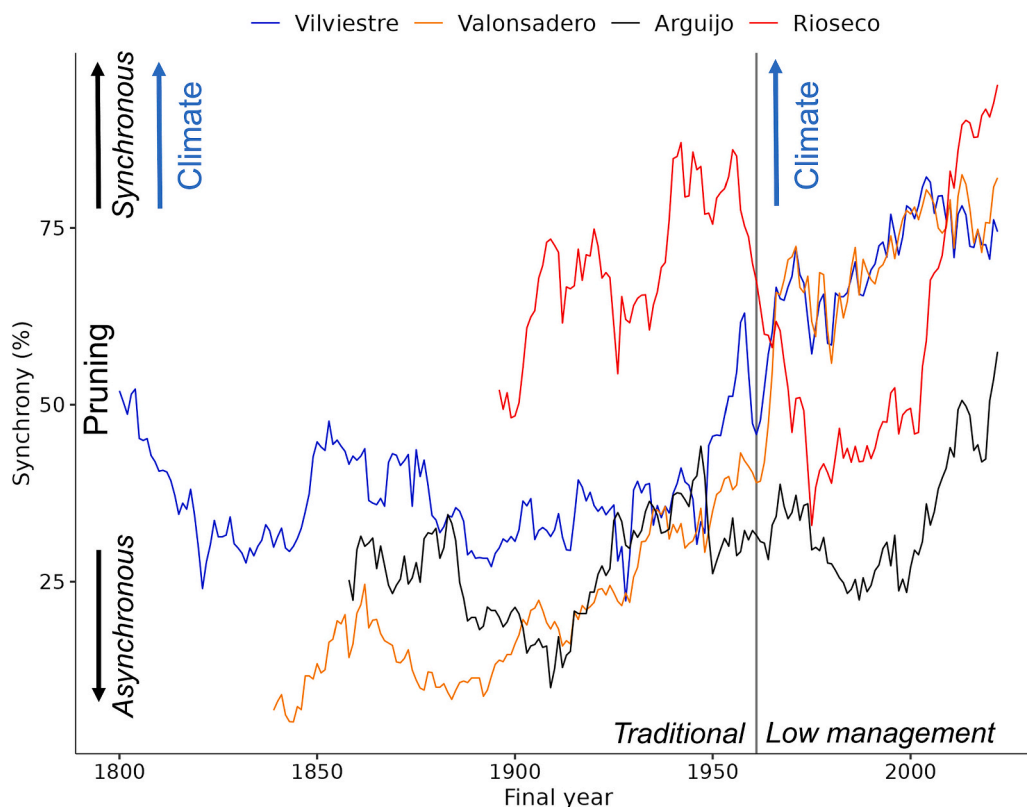
Fig. 5. Synchrony among individual tree-ring series from each site. Synchrony is calculated for 30-year moving windows with 1-year lag (total span = 1800–2022). Values indicate percentage of tree pairs within a site showing positive synchrony. Values are shown for periods with at least 20 trees. Synchronous pruning and climate increase synchrony, whereas asynchronous pruning decrease synchrony.

management can be used to reconstruct past climate conditions.

Secondary growth of pollarded oaks showed a strong climate response to variations in water availability. This high climate signal can be attributed to a combination of tree-specific and environmental factors. Deciduous oaks have ring porous wood anatomy and annual foliage loss. Thus, photosynthetic apparatus and most of the hydraulic system must be renewed annually, increasing the dependence of trees on current year conditions (Zweifel and Sterck, 2018). Moreover, oaks use water accumulated in the soil profile to deal with summer drought (Gallego et al., 1994; Hernández-Santana et al., 2008). In wetter climates, as those characterizing the habitat of Eurosiberian oaks, such as *Quercus robur*, excess winter precipitation replenishes soil water every winter (Paz et al., 1996), which translates into non-significant winter precipitation signals, or even significant negative signals due to anoxic conditions when soil is water-saturated (Rozas and García-González, 2012), restricting positive precipitation signals to late spring-summer when water availability limitation usually occurs (Rozas, 2001). In contrast, soil water profile in Mediterranean oaks forests, particularly under subhumid and dry climates, is not replenished every year and the length and strength of the climate signal is determined by the accumulated precipitation since the last growing season, as shown by higher responsiveness in drier climates (Gea-Izquierdo and Cañellas, 2014). This difference could be appreciated within our sampling sites, with the site under the most humid climatic and edaphic conditions (Arguijo) showing the lowest climate signal. In the remaining sites, the combination of a reduced annual precipitation and draining soils maximized the climate signal. Finally, the low tree density of pollarded woodlands reduces inter-tree competition leading to a higher climate signal than in closed forests (Gea-Izquierdo and Cañellas, 2014; Leal et al., 2015).

Pruning induced abrupt growth reductions by introducing high-frequency noise in the tree ring series and diminishing the climate signal. However, if pruning events were asynchronous as occurred in all

sites except Rioseco (Fig. 5), the reduction in climate signal was moderate (≈30 %), since the growth reduction experienced by trees pruned in a particular year was compensated by the larger number of unaffected individuals. These non-pruned individuals retained most of the climate signal in the chronology. In contrast, synchronous pruning introduced a systematic bias in the chronology, propagating the effects of pruning events to the entire chronology, resulting in a drastic diminution of the climate signal (≈70 %). Synchronous pruning could have enhanced climate signal if pollard trees had been managed for fodder, with pruning being more intense in dry years, however, this is not the case because wood was the primary product from pollarded oaks. A sampling schema with spatially segregated trees seems important to avoid synchronous management units (Candel-Pérez et al., 2022; Camarero and Valeriano, 2023), to preserve a reliable climate signal. Sample size was relevant for the strength of the climate signal, since climate signal increased sharply when 15–20 trees were included in the chronology (Fig. 3). However, such sample size exhibited a considerable variability in the climate signal intensity, and larger sample sizes resulted in marginally larger and more stable climate signals, suggesting the need of larger sample size to have a robust estimate of climate signal in tree pollards. Nonetheless, we acknowledge that our resampling method to detect effects of sample size is limited as we approached our maximum sample size (≈50) due to a reduction in subgroup variability. Further analyses with larger sample sizes are needed to determine the optimal sample size.

Most of the climate reconstructions in the Iberian Peninsula are based on mountain trees where temperature is usually the main limiting factor (Dorado Liñán et al., 2015; Tejedor et al., 2017; Esper et al., 2020). Although precipitation can also be limiting in Mediterranean mountains, the climate signal is usually lower and constrained to one or a few months in late spring or summer (Esper et al., 2015; Andreu-Hayles et al., 2017; García-Cervigón et al., 2018; *but see* Tejedor et al.,

2016). This is not the case for Mediterranean lowland forests where climate signal is strong and responds to hydroclimatic conditions across most of the year (Pasho et al., 2011; Arzac et al., 2018). However, until now, it has not been possible to develop long chronologies due to the limited age of explored trees. Pollarded deciduous oaks might contribute to fill this gap, since they can reach 400–500 years, are relatively abundant, and their climate signal comprises most of the hydrological year (October–November to June–July). These woodlands may prove useful to reconstruct hydroclimate conditions at a finer spatial scale and covering critical temporal windows for basic socioeconomic elements as yields of staple crops (wheat and barley) that are constrained in the Iberian Peninsula by water availability along their whole vegetative period (Vicente-Serrano et al., 2006; Páscoa et al., 2017).

Our results show the enormous potential of pollarded oak woodlands to reconstruct climate conditions in the Mediterranean with a fine spatial grain. Our study surfaced some key aspects to design a sample schema for these forests. Large woodlands should be preferred over small ones, since the highest the number and the spatial dispersion of trees, the lowest the chances of a synchronous management. Sampling should be scattered within the woodland as management units could had been established in the past synchronizing spatially tree pollarding (Candel-Pérez et al., 2022; Camarero and Valeriano, 2023). Finally, one single core per tree should be preferred over multiple cores per tree, since a larger tree number reduces synchronicity and amplifies climate signal. Studying pollarded trees is an urgent task, since the temporal window to retrieve the valuable information in pollarded trees is closing, as these giants collapse and their internal wood rots.

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.

CRediT authorship contribution statement

JMO conceived the idea, wrote the first draft and led woodland prospection, field sampling and crossdating. GS, MGH, HHA, HH, MGL, MEC participated in field-sampling. MEC digitized the samples. MGL and MEC collaborated with crossdating. HHA led data analysis. HHA and MGL led artwork design. All authors revised critically the manuscript and approved the final version.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.166591.

References

Andreu-Hayles, L., Ummenhofer, C.C., Barriendos, M., Schleser, G.H., Helle, G., Leuenberger, M., Gutiérrez, E., Cook, E.R., 2017. 400 years of summer hydroclimate from stable isotopes in Iberian trees. Clim. Dyn. 49, 143–161. https://doi.org/10.1007/s00382-016-3332-z.

Arzac, A., Rozas, V., Rozenberg, P., Olano, J.M., 2018. Water availability controls Pinus pinaster xylem growth and density: a multi-proxy approach along its environmental range. Agric. For. Meteorol. 250–251, 171–180. https://doi.org/10.1016/j.agrformet.2017.12.257.

Astigarraga, J., Calatayud, J., Ruiz-Benito, P., Madrigal-Gonzalez, J., Tijerin-Trivino, J., Zavala, M.A., Andivia, E., Herrero, A., 2023. Forest Structural Diversity Determines Tree Growth Synchrony in Response to Climate Change. bioRxiv, 2023-03. https://doi.org/10.1101/2023.03.17.532989.

Babst, F., Poulter, B., Bodesheim, P., Mahecha, M.D., Frank, D.C., 2017. Improved tree-ring archives will support Earth-system science (commentary). Nat. Ecol. Evol. 1, 0008. https://doi.org/10.1038/s41559-016-0008.

Beguería, S., Vicente-Serrano, S.M., 2023. SPEI: Calculation of the Standardized Precipitation-Evapotranspiration Index. R package version 1.8.1.

Beniston, M., 2002. Climate modeling at various spatial and temporal scales: where can dendrochronology help? Dendrochronologia 20, 117–131. https://doi.org/10.1078/1125-7865-00012.

Brienen, R.J.W., Caldwell, L., Duchesne, L., et al., 2020. Forest carbon sink neutralized by pervasive growth-lifespan trade-offs. Nat. Commun. 11, 4241. https://doi.org/10.1038/s41467-020-17966-z.

Bunn, A.G., 2008. A dendrochronology program library in R (dplR). Dendrochronologia 26, 115–124. https://doi.org/10.1016/j.dendro.2008.01.002.

Bunn, A.G., 2010. Statistical and visual crossdating in R using the dplR library. Dendrochronologia 28, 251–258. https://doi.org/10.1016/j.dendro.2009.12.001.

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 https://doi.org/10.1016/j.scitotenv.2023.163680.

Camarero, J.J., González de Andrés, E., Colangelo, M., de Jaime, Loren C., 2022. Growth history of pollarded black poplars in a continental Mediterranean region: a paradigm of vanishing landscapes. For. Ecol. Manag. 517, 120268 https://doi.org/10.1016/j.foreco.2022.120268.

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 36, 1909–1921. https://doi.org/10.1007/s00468-022-02343-8.

Costa, M., Morla, M., Sainz, H., 1997. In: Planeta (Ed.), Los bosques ibéricos.

Coulthard, B.L., George, S.S., Meko, D.M., 2020. The limits of freely-available tree-ring chronologies. Quat. Sci. Rev. 234, 106264 https://doi.org/10.1016/j.quascirev.2020.106264.

DeSoto, L., Olano, J.M., Rozas, V., De la Cruz, M., 2010. Release of Juniperus thurifera woodlands from herbivore-mediated arrested succession in Spain. Appl. Veg. Sci. 13, 15–25. https://doi.org/10.1111/j.1654-109X.2009.01045.x.

Dorado Liñán, I., Zorita, E., González-Rouco, J.F., Heinrich, I., Campello, F., Muntán, E., Andreu-Hayles, L., Gutiérrez, E., 2015. Eight-hundred years of summer temperature variations in the southeast of the Iberian Peninsula reconstructed from tree rings. Clim. Dyn. 44, 75–93. https://doi.org/10.1007/s00382-014-2348-5.

Droogers, P., Allen, R.G., 2002. Estimating reference evapotranspiration under inaccurate data conditions. Irrig. Drain. Syst. 16, 33–45. https://doi.org/10.1023/A:1015508322413.

Esper, J., Großjean, J., Camarero, J.J., García-Cervigón, A.I., Olano, J.M., González-Rouco, F., Domínguez-Castro, F., Buntgen, U., 2015. Atlantic and Mediterranean synoptic drivers of central Spanish juniper growth. Theor. Appl. Climatol. 121, 571–579. https://doi.org/10.1007/s00704-014-1254-4.

Esper, J., St. George, S., Anchukaitis, K., D'Arrigo, R., Ljungqvist, F.C., Luterbacher, J., Schneider, L., Stoffel, M., Wilson, R., Büntgen, U., 2018. Large-scale, millennial-length temperature reconstructions from tree-rings. Dendrochronologia 50, 81–90. https://doi.org/10.1016/j.dendro.2018.06.001.

Esper, J., Hartl, C., Tejedor, E., de Luis, M., Günther, B., Büntgen, U., 2020. High-resolution temperature variability reconstructed from black pine tree ring densities in Southern Spain. Atmosphere 11, 748. https://doi.org/10.1007/s00704-014-1254-4.

Friedrich, M., Remmele, S., Kromer, B., Hofmann, J., Spurk, M., Felix, Kaiser K., Küppers, M., 2004. The 12,460-year Hohenheim oak and pine tree-ring chronology from Central Europe—a unique annual record for radiocarbon calibration and paleoenvironment reconstructions. Radiocarbon 46, 1111–1122. https://doi.org/10.1017/S003382220003304X.

Gallego, H.A., Rico, M., Moreno, G., Santa Regina, I., 1994. Leaf water potential and stomatal conductance in Quercus pyrenaica Willd forests: vertical gradients and response to environmental factors. Tree Physiol. 14, 1039–1047.

García-Cervigón, A.I., Linares, J.C., García-Hidalgo, M., J. Julio Camarero, J.J., Olano, J.M., 2018. Growth delay by winter precipitation could hinder Juniperus sabina persistence under increasing summer drought. Dendrochronologia 51, 22–31. https://doi.org/10.1016/j.dendro.2018.07.003.

García-Hidalgo, M., García-Pedrero, Á., Colón, D., Sangüesa-Barreda, G., García-Cervigón, A.I., López-Molina, J., Hernández-Alonso, H., Rozas, V., Olano, J.M., Alonso-Gómez, 2022. CaptuRING: a do-it-yourself tool for wood sample digitization. Methods Ecol. Evol. 13, 1185–1191. https://doi.org/10.1111/2041-210X.13847.

Gea-Izquierdo, G., Cañellas, I., 2014. Local climate forces instability in long-term productivity of a Mediterranean oak along climatic gradients. Ecosystems 17, 228–241. https://doi.org/10.1007/s10021-013-9719-3.

González-González, B.D., García-González, I., Vázquez-Ruiz, R.A., 2013. Comparative cambial dynamics and phenology of *Quercus robur* L. and *Q. pyrenaica* Willd. in an Atlantic forest of the northwestern Iberian Peninsula. Trees 27, 1571–1585. https://doi.org/10.1007/s00468-013-0905-x.

Haneca, K., 2009. Oaks, tree-rings and wooden cultural heritage: a review of the main characteristics and applications of oak dendrochronology in Europe. J. Archaeol. Sci. 36, 1–11. https://doi.org/10.1016/j.jas.2008.07.005.

Harris, I., Osborn, T.J., Jones, P., Lister, D., 2020. Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. Sci. Data 7, 109. https://doi.org/10.1038/s41597-020-0453-3.

Hernández-Santana, V., Martínez-Fernández, J., Morán, C., Cano, A., 2008. Response of *Quercus pyrenaica* (melojo oak) to soil water deficit: a case study in Spain. Eur. J. For. Res. 127, 369–378. https://doi.org/10.1007/s10342-008-0214-x.

Lasanta, T., Nadal-Romero, E., Khorchani, M., Romero-Díaz, A., 2021. A review of abandoned lands in Spain: from local landscapes to global management strategies. Geogr. Res. Lett. 47, 477–521. https://doi.org/10.18172/cig.4755.

Leal, S., Campelo, F., Al, Luz, Carneiro, M.F., Santos, J.A., 2015. Potential of oak tree-ring chronologies from Southern Portugal for climate reconstructions. Dendrochronologia 35, 4–13. https://doi.org/10.1016/j.dendro.2015.05.003.

Ljungqvist, F.C., Piermattei, A., Seim, A., Krusic, P.J., Büntgen, U., He, M., Kirdyanov, A. V., Luterbacher, J., Schneider, L., Seftigen, K., Stahle, D.W., Villalba, R., Yang, B., Esper, J., 2020. Ranking of tree-ring based hydroclimate reconstructions of the past millennium. Quat. Sci. Rev. 230, 106074 https://doi.org/10.1016/j.quascirev.2019.106074.

Mugarza, V., 2012. LIFE+ Naturaleza, Biodiversidad y Trasmochos. Foresta 55, 134–141.

Páscoa, P., Gouveia, C.M., Russo, A., Trigo, R.M., 2017. The role of drought on wheat yield interannual variability in the Iberian Peninsula from 1929 to 2012. Int. J. Biometeorol. 61, 439–451. https://doi.org/10.1007/s00484-016-1224-x.

Pasho, E., Camarero, J.J., de Luis, M., Vicente-Serrano, S.M., 2011. Impacts of drought at different time scales on forest growth across a wide climatic gradient in north-eastern Spain. Agric. For. Meteorol. 151, 1800–1811. https://doi.org/10.1016/j.agrformet.2011.07.018.

Paz, A., Neira, A., Castelao, A., 1996. Soil water regime under pasture in the humid zone of Spain: validation of an empirical model and prediction of irrigation requirements. Agric. Water Manag. 29, 147–161 doi: 0.1016/0378-3774(95)01198-6.

R Core Team, 2022. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. URL. https://www.R-project.org/.

Read, H.J., 2000. Veteran Trees: A Guide to Good Management. English Nature, Peterborough.

Read, H.J., 2008. Pollards and pollarding in Europe. Br. Wildl. 19, 250–259.

Read, H.J., Dagley, J., Elosegui, J.M., Sicilia, A., Wheater, C.P., 2013. Restoration of lapsed beech pollards: evaluation of techniques and guidance for future work. Arboric. J. 35, 74–90. https://doi.org/10.1080/03071375.2013.747720.

Rozas, V., 2001. Detecting the impact of climate and disturbances on tree-rings of Fagus sylvatica L. and Quercus robur L. in a lowland forest in Cantabria, Northern Spain. Ann. For. Sci. 58, 237–251. https://doi.org/10.1051/forest:2001123.

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. https://doi.org/10.1016/j.foreco.2004.02.058.

Rozas, V., García-González, I., 2012. Too wet for oaks? Inter-tree competition and recent persistent wetness predispose oaks to rainfall-induced dieback in Atlantic rainy forest. Glob. Planet. Chang. 94–95, 62–71. https://doi.org/10.1016/j.gloplacha.2012.07.004.

Sangüesa-Barreda, G., Esper, J., Büntgen, U., Camarero, J.J., Di Filippo, A., Baliva, M., Piovesan, 2020. Climate–human interactions contributed to historical forest recruitment dynamics in Mediterranean subalpine ecosystems. Glob. Chang. Biol. 26, 4988–4997. https://doi.org/10.1111/gcb.15246.

Sangüesa-Barreda, G., García-Cervigón, A.I., García-Hidalgo, M., Rozas, V., Martín-Esquivel, J.L., Martín-Carbajal, J., Martínez, R., Olano, J.M., 2022. Vertical cliffs harbor millennia-old junipers in the Canary Islands. Ecology 103, e3633. https://doi.org/10.1002/ecy.3633.

Schmid, B.V., Büntgen, U., Easterday, W.R., Ginzler, C., Walløe, L., Bramanti, B., Stenseth, N.C., 2015. Climate-driven introduction of the Black Death and successive plague reintroductions into Europe. PNAS 112, 3020–3025. https://doi.org/10.1073/pnas.1412887112.

Speer, J.H., 2010. Fundamentals of Tree-Ring Research. University of Arizona Press.

Tejedor, E., de Luis, M., Cuadrat, J.M., Esper, J., Saz, M.A., 2016. Tree-ring-based drought reconstruction in the Iberian Range (east of Spain) since 1694. Int. J. Biometeorol. 60, 361–372. https://doi.org/10.1007/s00484-015-1033-7.

Tejedor, E., Saz, M.A., Cuadrat, J.M., Esper, J., de Luis, M., 2017. Temperature variability in the Iberian Range since 1602 inferred from tree-ring records. Clim. Past 13, 93–105. https://doi.org/10.5194/cp-13-93-2017.

Vicente-Serrano, S.M., Cuadrat-Prats, J.M., Romo, A., 2006. Early prediction of crop production using drought indices at different time-scales and remote sensing data: application in the Ebro Valley (north-east Spain). Int. J. Remote Sens. 27, 511–518. https://doi.org/10.1080/01431160500296032.

Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., 2010. A multi-scalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index - SPEI. J. Clim. 23, 1696–1718. https://doi.org/10.1175/2009JCLI2909.1.

Vicente-Serrano, S.M., Gouveia, C., Camarero, J.J., Beguería, S., Trigo, R., López-Moreno, J.I., Azorín-Molina, C., Pasho, E., Lorenzo-Lacruz, J., Revuelto, J., Morán-Tejeda, E., Sanchez-Lorenzo, A., 2012. Response of vegetation to drought time-scales across global land biomes. PNAS 110, 52–57. https://doi.org/10.1073/pnas.1207068110.

Zweifel, R., Sterck, F., 2018. A conceptual tree model explaining legacy effects on stem growth. Front. For. Glob. Chang. 1, 9. https://doi.org/10.3389/ffgc.2018.00009.