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Lack of management, land-use changes, poor site conditions and drought contribute to the decline of old pollarded oaks

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A B S T R A C T

In Europe, people have managed forests and woodlands for centuries. Old pollarded oaks reflect historical legacies, and their conservation is threatened by the abandonment of this traditional forest use. However, site conditions (topography, soil features, land cover, and historical use) and warming-triggered drought stress also contribute to their growth decline, particularly in seasonally dry regions. We investigated two stands of pollarded Mediterranean oaks (*Quercus subpyrenaica*), where pollarding was abandoned in the 1950s, showing contrasting land cover and tree sizes in north-eastern Spain. Changes in land cover, soil characteristics (texture, pH, and nutrient concentrations), climate conditions, and tree-ring data (basal area increment –BAI–, and ring-width indices) were analysed. The Artosilla site, showing the smallest trees, presented the lowest long-term growth rates (period 1730–2022, mean BAI = 19.7 $cm^2\ yr^{-1}$) as compared with the Aineto site with bigger oaks (mean BAI = 32.9 $cm^2\ yr^{-1}$). Old trees were found in both sites with ages ranging 293–311 years. The less fertile soils in Artosilla, where pine plantations diminish canopy thermal amplitude, may contribute to the long-term growth decline observed there. Moreover, more major growth suppressions were found in this site, particularly in the 1940s, which suggest a more intensive historical use. Aineto showed a stronger BAI decline since the 1950s, which could be a response to increasingly warmer and drier summer conditions. In contrast, growth in Artosilla is decoupling from soil and atmospheric drought suggesting chronic growth stagnation. Poor site conditions (steeper slope, less fertile soils, intensive historical use) contributed to the decline of pollarded oaks. Active management is required to preserve these unique old, monumental trees.

1. Introduction

Many European forests and woodlands are anthropogenic landscapes created through historical uses such as pollarding (Rackham, 2008). In the case of pollarded broadleaf tree species (oak, poplar, beech, ash, willow), branches were lopped at a certain height above the ground, away from cattle, and harvested shoots were used for firewood, timber, fodder, charcoal, beams, and osier wickers for basketry (Read, 2008). Monumental pollarded oaks are iconic components of European woodlands and often show longer lifespans than maiden trees, attracting interest due to their large size and crown morphology (Read, 2000). They also constitute biodiversity foci hosting, for instance, threatened saproxylic beetles (Ranius and Jansson, 2000). The exodus of the rural population to cities during the mid-20th century led to the abandonment of traditional pollarding which threatens the conservation of pollarded stands (Read, 2000, 2006, Camarero et al., 2022, Candel-Pérez et al., 2022). These large old trees should, therefore, be a conservation priority (Lindenmayer, 2016).

In Mediterranean European countries such as Spain, the intensity and frequency of oak pollarding declined during the mid to late 20th century as rural population and firewood demand declined due to the migration to cities and the widespread use of fossil fuels (Rozas, 2004, 2005; Camarero et al., 2022). Traditional forest uses such as pollarding were either drastically reduced or ceased leading to land abandonment (Collantes and Pinilla, 2011; Lasanta et al., 2021, Infante-Amate et al., 2022). Currently, about 3.5 million ha of pollard oak woodlands exist in

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the Iberian Peninsula, often forming open savanna-like woodlands ("dehesas"), and represent the largest agroforestry system in Europe (Eichhorn et al., 2006). Furthermore, pollarded trees are also threatened by rising temperatures and aridification, particularly in seasonally dry areas of southern Europe where tree growth is constrained by water shortage (Olano et al., 2023). Climate warming is amplifying drought stress on these regions making forest productivity and tree growth more dependent on precipitation, soil moisture and atmospheric water demand (Babst et al., 2019). Specifically, tree growth is becoming more coupled to increased vapor pressure deficit (VPD), which measures the water evaporative demand (Camarero et al., 2021; Grossiord et al., 2020). Therefore, we need to disentangle the impacts of past use and management legacies, site conditions and recent climate warming on tree growth in formerly pollarded stands (e.g., Alfaro-Sánchez et al., 2019; Marqués et al., 2022). This new knowledge will help to better conserve these unique landscape components.

Nevertheless, there are still few and incomplete retrospective assessments on radial growth dynamics of Mediterranean pollarded oak stands, particularly in drought-prone areas (but see Camarero and Valeriano, 2023; Olano et al., 2023). Long-term growth data are needed to forecast how these human-shaped woodlands will respond to multiple stressors including the cessation of their traditional management, increased aridification, and unfavorable site conditions. Regarding the last factor, some of these pollarded oak stands are located in sub-optimal locations (e.g., steep slopes and poor soils) dominated by pine plantations which can contribute to oak decline. In Spain, there was a massive pine plantation campaign promoted by the state during the 1950s and 1960s, when most rural population moved to cities. About 3678,522 ha were reforested in Spain from 1940 to 1984 and the reforestation rate peaked in 1957, when 143,968 ha were planted, i.e. 1.8 times the mean annual reforested area (Vadell et al., 2016). Thus, we also considered the role played by site conditions and pine plantations on pollarded oak conservation since steep slopes and formerly cultivated terraces were converted into pine plantations, probably reducing soil water and nutrient availability. To answer these questions, we selected a study area located in north-eastern Spain (Guarguera Valley), where the National Forest Patrimony started buying croplands to convert them into pine (mainly *Pinus nigra* and *Pinus sylvestris*) plantations in 1949 (Villuendas-Díaz, 1966; Chauvelier, 1990). We adopted a landscape view and considered historical cover changes since the 1950s because this scale is important for understanding pollarded oak growth dynamics considering diverse aspects such as local climate or soil water yield (Bobiec et al., 2018). For instance, it could be expected a lower thermal amplitude and soil fertility in steeper landscapes dominated by pine plantations than in open woodlands located on flatter sites with fertile soils (Cifuentes-Croquevielle et al., 2020).

Here, we compared historical changes in land use cover, soil characteristics, microclimate conditions, and growth dynamics in two pollarded oak (*Quercus subpyrenaica* E.H. del Villar) woodlands situated in north-eastern Spain. These two sites show different oak sizes with trees being bigger in Aineto than in Artosilla. Our objectives were: (i) to compare changes in land cover since the 1950s, (ii) to assess site conditions that could influence on oak radial growth such as soil characteristics (texture, pH, nutrients) and microclimate (air temperature measured in oak and pine canopies), (iii) to assess and reconstruct growth trends and pollarding events, assuming they corresponded to growth suppressions (negative growth changes), using dendrochronology, and (iv) to compute climate− and drought−growth correlations, with a particular emphasis on soil (drought index) and atmospheric drought (VPD). We expected that the site with the worst local conditions (steeper slopes, less fertile soils, higher cover of pine plantations) and smaller trees (Artosilla) would show lower growth rates, a more negative long-term growth trend, a more intense use (pollarding) in the past, and a higher growth dependence on drought after massive pine plantations carried out in the 1950s. In contrast, we expect that the site with the biggest pollarded oaks (Aineto) should show the opposite characteristics. In summary, we aim to answer two questions: Does pollarding serve as an effective management strategy to mitigate drought stress, ultimately resulting in reduced sensitivity to climate fluctuations and increased resilience during extreme droughts? Alternatively, is the lower sensitivity to climate signaling poorer health and growth decline of trees in Artosilla?

2. Material and methods

2.1. Study sites

We selected two oak stands with contrasting landscape contexts which have not been pollarded for the past five decades and are located near Aineto and Artosilla villages, Guarguera Valley, Huesca province, north-eastern Spain (Table 1, Fig. 1). Pollarded oaks form open woodlands and often grow near formerly cultivated or grazed fields or terraces. In Aineto, pollarded oaks are big and vigorous surrounding a formerly habited rural house (Pardina de San Esteban). In Artosilla, oaks are located within a landscape dominated by dense pine plantations. The main planted pine species are *P. nigra* and *P. sylvestris*. Pines were planted mainly during the late 1950s when most villages of the study area were abandoned (Tarazona-Grasa, 2006).

The climate in the study area is Mediterranean continental with dry summers and cold winters (Fig. S1). The mean annual temperature is 12.5 °C and the total annual precipitation is 764 mm in the nearby Nueno station (42.402º N, 0.332º W, 795 m a.s.l., period 1993−2022). Soil moisture is recharged in winter, but there is a negative water balance in August and September (Fig. S1). Soils are basic of clay-sand texture (Table 2).

In addition to oak and planted pines, we found other minor tree and shrub species such as *Crataegus monogyna* Jacq., *Buxus sempervirens* L., *Genista scorpius* (L.) DC., *Amelanchier ovalis* Medik., *Juniperus communis* L., *Juniperus oxycedrus* L., and *Lonicera* spp. The study area is one of the less densely populated regions in Europe with population densities of 1−5 inhabitants km^{-2} (Gutiérrez et al., 2020).

2.2. Sampled oak species

In north-eastern Spain, *Quercus pubescens* Willd. and *Quercus faginea* Lam. characterize the transition between Eurosiberian and Mediterranean regions (Fig. 1). They mix in this mountainous region leading to the hybrid *Quercus subpyrenaica* E.H. del Villar (Amaral Franco, 1990). Our study stands are dominated by *Q. subpyrenaica* which is a species showing a moderate tolerance to drought (Himrane et al., 2004). Its radial growth is reduced by mid-term (6–9-month long) droughts ending in late summer and early autumn (Tonelli et al., 2023). It is a ring-porous, winter-deciduous species with anisohydric behavior, maintaining higher transpiration rates under mild-to-moderate dry conditions but being vulnerable to severe droughts (Poyatos et al., 2008; Martín-Gómez et al., 2017).

2.3. Quantifying land-use changes

We quantified land-use changes in the two sampled stands by comparing aerial photographs taken in four periods (1956−1957, 1997−1998, 2006, and 2018) using ArcGIS software release 10.8 (Redlands, ESRI, USA). The selection of these years was justified by the availability of good quality aerial images and because they captured periods before and after the massive rural migration and land-use alterations in Spain during the 1950s−1960s. This was done by inspecting cover types in areas of similar size in both sites, specifically 25 ha. We considered three major land cover types (croplands, pine plantations, and oak woodlands including pollards). In addition, to characterize the recent industrial transition, when most Spanish rural population migrated to cities (Collantes and Pinilla, 2011), and how it impacted on the study area we reconstructed the local human population from 1900

Table 1
Geographical, size and age features of the sampled oaks in the two study sites. The dbh is the diameter at breast height. Different letters indicate significant ($p < 0.05$) differences between sites. In the last column, the distance (in m) and dbh (in cm) of neighbouring trees are presented.

Site	Latitude (N)	Longitude (W)	Elevation (m a.s.l.)	Slope (°)	Aspect	dbh (cm)	Height (m)	Pollarding height (m)	Age at 1.3 m (yrs.)	Species, distance (m) and dbh (cm) of neighbours (m)
Aineto	42° 22' 51''	0° 12' 12''	1010	0–5	S-SW	114. 7 ± 6.0b	11.1 ± 0.6b	3.0 ± 0.2	260 ± 9	Oak, 8.6, 39.6
Artosilla	42° 24' 48''	0° 15' 31''	870	20–30	S-SW	83.9 ± 9.9a	7.5 ± 0.7a	3.4 ± 0.3	257 ± 11	Pine, 6.4, 26.0; oak, 5.4, 48.2

to the 2010s using demographic data from the Sabiñánigo municipality (Fig. S2).

2.4. Climate data, drought indices, and local air temperatures

Due to the lack of homogeneous, long-term records in the study area, we obtained monthly climate variables (Tx, mean maximum temperature; Tn, mean minimum temperature; Pr, total precipitation, and VPD; period 1950−2022) from the 4-km-gridded Terraclimate dataset (Abatzoglou et al., 2018).

To describe long-term changes in drought severity, we obtained reconstructed (period 1500–2010) 0.5°-gridded data of the summer (June to August) Palmer Drought Severity Index (PDSI) in the study area. This reconstruction corresponded to the Old World Drought Atlas (Cook et al., 2015) and data were downloaded from the webpage http://drought.memphis.edu/OWDA/. The PDSI data showed dry summer conditions in the late 1940s and early 1990s (Fig. S3). To characterize drought severity in the study area during the period 1950−2022, 0.5°-gridded monthly data of the Standardized Precipitation Evapotranspiration Index (SPEI) were obtained from the SPEI Global Drought Monitor webpage (https://spei.csic.es/). The SPEI is a multi-scalar index calculated as cumulative water balances which are estimated using temperature and precipitation data (Vicente-Serrano et al., 2010). We obtained SPEI at temporal resolutions from 1 to 24 months. Positive and negative SPEI values indicate wet and dry conditions, respectively.

To assess if there were differences in air temperature between oaks and nearby pine plantations, data loggers (EL-USB-1, Lascar, Whiteparish, UK) were placed in the Artosilla site. Six data loggers were placed in oak canopies and the other four were placed in pine canopies, always at mid-canopy in the SW aspect. They recorded air temperature with hourly resolution from 1 April to 30 August 2023. Air temperatures were significantly higher ($U = 6.8\ 10^6$, $p = 0.01$) in oak (mean ± SE = 17.4 ± 0.1 °C) than in pine (16.9 ± 0.1 °C) canopies (Fig. S4). In oaks, air temperatures reached lower minimum (-7.0 vs. −6.0 °C) and higher maximum (42.0 vs. 39.5 °C) values than in pines in spring and late summer, respectively. This wider thermal amplitude translated into a higher temporal variability of air temperatures in oaks (CV = 55 %) than in pines (48 %).

2.5. Field sampling

Field sampling was done in late autumn 2022 and winter 2022–2023. We obtained data from 15 and 9 apparently old, pollarded oaks in the Aineto and Artosilla sites, respectively (Table 3). More trees were inventoried and sampled in each site, but several of them have rotten sapwood or heartwood and they were discarded for further tree-ring analyses. The size (dbh, diameter at breast height measured at 1.3 m; total height and pollarding height) and the distance to the nearest neighboring tree, which species was identified, were measured using tapes and a laser rangefinder (Nikon Forestry Pro II). Then, we extracted two cores per tree at 1.3 m and at opposite directions using a Pressler increment borer. We also took five soil samples near each sampled tree, i.e. below its canopy and at 2 m from the main stem. Three soil subsamples were collected from the uppermost 15 cm and then pooled to get each individual sample. Litter was carefully removed before soil sample collection.

Soil samples for physical-chemical analyses were air-dried on a glasshouse and sieved with a 2-mm mesh size. Soil texture was determined with a laser diffraction method in a particle analyzer (Coulter Mastersizer, 2000), and clay content was corrected following Taubner et al. (2009). Soil C (organic and total), N, P, Ca, K and Mg concentrations were determined with an elemental analyzer (Element Analyzer VarioMAX N/CM, Hanau, Germany). The soils were basic in both sites, but siltier in Aineto and sandier in Artosilla. Regarding chemical characteristics, we found higher and element concentrations (N, P, and K) in Aineto than in Artosilla. In contrast, the C/N ratio and the Ca and Mg concentrations were higher in Artosilla (Table 2).

2.6. Quantifying growth trends, responses to climate and drought, and reconstructing pollarding events

Cores were air-dried, glued to wooden mounts, and surfaced with progressively finer grades of sandpaper for clearly detecting the ring boundaries. Sanded samples were scanned at 2400 dpi resolution and visually cross-dated (Yamaguchi, 1991). Then, ring widths were measured with a 0.01 mm resolution using scanned images and the CooRecorder-CDendro software (Larsson, 2005). The quality of cross-dating was checked using the COFECHA software which calculates moving correlations between individual ring-width series and the mean sites series (Holmes, 1983).

First, to accurately estimate tree age at 1.3 m we used graphical methods (template with concentric rings) in cores with innermost, curved rings, whereas in the other cases we estimated the length of the missing radius using diameter at breast height data after removing bark thickness (Norton et al., 1987). Second, to quantify growth trends, tree-ring width data were converted into basal area increment (BAI) assuming concentric radial growth. Trends in BAI were assessed using linear regressions and decadal variations were plotted using smoothing loess functions. Third, to assess the relationships between monthly climate variables (Tx, Tn, and Pr) or SPEI and growth, BAI series were detrended by fitting 32-year cubic smoothing splines and then dividing observed by fitted values.

The resulting series of dimensionless BAI indices were pre-whitened by fitting autore-regressive models, and their bi-weight robust mean was computed to obtain residual series. These pre-whitened BAI chronologies kept high-frequency variability at annual to decadal scales. Then, Pearson correlations were computed between the residual BAI series of each site and climate variables from the prior to current September. In the case of SPEI, correlations were calculated from current January to December considering 1- to 24-month long time scales.

Finally, we calculated the means and first-order autocorrelation (AR1) using raw ring-width series, and the mean sensitivity (MS) or relative difference in width between consecutive rings and the mean correlation between series (rbar) using indexed series (Fritts, 1976; Briffa and Jones, 1990) to characterize raw and indexed tree-ring width series, respectively. Calculated over the common 1870–2022 period (Table 3), an Expressed Population Signal (EPS) ≥ 0.85 indicates a high common signal in all sites (Wigley et al., 1984).

To estimate periods of growth suppression, which we attributed to past pollarding events, we calculated negative growth changes (*NGC*)

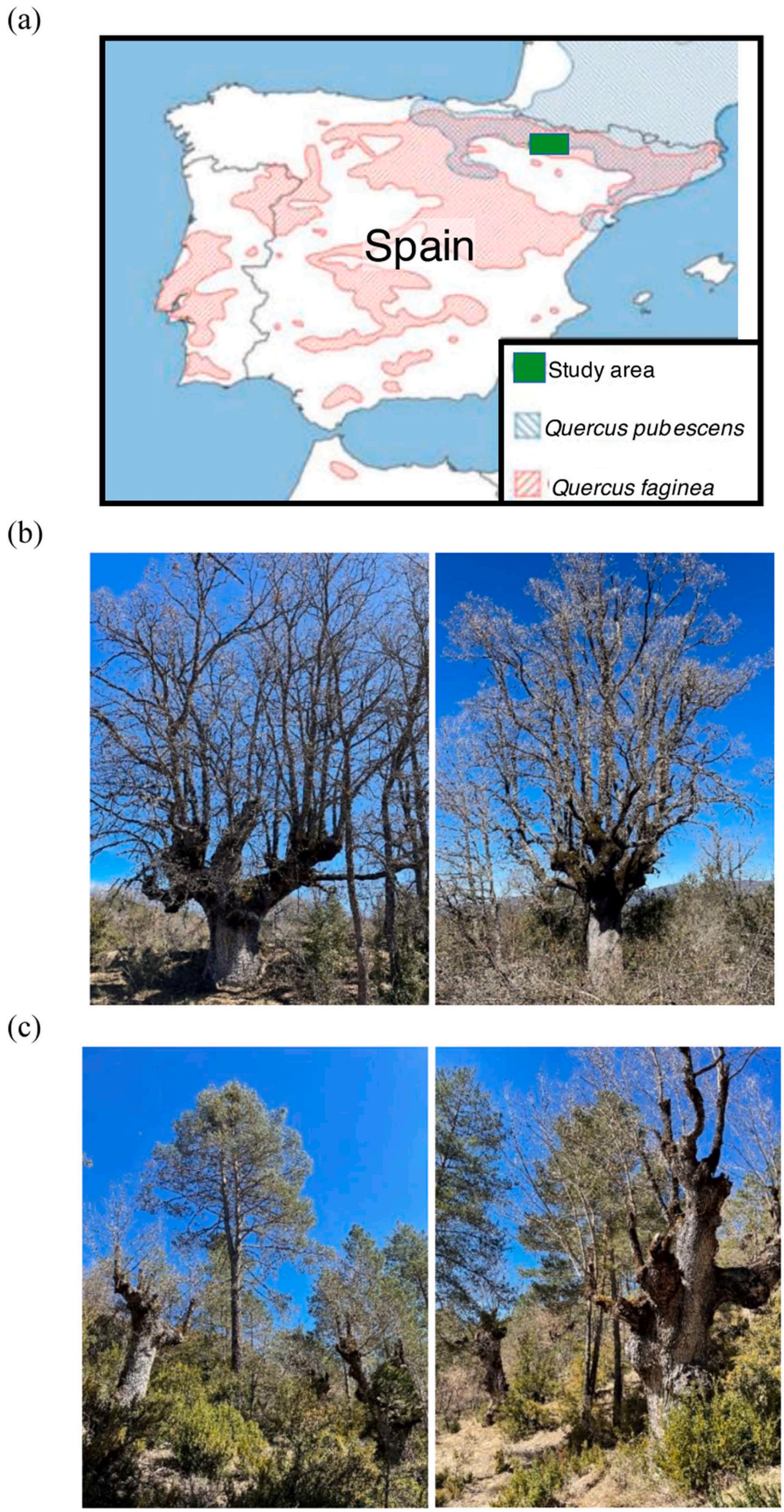

Fig. 1. Map showing the (a) location of the study area in the Spanish Pre-Pyrenees and views of sampled oaks in (b) Aineto and (c) Artosilla study sites.

Table 2
Soil characteristics of each sampled site. Different letters indicate significant ($p < 0.05$) differences between sites. Values are means ± SE.

Site	Texture			Chemical characteristics									
	Clay (%)	Silt (%)	Sand (%)	pH	$CaCO_3$ (%)	Organic C (%)	Organic matter (%)	N (%)	C/N	P (ppm)	Ca (ppm)	K (ppm)	Mg (ppm)
Aineto	19.8 ± 1.3	45.4 ± 0.8b	34.7 ± 1.2a	7.8 ± 0.1	28.7 ± 0.8	5.4 ± 0.7	9.3 ± 1.2	0.43 ± 0.05b	12.6 ± 0.3a	48.8 ± 10.0b	14235 ± 223a	480 ± 83b	231 ± 19a
Artosilla	16.6 ± 1.2	37.5 ± 1.4a	45.9 ± 2.6b	7.6 ± 0.1	29.9 ± 0.9	6.3 ± 0.1	10.9 ± 0.2	0.27 ± 0.01a	23.7 ± 1.0b	25.7 ± 1.9a	16556 ± 286b	309 ± 15a	549 ± 66b

Table 3
Tree-ring statistics of the sampled oaks in the two study sites calculated for the common period 1730–2022. Different letters indicate significant ($p < 0.05$) differences between sites. Values are means ± SE.

Site	No. trees (No. radii)	Maximum timespan	Tree-ring width (mm)	Basal area increment ($cm^2 yr^{-1}$)	AR1	MS	rbar	EPS (timespan)
Aineto	15 (30)	1712–2022	1.25 ± 0.11b	32.90 ± 0.43b	0.70 ± 0.08	0.25 ± 0.03	0.29	0.88 (1870–2022)
Artosilla	9 (18)	1730–2022	0.93 ± 0.06a	19.69 ± 0.29a	0.79 ± 0.03	0.23 ± 0.02	0.27	0.85 (1885–2022)

following Nowacki and Abrams (1997):

$$NGC = [(M_1 - M_2) / M_2] \times 100 \quad (1)$$

where M_1 and M_2 are previous and subsequent 10-year ring-width medians calculated on individual series and shifted every year.

We considered a 50 % threshold in NGC observed in at least 50 % of trees in each site for defining major growth suppressions, whereas a 25 %-threshold in at least 50 % of trees was regarded as moderate growth suppressions (Camarero et al., 2022; Camarero, and Valeriano, 2023.). The NGCs were obtained for periods with at least 10 sampled trees. Since the annual frequencies (f) of major and moderate growth suppressions depends on the changing sample size (number of measured trees, n) we corrected these frequencies (f_c) following Osborn et al. (1997):

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

Resilience indices were calculated on the standardized, detrended BAI series to assess post-drought recovery. We calculated the three indices proposed by Lloret et al. (2011), namely the resistance (R_t), recovery (R_c), and resilience (R_s) indices. calculated following Lloret et al. (2011):

$$R_t = G_d / G_{pre} \quad (3)$$

$$R_c = G_{post} / G_d \quad (4)$$

$$R_s = G_{post} / G_{pre} \quad (5)$$

where G_d is the mean of growth indices during drought years, and G_{pre} and G_{post} are the mean growth indices 3 years before and after drought years, respectively. We considered three-year periods because they provided reliable results on post-drought recovery in oak species (Anderegg et al., 2015; Bose et al., 2024). These were calculated considering four years characterized by very dry-warm summer conditions during the period 1950–2022: 1964, 1994, 2003, and 2012. Summer climatological conditions in these selected years are shown in Table S1.

To compare variables (tree dbh and height, ring widths, BAI, soil features, resilience indices) among sites the non-parametric Mann-Whitney test was used. To assess trends in BAI and climate-growth relationships linear regressions were fitted.

Analyses were carried out using the R statistical package (R Development Core, 2023). The tree-ring width series were detrended and standardized using the dplR package (Bunn, 2008, 2010; Bunn et al., 2023). The NGCs were calculated using the TRADER package (Altman et al., 2014).

3. Results

3.1. Changes in land-use cover

The analyses of aerial photographs allowed reconstructing changes in land cover types at a landscape scale (Figs. S5, S6). Oak woodland increased in Aineto passing from 18 % to 33 % in 1956–1957 and 2018, respectively, whereas it steadily decreased in Artosilla passing from 4 % to 1 % (Fig. 2). Pine plantations cover increased through time, but it was much higher in Artosilla (80–94 %) than in Aineto (14–46 %). In contrast, cropland cover, which has diminished in both sites, was higher in Aineto (21–68 %) than in Artosilla (5–17 %).

3.2. Growth patterns and trends

Considering the common period 1730–2022, the mean BAI of Aineto (32.9 $cm^2 yr^{-1}$) was significantly higher than that of Artosilla (19.7 $cm^2 yr^{-1}$; Table 3, Fig. 3**a**). In that period, the Aineto BAI linear trend was positive but not significant (slope = 0.001, r = 0.01, p = 0.86), whereas the Artosilla BAI trend was negative and significant (slope = −0.026, r =

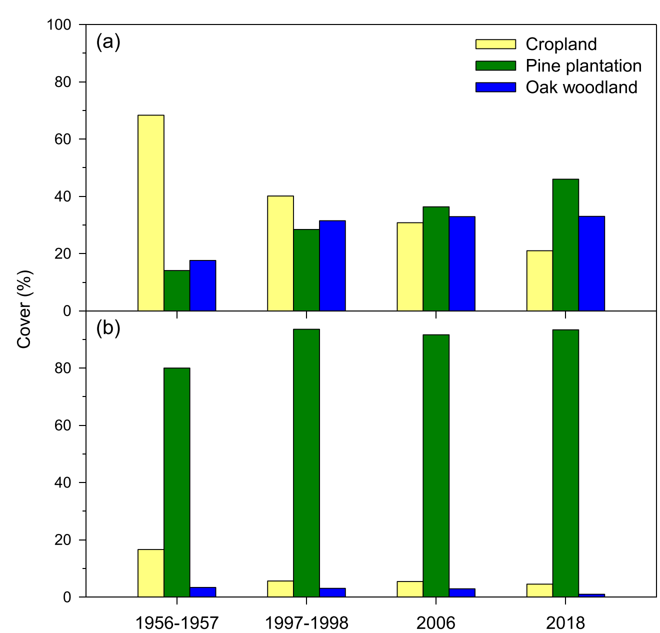

Fig. 2. Changes in land use in the two study sites (a, Aineto; b, Artosilla). The cover of the main land use types is given as percentages (see also Figs. S5 and S6).

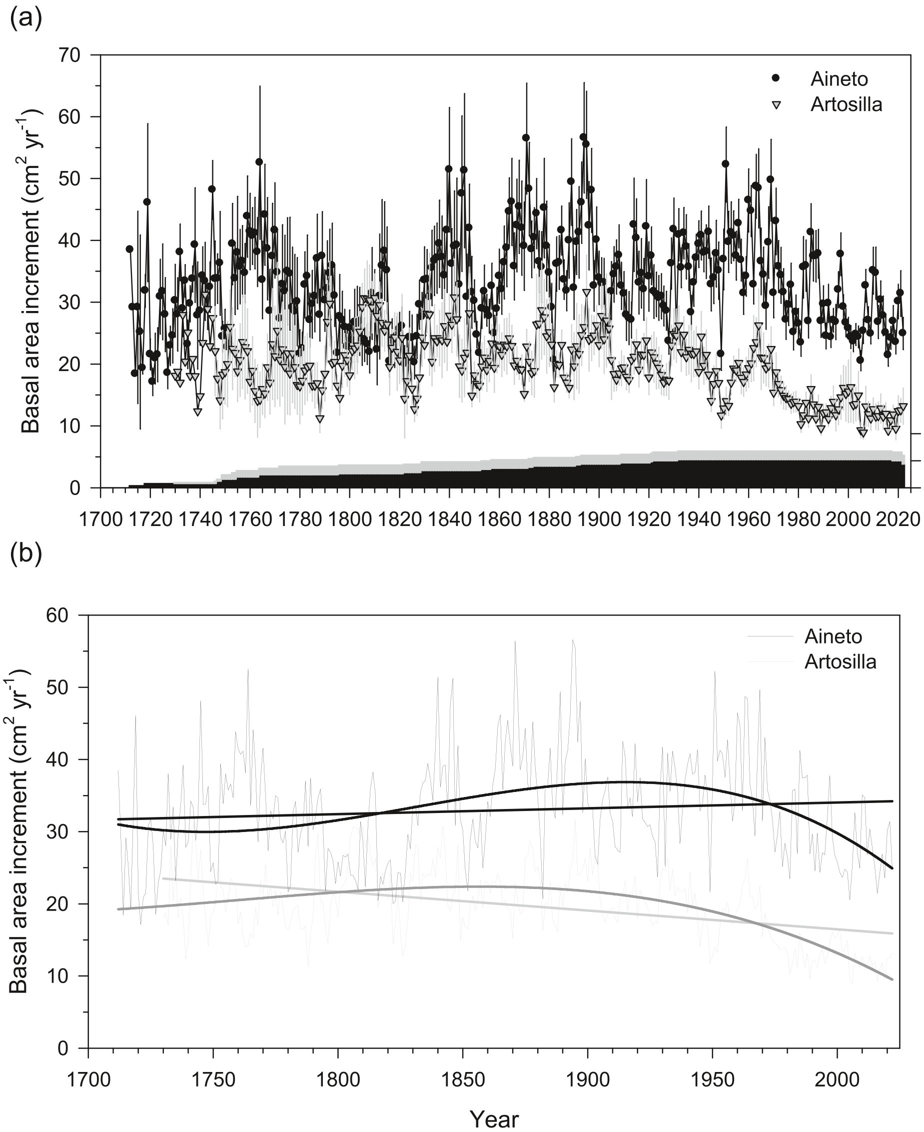

Fig. 3. (a) Oak basal area increment series (BAI) obtained in the Aineto and Artosilla study sites. Values are means ± SE. The right y axis shows the sample depth. (b) Trends in BAI. The lines show mean BAI series, linear regressions, and smoothed BAI functions (1-degree loess, 0.1 sampling proportion).

−0.44, $p = 0.0001$; Fig. 3**b**). According to ANCOVAs, the slope of Aineto BAI was significantly higher than that of Artosilla BAI ($F = 20.42$, $p < 0.001$). However, the BAI slopes were negative in both sites since the 1950s (Aineto, slope = −0.234; Artosilla, slope = −0.118; $p = 0.0001$ in both sites) and significantly differed ($F = 11.25$, $p = 0.0010$). The moving correlations between the sites' standardized BAI series showed they were increasingly synchronized after the 1950s, particularly in the warm-dry 1980s and 1990s, but this common signal recently decreased in the 2010s (Fig. S7).

3.3. Negative growth changes and resilience indices

Negative growth changes (NGCs) were common in the 1810s, 1820s, 1840s, 1890s, 1940s, and 1960s in both sites (Fig. 4). In Aineto, NGCs were also important in the 1790 s and 1870s, whereas in Artosilla they were prominent in the 1760 s and 1810s. The mean (± SE) duration of major growth suppressions in Aineto and Artosilla were 4 ± 1 and 5 ± 1 years, respectively. We found a main peak of major growth suppressions in the 1940s when 31 % and 75 % of trees showed major growth suppressions in Aineto and Artosilla, respectively (Fig. 5). The 1940s peak in NGCs showed clustered patterns with neighboring trees showing major growth suppressions in the two study sites (Fig. S8). The mean decadal frequency of major growth suppressions was the highest in that decade, affecting 53 % of trees as compared with a long-term (1750–2020) average of 11 % of trees. When comparing decades presenting major growth suppressions and excluding those without suppressions, we found a higher decadal frequency in Artosilla (23.8 ± 4.6 %) than in Aineto (13.0 ± 2.1 %), and differences were significant ($U = 72$, $p = 0.033$). No event of major growth suppressions was detected after the 1950s.

The resilience indices showed a higher resistance in Artosilla than in Aineto during the 2012 drought, but a higher recovery in Aineto during the 1994 drought (Table 4).

3.4. Relationships between growth, climate variables, and the SPEI drought index

In Aineto, oak growth decreased in response to high maximum temperatures and VPD in the prior winter (December, January) and current summer (July, August), whereas this was observed for March in the case of Artosilla (Fig. 6). Elevated minimum temperatures in April and high precipitation in June enhanced growth in Aineto. High

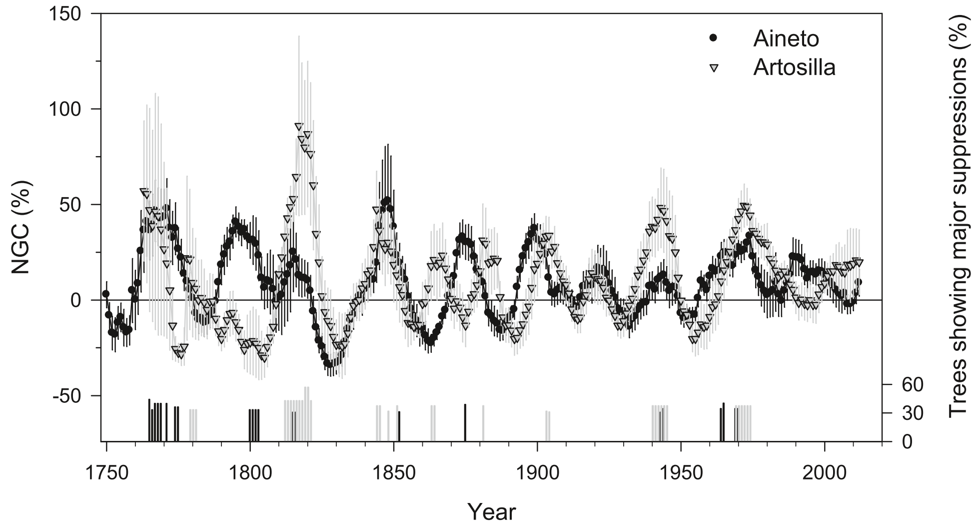

Fig. 4. Series of negative growth changes (NGC) in the Aineto (black lines and bars) and Artosilla (grey lines and bars) study sites. Values are means ± SE. The right y axis shows the frequency of trees showing major suppressions, i.e. NGC values above the 50 % threshold.

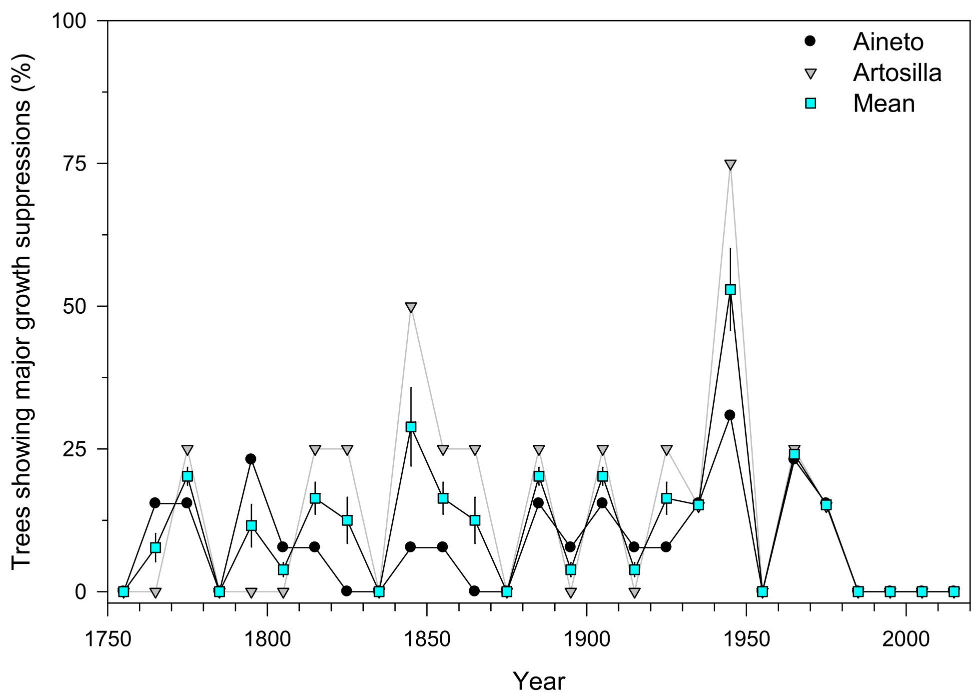

Fig. 5. Decadal frequencies of trees showing major growth suppression in the two study sites. The blue symbols show mean ± SE values.

Table 4
Resilience statistics of oak growth calculated for selected dry-warm years (1964, 1994, 2003 and 2012) in the two study sites. Different letters indicate significant ($p < 0.05$) differences between sites. Values are means ± SE.

Years	Resistance		Recovery		Resilience	
	Aineto	Artosilla	Aineto	Artosilla	Aineto	Artosilla
1964	1.15 ± 0.05	1.13 ± 0.07	0.74 ± 0.03	0.80 ± 0.06	0.85 ± 0.05	0.90 ± 0.07
1994	1.05 ± 0.05	1.13 ± 0.10	1.07 ± 0.05b	0.87 ± 0.03a	1.10 ± 0.06	0.98 ± 0.10
2003	1.04 ± 0.05	1.00 ± 0.06	0.92 ± 0.04	0.90 ± 0.05	0.93 ± 0.03	0.89 ± 0.06
2012	0.79 ± 0.03a	0.95 ± 0.07b	1.09 ± 0.04	1.09 ± 0.10	0.86 ± 0.04	0.97 ± 0.07

precipitation in the previous December enhanced growth in both sites.

Correlations between growth indices and the SPEI drought index were higher in Aineto than in Artosilla (Fig. 7). The maximum correlations were obtained considering 2- to 12-month temporal scales from March to October. In Aineto, the maximum correlation between the SPEI and the residual chronology ($r = 0.41$, $p = 0.0004$) was obtained for August considering 10-month temporal scales, whereas this occurred in April considering 6-month scales in the case of Artosilla ($r = 0.28$, $p = 0.019$). Moving BAI−SPEI correlations showed increased coupling of growth with drought stress in the 1960s and 2000s. In the late 2000s there was a decoupling of BAI−SPEI relationships, which was particularly strong in Artosilla. Here, there has been a significant decrease in the BAI−SPEI correlations (slope = −0.004, $p = 0.0001$).

The decrease in BAI series of both sites after 1965 coincided with increasingly drier summer conditions according to the reconstructed

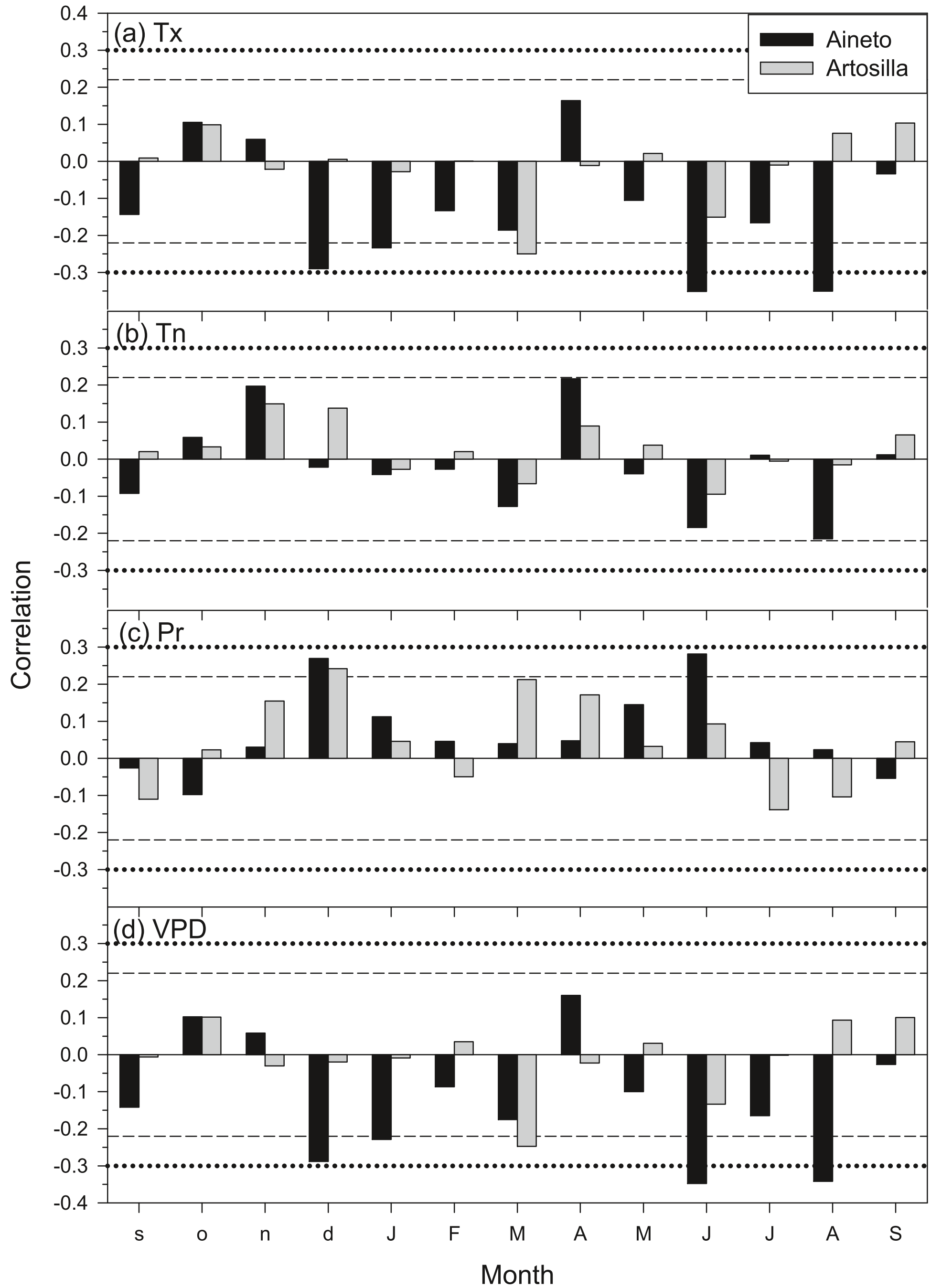

Fig. 6. Climate-growth relationships calculated for the Aineto and Artosilla study sites. Bars are Pearson correlations obtained for the common period 1950–2022 by relating monthly climate variables (a, Tx, mean maximum temperature; b, Tn, mean minimum temperature; c, Pr, precipitation; d, VPD, vapour pressure deficit) 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 dashed and dotted lines show 0.05 and 0.01 significance levels, respectively.

PDSI (Fig. S9). In contrast to what was found with the SPEI (Fig. 7), Artosilla showed a stronger response to the long-term summer PDSI which has strengthened and peaked during dry periods such as the late 1940s, early 1950s, and 1990s (Fig. S10). Overall, Artosilla growth responded more to summer drought in the past.

Growth in Aineto responded more negatively to summer VPD than in Artosilla (Fig. 8) in agreement with climate− (Fig. 6) and SPEI−growth (Fig. 7) correlations. We found negative and significant moving correlations between summer VPD and the Aineto growth indices in 1920−1943, 1948− 1982, and 2003−2022. Since the 1990s, record summer VPDs have been calculated. For instance, the summer VPD values in 1994 (1.45 kPa), 2003 (1.31 kPa), and 2022 (1.57 kPa) were significantly ($p < 0.05$) higher than the 1920−2022 mean VPD (1.08 kPa).

4. Discussion

The abandonment of historical forest use (pollarding), site conditions (topography, soil features, and pine plantations), and current drying trends contribute to the decline of old pollarded oaks. Pollarding allowed mitigating drought stress and the cessation of this forestry practice is predisposing to drought-induced decline in the sites with worst growing conditions (Artosilla). Growth decline and a loss of tree vigor in this site are reflected by a loss in growth sensitivity to climate

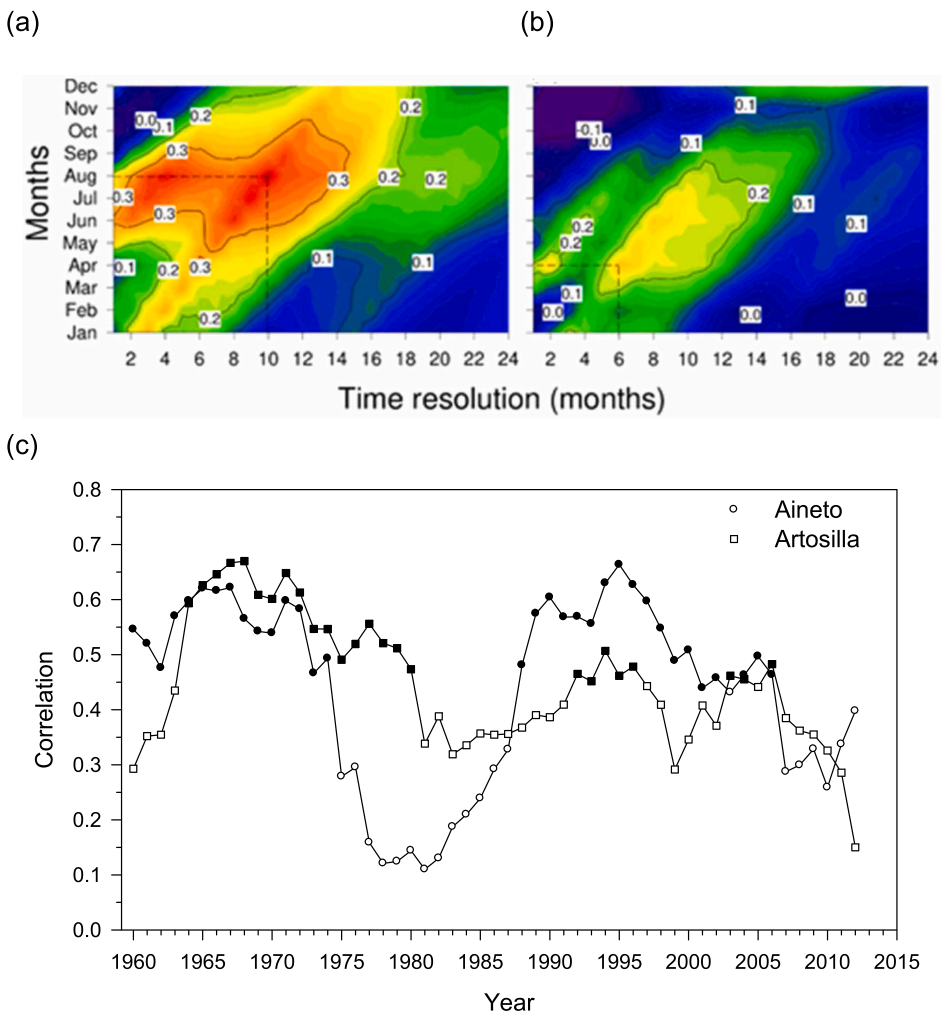

Fig. 7. Relationships between oak growth indices and the SPEI drought index calculated for the (a) Aineto and (b) Artosilla study sites. The color scales show Pearson correlation coefficients obtained for the common period 1950–2022 by relating monthly SPEI values (y axes) calculated at 1- to 24-month long scales (x axes). The lines indicate the month and temporal scale when the maximum correlation was obtained. Correlations were significant ($p < 0.05$) for $r > 0.23$. (c) Moving correlations between the SPEI values showing the maximum correlation and growth indices. These correlations were computed using 20-year intervals. The filled symbols indicate significant ($p < 0.05$) correlations.

and drought severity as compared with the site with better growing conditions (Aineto). As hypothesized, the Artosilla site with steeper slopes, less fertile soils, smallest trees, and higher cover of pine plantations showed the lowest growth rates. The lowest long-term growth trend was also more negative in that site than in the sites with the biggest trees showing faster growth rates (Aineto). Interestingly, the post-1975 BAI trend was lower in Aineto indicating growth stagnation in both sites. More major growth suppressions were found in Artosilla than in Aineto which suggested a more intense pollarding frequency or severity in the first site. Pollarding may lengthen tree lifespans, but if it is too severe or frequent could also reduce the vigour of trees, particularly under sub-optimal climate conditions (Camarero and Valeriano, 2023).

The adverse growing conditions in Artosilla could reduce soil water and nutrient uptake, decreasing oak cambial activity and reducing post-drought recovery as was found in 1994 (Bose et al., 2024). Here, pine plantations buffered the thermal amplitude and its daily variability as compared with open oak stands, suggesting lower radiation levels and higher competition for soil water and nutrients near dense pine stands. Dense pine plantations also reduce water yield and soil nutrients at local scale (Jobbágy et al., 2013; Moyano et al., 2024) and decrease the albedo and rise local temperatures (Moyano et al., 2024). This could amplify drought stress and reduce soil quality in Artosilla, but detrimental effects of pine plantation on oak growth should be further investigated by assessing direct competition between the two species. In contrast, the more fertile soils in the flatter Aineto site could have contributed to better growing conditions. Here, the higher soil concentrations of some important nutrients (N, P, K) could reflect a more intensive use of nearby fields for grazing and cultivation and historical fertilization, better soil conditions (water holding capacity, N uptake), or a higher activity of soil microbiota. The more open conditions of Aineto oak woodland could also lead to a higher availability of soil nutrients as compared with Artosilla, where pine cover was much higher.

Past pollarding events were found in the tree-ring series of both study sites and corresponded to the already described abrupt drop in latewood production 2–5 years following the cutting of branches and recovery afterwards (Bernard et al., 2006). Artosilla presented stronger NGCs and more trees showing major growth suppressions in the 1810s, 1820s and 1940s indicating a more intense, historical use of these oaks. The severe growth reduction after pollarding events lasted 4−5 years, which concurs with previous studies (Rozas, 2004). It is remarkable the elevated frequency of trees which showed major growth suppressions in Aineto during the 1940s, which may reflect an increased demand for firewood and timber after the Spanish Civil War (1936−1939), prior to massive pine plantations. A similar pattern was found for pollarded black poplars

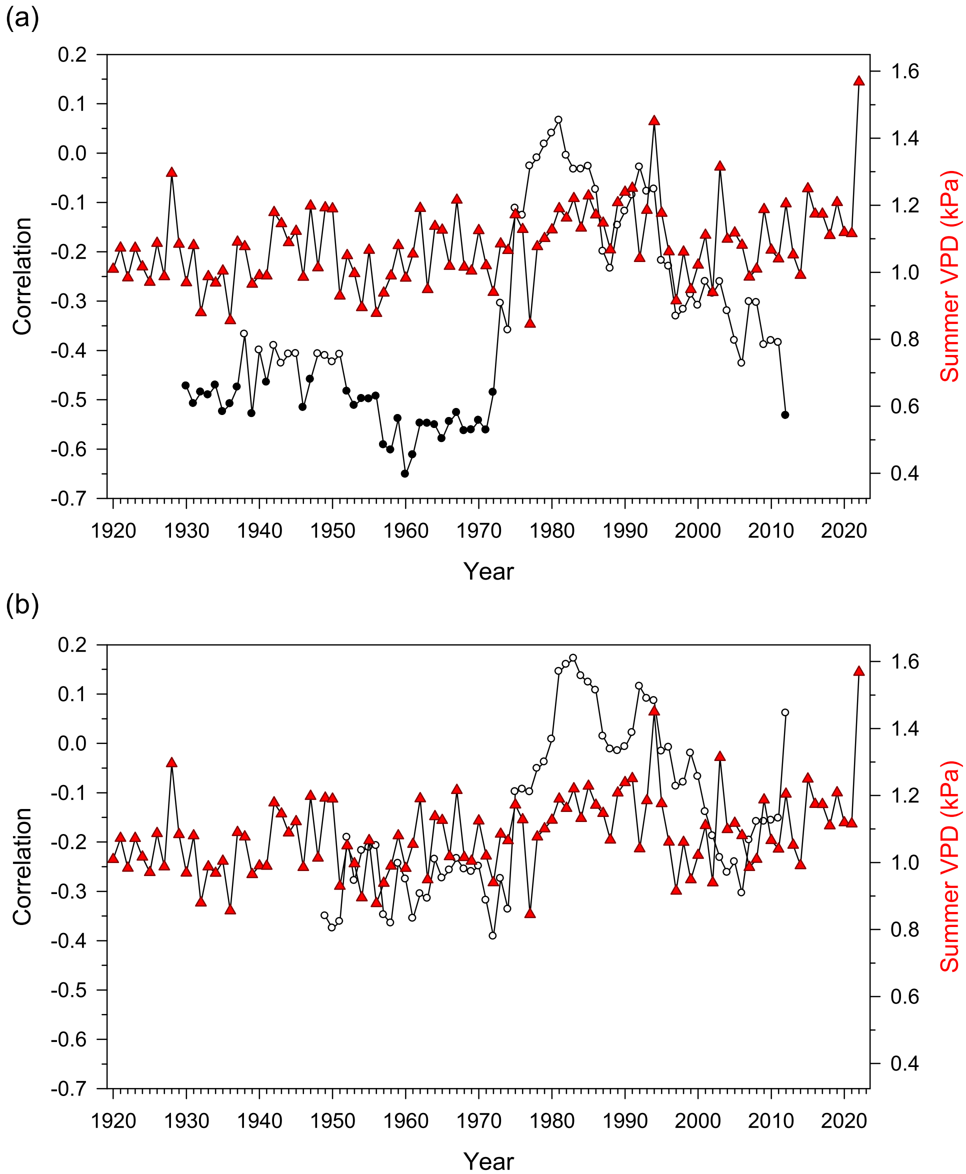

Fig. 8. Moving correlations (black and white symbols, left y axis) calculated by relating the oak growth chronologies from (a) Aineto and (b) Artosilla sites and mean summer VPD (red triangles, right y axis) using 20-year intervals. The filled black symbols indicate significant ($p < 0.05$) correlations.

(*Pinus nigra*) in eastern Spain (Camarero et al., 2022). This could reflect that pollarding was carried out until more recently in Artosilla than in Aineto, or that there were more and bigger oaks in Aineto available for pollarding (Fig. S8). To reach more robust conclusions on these questions, a more extensive and detailed inventory of pollarded oak stands should be carried out in the Guarguera Valley and in other areas affected by different past (intensive use) or recent (drought, soil loss, pine plantations) stressors.

We found that oak growth was constrained by warm-dry conditions in the previous winter and current summer, particularly in Aineto, and also by warm-dry conditions in early spring, particularly in Artosilla. These relationships and the response to mid-term summer droughts found in Aineto are in agreement with previous studies (Tonelli et al., 2023). The responsiveness to spring droughts in Artosilla could be an indication of vulnerability to warm conditions in the early growing season. Nevertheless, this influence seems to be decreasing, whereas long-term relationships with the summer PDSI were stronger in Artosilla than in Aineto and they are strengthening. This difference may reflect longer or chronic stressful climate conditions in Artosilla, at least in response to reconstructed summer drought, which could explain its recent loss in responsiveness to soil (SPEI) and atmospheric (VPD) drought. However, Aineto showed a higher sensitivity to drier summer conditions, particularly to elevated VPD values which were linked to reduced growth, since the 1950s, when its BAI rates rapidly declined. Given the anisohydric strategy of the study oak species, warm-dry summer conditions characterized by high atmospheric demand should lead to higher rates of water loss through leaves and decrease cambium divisions reducing growth rates (Alla and Camarero, 2012). In addition, warm-dry conditions in the prior winter and spring would amplify summer drought stress because the soil water recharge mainly happens from November to April (Fig. S1). It has been shown that winter precipitation, before growth onset in spring, is critical to the growth of Mediterranean oaks subjected to summer drought (Alla and Camarero, 2012; Gea-Izquierdo and Cañellas, 2014). In summer, Mediterranean oaks are able to uptake deep soil water sources to keep high transpiration rates (Hernández-Santana et al., 2008; Ripullone et al., 2020).

Oak trees showed a noticeable decline in growth in response to dry conditions in the late 1940s, before drastic land-use changes. This could be related to dry and warm conditions, but it is challenging to distinguish potential interacting impacts of drought and pollarding on growth without external records of management treatments. Further research should consider obtaining indirect historical sources of pollarding severity including the amount of extracted firewood. Regrettably, such information would only be available in few pollarded oak woodlands subjected to intensive historical exploitation. In addition, the resilience indices showed mixed results, which could depend on drought timing and post-drought climate conditions. For instance, oaks showed a good recovery after the dry-warm 1964 spring because the autumn was wet and it was followed by high precipitation in spring 1965.

To conclude, our findings suggest that the two studied pollarded oak stands could show an irreversible growth decline in the late 21st century. This is a very probable scenario for the declining Artosilla site which showed low growth rates, but also plausible for the fast-growing Aineto site where growth rapidly decreased in response to aridification and hotter-drier summer conditions since the 1980s. In general, the positive correlations between the BAI series of both sites after the cessation of pollarding and the increase of temperatures in the 1980s point to a shared climate forcing, specifically warming-related drought stress. Pollarding cessation is predisposing to drought-induced decline in sites with poor growing conditions, and this progressive loss of vigor is manifested as reduced growth sensitivity to climate. Pollarded oaks require active management measures (periodic pollarding by cutting branches in winter, pine removal to increase local water yield, and buffer drought stress) to avoid collapsing and dying.

CRediT authorship contribution statement

Cristina Valeriano: Writing – review & editing, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **Ester Gonzalez de Andres:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation. **Michele Colangelo:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **J. Julio Camarero:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Manuel Pizarro:** Writing – review & editing, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Enrique Murria:** Writing – review & editing, Visualization, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of Competing Interest

Authors declare no conflict of interest.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dendro.2024.126232.

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