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ORIGINAL PAPER

Radial growth variations of black pine along an elevation gradient in the Cazorla Mountains (South of Spain) and their relevance for historical and environmental studies

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Abstract In southern Spain, the Cazorla Mountains (500–2,100 m a.s.l.) have supplied construction timber from black pine (*Pinus nigra* Arn.) for buildings and ships since at least the Middle Ages. To establish the age and provenance of wooden cultural heritage originating from this area, well-replicated long-span chronologies are needed. Old-living trees occur at high elevations, whereas many historical timbers originated from lower altitudes; hence, crossdating possibilities were questionable. To assess the potential of this species for the development of a multi-millennia tree-ring data set with living trees and historical timbers for the western Mediterranean, we developed four ring-width chronologies along the circa 1,000 m altitudinal range of black pine in these mountains and examined crossdating patterns and climate–growth responses along with altitude and through time. Teleconnections with other Iberian and Mediterranean tree-ring data were also tested. A well-replicated chronology spanning AD 1331–2009 was obtained at the upper site, while lower elevations delivered shorter chronologies. Similarity among chronologies and responses to climate were dependent on elevation. Tree-ring width was negatively related to temperature in previous late summer and positively to February–March, whereas precipitation had an opposite effect; some negative influence of early summer temperature was also observed. However, growth responses were rather unstable throughout the twentieth century. These chronologies showed good tele- and heteroconnections with conifer chronologies from Iberia, northern Morocco and Turkey, evidencing the existence of a common macroclimatic signal, which also varied along with elevation. The relevance of these results for dendrohistorical studies is discussed.

Keywords Dendrochronology · Pinus nigra · Tree-ring width · Radial growth responses · Teleconnections · Cultural heritage

Introduction

Radial tree growth is the result of several endogenous and exogenous factors (Fritts 1976; Cook 1990). Among these, the climate-related environmental signal is assumed to be always present in tree-ring series to a greater or lesser extent, depending on the limiting effects of climatic variables such as temperature and water availability (Fritts 1976; Kozlowsky and Pallardy 1997). Annual differences in temperature and precipitation induce year-to-year (i.e.,

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high-frequency) growth variations. These variations are the keystone for crossdating tree-ring series (i.e., matching them in their exact position) from trees of the same or different species that have grown under similar environmental conditions during specific periods of time, as they are likely to have synchronous patterns (Fritts 1976). In central and northern Europe, tree-ring patterns of oak (*Quercus robur* L. and *Q. petraea* Matuschka Liebl.) and different conifer species show highly significant correlations (i.e., tele- and heteroconnections) over large areas for the Holocene (e.g., Leuschner et al. 2002; Eckstein et al. 2008, 2010), and from the Roman times to the Modern Period (e.g., Baillie 1982; Briffa et al. 1992; Büntgen et al. 2011a,b).

Such tele- and heteroconnections, which are the result of macroclimatic signals prevailing across large territories (Fritts, 1976), allowed the construction of ultra-long supra-regional chronologies that served, for example, to reconstruct former (and predict future) environmental conditions (Briffa et al. 1992; Leuschner et al. 2002; Büntgen et al. 2005, 2011a, b), to calibrate the radiocarbon curve for the northern hemisphere (see for an overview Kromer 2009 and references therein) and to absolutely date (pre)historical constructions, artifacts and vegetation-remains from the cultural and natural heritage (e.g., Jansma 1996; Kuniholm 1996; Haneca et al. 2009 and references therein).

At regional levels, however, the spatiotemporal behavior of tree-growth response to climate still remains intriguing, as it has been observed to have a dynamic character (e.g., Mäkinen et al. 2002; Carrer and Urbinati 2006; Andreu et al. 2007; Büntgen et al. 2012). In practice, climate-induced high growth-variability within small geographical areas (along elevation gradients for example) may hamper crossdating of tree-ring series (Wilson and Hopfmueller 2001), therefore limiting the retrospective extension of chronologies with local wood from (pre)historical sources originating from different elevations.

The south of Spain, influenced by Mediterranean climate, but also by Atlantic weather conditions, represents the southern and/or western distribution limit for several species, therefore is a critical spot for ecological and climatological studies (e.g., Linares and Tíscar 2011 and references therein). Furthermore, its strategic position along historical trade routes, and the abundance of cultural heritage in and originating from the region (De Aranda y Antón 1999; Rodríguez Trobajo 2008), makes it a highly interesting area for dendrohistorical and archeological research. Within this area, the Cazorla Mountains have supplied construction timber for buildings and ships since at least the Middle Ages (e.g., Córdoba de la Llave 1990; De Aranda y Anton 1990; De la Cruz Aguilar 1994; Araque Jiménez 2007), especially from black pine (*Pinus nigra* Arnold subsp. *salzmannii* (Dunal) Franco). This species was highly appreciated for the quality of its wood for construction purposes (Fernández-Golfín et al. 2001). Consequently, black pine from the Cazorla Mountains can be found nowadays in a great number of historical buildings in the western Mediterranean, and in shipwrecks all over the world, offering an invaluable source of tree-ring data for environmental, timber-trade and historical studies.

Black pines of the Cazorla Mountains represent relic forests growing at the southwestern distribution limit of this subspecies (Alejano and Martínez 1996), and despite centuries of intensive logging in most areas of the mountain range, trees reaching 1,000 years of age had been reported at the highest elevations close to 2,000 m a.s.l. (Creus 1988). Those trees are living archives of past climate, and they could also provide a much needed millennium-long tree-ring chronology for dating cultural heritage in the region. Such chronology could be in turn improved and extended retrospectively with local wood from historical sources. However, the possibility to crossdate historical timbers of this species that may have originated from low elevations with a chronology derived from the millennium-old black pines from the upper part of the mountains remained questionable. In the Bavarian region (south of Germany), heterogeneous tree-growth responses to climate along an elevation gradient make dendrochronological dating of timbers from historical buildings remarkably difficult (Wilson and Hopfmueller 2001; Dittmar et al. 2012). In the Cazorla mountains, studies including black pine tree-ring records are abundant (e.g., Richter et al. 1991; Andreu et al. 2007; Martín-Benito et al. 2008; Linares and Tíscar 2010, 2011; Dorado Liñán et al. 2012), but are exclusively focused on ecological or climatological questions. Consequently, the ring-width chronologies developed so far in this region are either too short to be suitable for dendrohistorical studies (Martín-Benito et al. 2008; Linares and Tíscar 2010, 2011) or include only trees from the highest elevations (Richter et al. 1991; Andreu et al. 2007; Dorado Liñán et al. 2012). A well-replicated long-span data set of black pine covering ca. 1,000-m elevation gradient in the Cazorla Mountains was therefore needed. Understanding radial growth responses to climate along the elevation gradient of this species in southern Spain would help defining appropriate strategies toward compilation of (historical) tree-ring data and chronology building for dating cultural heritage, and as historical and environmental archive. Therefore, the objectives of this study were the following:

- To develop long-span tree-ring chronologies along the whole elevation gradient (ca. 1,000 m) of black pine in the Cazorla Mountains;
- To analyze the climatic variables that regulate radial tree growth at different elevations;
- To assess the evolution of radial growth responses to those climatic variables through time;

- To study the tele- and heteroconnections of the created chronologies with existing chronologies of black pine and other conifer species from Iberia and the Mediterranean basin.

Materials and methods

Study area

The Cazorla Mountains (Fig. 1a) are included within the Cazorla, Segura and Las Villas Natural Park, a mountain woodland spreading northeast to southwest at the eastern corner of the Baetic System in the Andalusian region (southeast of the Iberian Peninsula). It is the largest protected area in Spain, covering 209,921 ha, and constitutes a very important hydrological area, where the river Guadalquivir, flowing west to the Atlantic Ocean, and the Segura River, flowing east to the Mediterranean Sea, originate (Fig. 1c).

The climatic regime is typically Mediterranean (Fig. 1b) characterized by a hard summer drought, changing precipitation between and within years, and strong differences between maximum and minimum temperatures along the year, sometimes even within a day (Tíscar 2004). Average rainfall is about 1,100 mm/year (ranging from 400 to 1,900 mm), November and April being the wettest months, and July and August the driest (Fig. 1b). Average temperature is 11.7 °C, with minima in January (4 °C) and maxima in August (21 °C), but weather is very variable with altitude and topography.

Lithology consists mainly of limestone and dolomites, the latter restricting the development of many tree species. A craggy topography characterizes these mountains, with altitudes ranging from 500 to 2,107 m a.s.l. at the highest point (*Empanadas* peak).

The most important coniferous species in the Cazorla Mountains are pines (*Pinus halepensis* Mill., *P. pinaster* Ait. and *P. nigra* subsp. *salzmannii*), which distribute in slopes and valleys according to edaphic conditions and elevation. Common hardwood species are *Quercus ilex* L. *and Q. faginea* Lam., which grow at lower altitudes, and are often mixed with maples (*Acer* spp.), aspens (*Populus* spp.), rowans (*Sorbus* spp.) and ashes (*Fraxinus* spp.). Black pine is the most abundant pine species, covering 60,000 ha between 1,000 and 2,000 m a.s.l. (Tíscar 2004). This pine is adapted to poor and shallow soils, steep slopes, and rocky areas, where other more demanding species cannot survive (Alejano 1997).

Site selection and sampling strategy

In April and September 2010, we selected and sampled four sites in the Cazorla Mountains along an elevation transect of ca. 1,000 m (Fig. 1c), covering the whole altitudinal range of black pine in the southeast of Spain. Cabañas (CBS, 1,755–1,953) lay at the altitudinal limit of the species in this mountain range; Navanoguera (NAV, 1,582–1,702), at mid-

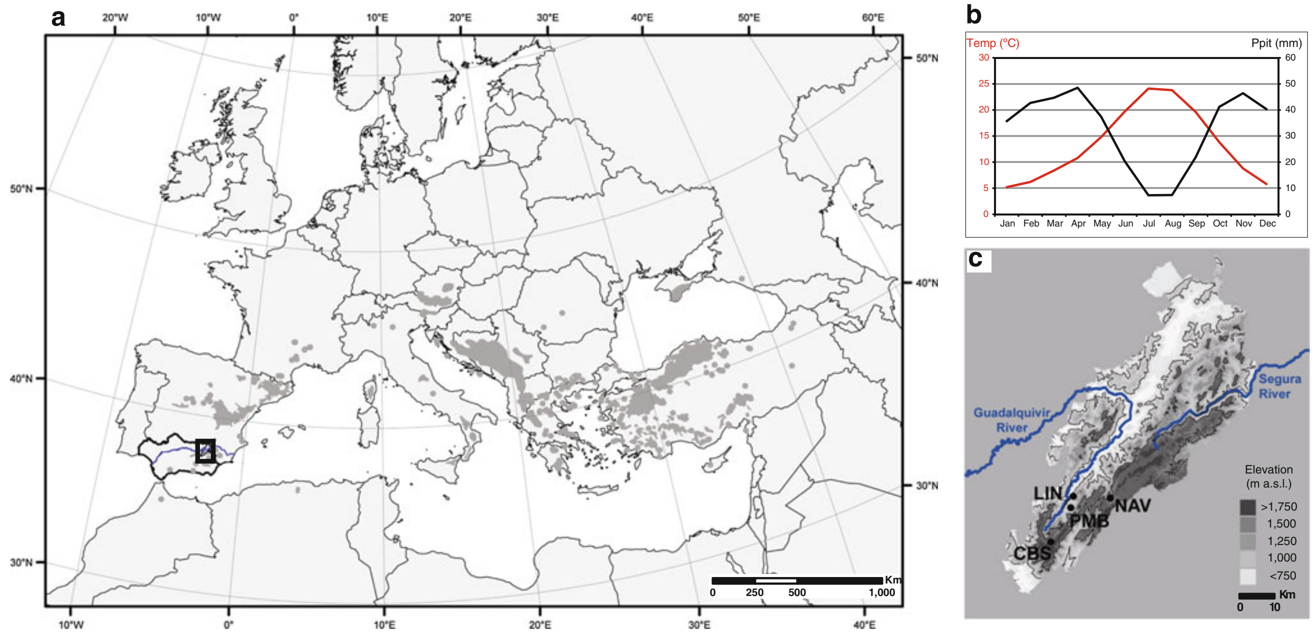


Fig. 1 **a** Distribution of *Pinus nigra* (source: EUFORGEN 2009, www.euforgen.org) and location of the Cazorla Mountains in the southeast of Spain (*square*); **b** Climatic diagram of the study area calculated for the period 1901–2009, using temperature (°C) and precipitation (mm) data from the Climate Research Unit (CRU), University of East Anglia, UK, available at http://climexp.knmi.nl; **c** Location of the selected sites in the Cazorla Mountains

elevation, represented an open valley with low smooth slopes located in the divide between the Atlantic and the Mediterranean aspects of the Cazorla Mountains; Poyos de la Mesa (PMB, 1,500–1,619), still mid-elevation site but slightly lower than NAV, was located on a high-elevation plain descending toward a southern slope; finally, Linarejos (LIN, 1,079–1,177 m a.s.l.), the site at the lowest altitude, represented a mixed forest of *P. nigra* and *P. pinaster* growing on a narrow valley.

To ensure a high replication of the chronologies, we selected a minimum of 19 trees (LIN) of different diameters and appearance at each location, trying to include most age classes. At the mid-elevation sites, we sampled 20 (PMB) and 21 (NAV) trees, and at the high-elevation site (CBS), up to 55 trees were selected, to ensure that some of the samples would have a continuous series where others could contain absent rings. For each selected tree, we extracted between two and five cores at breast height using 60-cm-long increment borers (5 mm diameter). The final data set comprised 270 cores. We recorded coordinates and elevation, as well as the most relevant characteristics of each individual (height, diameter and apparent anomalies) and its environment (soil appearance, slope and exposition).

Acquisition of tree-ring data

Cores were glued onto wooden supports with the tracheids placed vertically to allow the preparation of the transversal surface. A Stanley knife was used to facilitate the visualization of the rings, and chalk powder was applied to the cleaned surface to enhance the contrast between tree-ring boundaries. Ring widths were measured to the nearest 0.01 mm using a TimeTable measuring device (VIAS, University of Vienna) coupled with the PAST4 v.4.3 program (B. Knibbe, SCIEM).

Crossdating of series from the same site was done by statistical and visual comparison of tree-ring series using PAST4. During this step, numerous missing or locally absent rings were identified. Once the exact position of an absent ring was located in the sample, a ring with a low value was inserted into the measurement to allow the continuity of the series and yet register an anomaly for that year. Parts of the tree-ring series where absent rings were too numerous to allow an accurate insertion of rings were excluded from further analysis. The insertion of the rings and the quality of the crossdating among the series were verified with the software COFECHA (Holmes 1983; Grissino-Mayer 2001).

Computation and quality assessment of the Cazorla chronologies

After crossdating the individual tree-ring series, site standard (STD) and residual (RES) chronologies were computed with the program ARSTAN (Cook and Holmes 1986) using a single average series per tree. The purpose of standardization is to remove non-desired signal imbibed on raw ring-width series and caused, for example, by natural age-trends, successional changes in the forest stand, human-induced signals, etc. (Fritts 1976; Schweingruber 1996). As many series showed variations that could be due to forest dynamics and human interventions, and given the length of the series (> 100 years), we filtered them using a 100-year cubic smoothing spline and 50 % variance reduction. This spline length was found to maximize the signal-to-noise ratio (Wigley et al. 1984) of the chronologies, while removing age trend and other non-common variance (Cook and Peters 1981). The resulting dimensionless ring-width indices (RWI) were averaged with a biweight robust mean, which reduces the influence of outliers, into a STD chronology for each site. RES series were obtained after removing autocorrelation (i.e., previous year's influence on current year's growth) from the standardized series by first applying an autoregressive modeling (order 1) to the RWI and then averaging the residuals with a robust mean. We used the RES chronologies to compute climate–growth analyses.

The quality of both STD and RES chronologies was assessed with the mean correlation between trees (rbar) (Briffa and Jones 1990) and the expressed population signal (EPS) (Wigley et al. 1984). Rbar indicates the strength of the signal between trees (Fritts 1976), and EPS indicates the extent to which the sample size is representative of a theoretical infinite population for a given site. Intervals of a chronology attaining a value higher than 0.85 are commonly considered to have a high statistical quality (Wigley et al. 1984; Briffa 1995).

Analysis of the common signal between the Cazorla chronologies

The four standard chronologies were compared to each other for their common interval attaining an EPS > 0.85 (namely 1840–2009) using Pearson's correlation coefficient with its associated Student's t value (t), and the percentage of parallel agreement (GL), along with the statistical significance of the latter (P_{GL}). To observe the variability of the correlations between the chronologies through time, we calculated moving correlations between the chronologies, using 50-year segments lagged one year for the same period.

To assess the differences between the standard chronologies, we calculated principal components (PC) and used their loadings on the first and second PCs following a varimax rotation to study the ordination of the sites along the altitudinal gradient. This emphasizes the differences between sites, because each rotated PC tends to be associated with only some chronologies, so that the others do

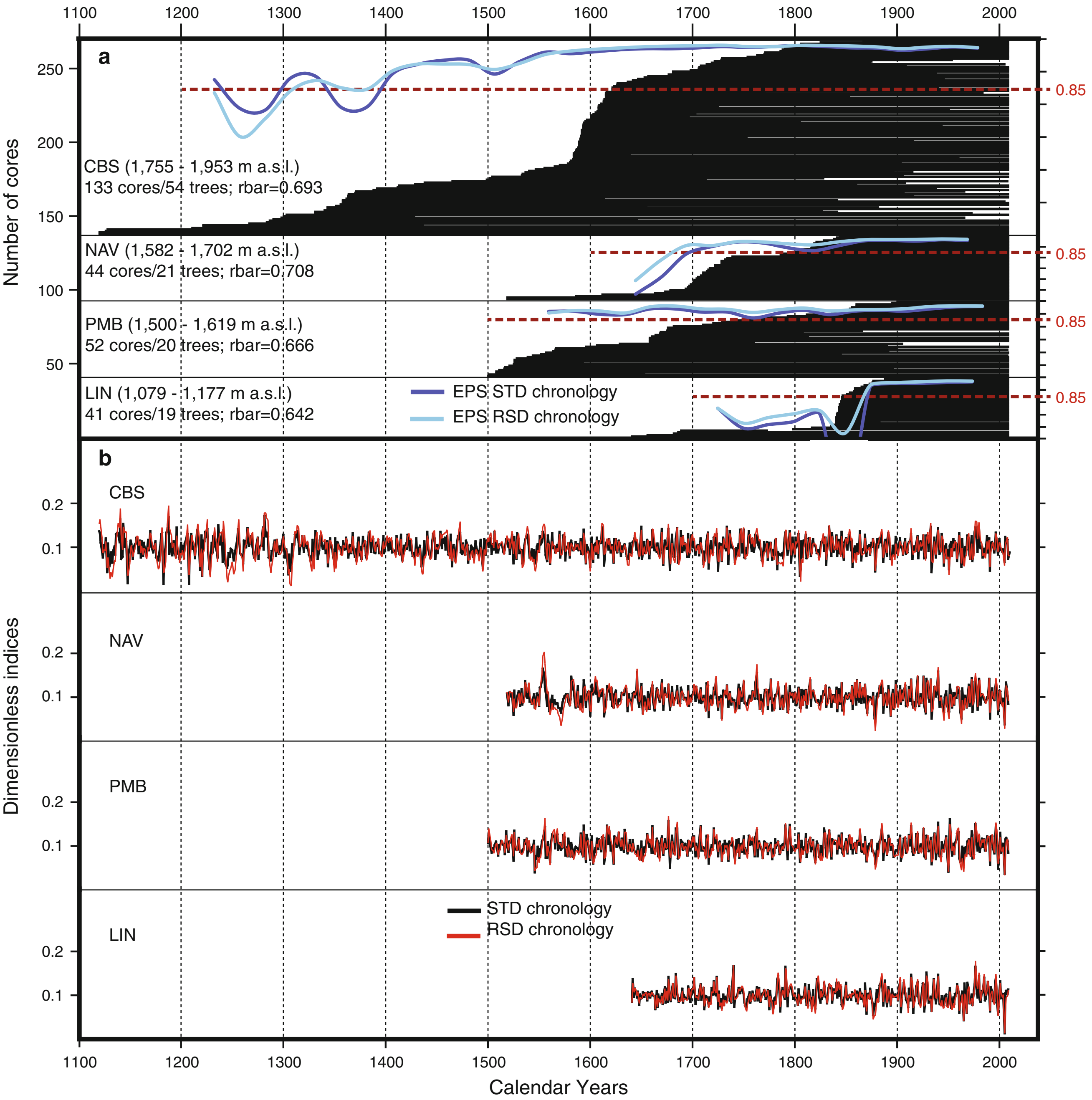


Fig. 2 **a** Time span and number of individual cores collected at each site; rbar: intra-site tree correlation; EPS from standard (STD) and residual (RSD) chronology computed by ARSTAN; **b** STD and RSD chronologies computed for each site

not bear any high positive loadings on the corresponding PC. These analyses were carried out in R (R Development Core Team 2012).

Evaluation of radial growth response to climate and its spatiotemporal variability

In order to obtain climate–growth relationships, we used climate gridded data (mean monthly temperature and total monthly precipitation) for the region, obtained from the Climate Research Unit (CRU), University of East Anglia, UK, publicly available at the website of the Royal Netherlands Meteorological Institute (http://climexp.knmi.nl/).

We calculated correlation and response functions using the RES chronologies and the available climatic data. As temperature and precipitation series covered the span 1901–2009, climate–growth relationships were calculated for a 16-month window (previous July to current October) along the period 1902–2009; in addition, climatic data were seasonalized to cover previous late summer (August–October) and current late winter-early spring (February–March). We first computed Pearsons' correlations and achieved their confidence intervals out of 10,000 bootstrap iterations applying the corrections proposed by Mason and Mimmack (1992), using a routine written in Embarcadero® Delphi® XE2. Response function analysis was also performed on the same data, by means of the program DendroClim2002 (Biondi and Waikul 2004), which calculates bootstrapped multiple regression on principal components. The functions were calculated for 1,000 iterations, and the significance of the regression coefficients was considered at $P < 0.05$. Afterward, to observe the variability of the climate–growth relationships obtained during the studied period and along the elevation transect, we computed moving correlation functions (Biondi 1997) covering 50-year periods and consecutively shifted 1 year.

Tele- and heteroconnections

The STD chronologies from Cazorla were compared with STD tree-ring reference chronologies of *P. nigra*, and other conifer species from Iberia and the Mediterranean basin to assess their similarities and the geographical extent of their common signal. A selection of 106 reference chronologies were downloaded from the International Tree-Ring Data Bank (ITRDB; website hosted by the NOAA Paleoclimatology Program and World Data Center for Paleoclimatology, http://www.ncdc.noaa.gov/paleo/treering.html), after having verified their quality (Table 1). We calculated Pearson's correlation coefficients, Student's t value, GL and P_{GL}:

- for the whole length of the chronologies (considering for the Cazorla chronologies the interval with EPS higher than 0.85);
- for an interval common to all (Cazorla and reference) chronologies (1840–1974).

We tested whether the differences between the chronologies from Cazorla Mountains along the elevation gradient followed a pattern when compared to the data set from the Mediterranean region. For this, we calculated Pearson's correlation (r) and GL on a matrix in which the sites from Cazorla served as variables and the values of crossdating to each of the Mediterranean chronologies as cases. The analysis was performed for the common period to all chronologies (1840–1974, 135 years). Afterward, both matrices entered a factor analysis with Varimax rotation, and the loadings on the two first principal components were used to understand the ordination of the site chronologies. These analyses were also performed in R.

Results

Common signal of site chronologies

The obtained data set comprised a total of 270 black pine tree-ring series from 114 trees located at elevations between 1,079 and 1,953 m a.s.l. Some attributes of the sampled trees (height, diameter, number of rings, ring-width and number of missing rings) are presented per site in Table 2. The chronologies developed showed a high statistical quality for dendrochronological purposes (Fig. 2). They shared the common period 1840–2009, restricted by the lowest elevation site (LIN) where the youngest trees were found. In contrast, the chronology from the highest elevation (CBS), which included five trees older than 700 years, reached back to AD 1331 with a high quality (EPS > 0.85). The chronologies at intermediate altitudes, PMB and NAV, provided a high statistical quality for intervals of variable length (1544–2009 and 1698–2009, respectively). The common signal of the chronologies, expressed as the mean correlation between trees (rbar), was very high for all four sites, ranging between 0.642 (LIN) and 0.708 (NAV) (Fig. 2). An EPS > 0.85 was attained with seven trees at LIN, NAV and CBS, and with eight trees at PMB.

The sites located at the upper (CBS) and lower (LIN) bounds of the elevation gradient showed the lowest similarity ($r = 0.45$, $t = 5.61$, $GL = 67.5$ % and $P_{\mathrm{GL}} < 0.001$) (Table 3). Accordingly, the best statistical match was provided by the sites located at a similar elevation, namely NAV and PMB ($r = 0.77$, $t = 13.35$, $GL = 84.3$ and $P_{\mathrm{GL}} < 0.0001$).

These relative correlation patterns remained rather stable over the common period 1840–2009 (Fig. 3). Interestingly, the variations of the correlations became highly synchronous toward the second half of the twentieth century, adopting an upward trend in the last decades of the compared period (specially the CBS-LIN correlation), indicating an increase in the strength of the common signal.

Rotated PCA clearly showed that elevation is the main factor explaining the differences between sites (Fig. 4), as the ordination of the loadings of the chronologies both two first PCs, which explained up to 90 % of the total variance, followed the distribution of the sites along the altitudinal gradient.

Radial growth response to climate

In general, simple correlations revealed more relationships than the response functions (Fig. 5), although both analyses showed a stronger influence of temperature than precipitation on radial growth, and clear differences between sites with elevation.

Table 1 Standard chronologies from the international tree-ring data bank used for the analyses of teleconnections (for coordinates, species codes and authors, see http://www.ncdc.noaa.gov/paleo/treering.html)

ITRDB code	Sp	Elev (m a.s.l.)	Begin year	End year	ITRDB code	Sp	Elev (m a.s.l.)	Begin year	End year
FRAN021	PIMU	1,750	1659	1977	SPAI018	PINI	1,500	1687	1989
FRAN023	PIMU	2,100	1769	1977	SPAI019	PINI	1,600	1523	1988
FRAN027	PINI	1,400	1518	1980	SPAI020	PISY	1,650	1763	1991
GREE001	PILE	1,750	1673	1981	SPAI021	PISY	1,650	1715	1988
GREE002	PINI	1,450	1825	1981	SPAI022	PIPI	1,225	1821	1985
GREE003	ABBO	1,350	1812	1981	SPAI024	PISY	1,275	1696	1985
GREE005	PILE	2,250	1583	1981	SPAI029	PINI	1,385	1711	1983
GREE008	PINI	1,500	1751	1978	SPAI030	PISY	1,400	1809	1983
GREE009	PINI	1,400	1657	1999	SPAI031	PINI	1,225	1728	1984
GREE011	PINI	1,320	1706	1979	SPAI032	PINI	1,440	1794	1983
ITAL001	PINI	1,550	1750	1987	SPAI033	PISY	1,465	1813	1985
ITAL004	PCAB	1,650	1836	1988	SPAI034	PISY	1,470	1769	1985
ITAL007	PCAB	1,900	1660	1975	SPAI035	PISY	1,550	1726	1983
ITAL008	ABAL	1,450	1827	1980	SPAI036	PISY	1,800	1749	1983
ITAL011	ABAL	1,720	1800	1980	SPAI037	PISY	1,950	1661	1985
ITAL012	ABAL	1,700	1654	1980	SPAI038	PISY	1,850	1599	1984
ITAL013	PINI	1,800	1773	1980	SPAI039	PINI	1,450	1681	1984
ITAL014	PCAB	1,650	1840	1980	SPAI041	PINI	1,475	1681	1985
LEBA001	CDLI	1,775	1829	2002	SPAI043	PINI	1,500	1829	1985
LEBA002	ABCI	1,175	1722	2001	SPAI044	PISP	1,625	1605	1985
LEBA003	CDLI	1,640	1809	2001	SPAI045	PINI	1,385	1638	1985
LEBA004	CDLI	1,900	1382	2002	SPAI046	PINI	1,440	1644	1985
LEBA005	CDLI	1,780	1778	2002	SPAI047	PISY	1,750	1567	1983
LEBA006	CDLI	1,720	1730	2002	SPAI048	PISY	1,840	1671	1983
MORC001	CDAT	2,200	1253	1984	SPAI049	PISY	1,840	1593	1985
MORC002	CDAT	1,700	1632	1984	SPAI050	PISY	1,750	1681	1983
MORC003	CDAT	2,200	1728	1984	SPAI051	PISY	1,920	1752	1985
MORC004	CDAT	2,000	1296	1987	SPAI052	PISY	880	1802	1985
MORC005	CDAT	2,000	1283	1987	SPAI053	PIUN	2,000	1811	1996
MORC006	CDAT	2,000	1210	1987	TURK003	PCOR	1,300	1686	1989
MORC007	CDAT	2,500	1408	1987	TURK004	PISY	1,300	1717	1988
MORC008	CDAT	2,200	1366	1987	TURK012	CDLI	1,400	1551	1998
MORC009	CDAT	2,150	1300	1987	TURK013	PINI	1,601	1772	2000
MORC010	CDAT	2,200	1281	1987	TURK014	JUEX	1,862	1246	2000
MORC011	CDAT	1,900	1549	1984	TURK015	PIBR	1,156	1730	2000
MORC012	CDAT	1,700	1748	1984	TURK016	JUEX	1,853	1332	2000
MORC014	CDAT	2,200	984	1984	TURK017	CDLI	1,853	1449	2,000
SPAI001	PIMU	1,870	1609	1977	TURK018	JUEX	1,047	1152	2000
SPAI002	PISY	2,050	1663	1977	TURK019	CDLI	1,469	1693	2000
SPAI003	PIMU	2,100	1793	1977	TURK020	PINI	1,633	1586	2000
SPAI004	PIMU	1,760	1808	1977	TURK021	CDLI	1,723	1628	2000
SPAI005	PIMU	1,960	1820	1977	TURK030	PINI	1,600	1771	2002
SPAI007	ABPN	1,650	1728	1982	TURK031	PINI	1,500	1475	2001
SPAI008	PINI	1,750	1610	1988	TURK032	PIBR	700	1738	2001
SPAI009	PINI	1,250	1688	1988	TURK033	PINI	1,500	1567	1995
SPAI010	PINI	1,350	1615	1988	TURK035	JUEX	-	1017	2001
SPAI011	PINI	1,500	1485	1988	TURK036	PIBR	1,047	1694	2000
SPAI012	PISY	1,950	1527	1988	TURK037	PINI	1,650	1794	2002

Table 1 continued

ITRDB code	Sp	Elev (m a.s.l.)	Begin year	End year	ITRDB code	Sp	Elev (m a.s.l.)	Begin year	End year
SPAI013	PISY	1,900	1685	1992	TURK038	PINI	1,650	1771	2002
SPAI014	PISY	1,630	1787	1992	TURK039	PINI	1,480	1792	2004
SPAI015	PISY	1,525	1791	1992	TURK040	JUEX	1,800	1330	2001
SPAI016	PINI	1,450	1667	1988	TURK041	JUEX	1,790	1350	2001
SPAI017	PINI	1,350	1760	1991	TURK042	JUEX	1,725	1235	2001

Sp species, *Elev* elevation, - unknown

Table 2 Attributes of the sampled trees and number of measured and missing rings (mean ± SD)

Sites	DBH trees (cm)	Height trees (m)	Rings present in samples	Missing rings in sample	% missing rings
CBS	89.8 ± 23.2	10.6 ± 2.4	452.0 ± 157.4	3.4 ± 4.8	0.83
NAV	103.5 ± 23.7	14.6 ± 3.1	280.8 ± 94.6	0.6 ± 1.1	0.21
PMB	96.1 ± 21.6	15.1 ± 4.2	386.0 ± 109.0	1.4 ± 2.0	0.46
LIN	81.0 ± 28.6	19.9 ± 4.6	183.8 ± 59.9	0.4 ± 0.7	0.22

Table 3 Statistical comparison of chronologies for the common interval attaining EPS > 0.85 (1840–2009); *r*: Pearson's correlation; *t*: Student's *t* value; *GL*: % parallel variation; P_{Gl}: signification level of GL

Cazorla site chronologies	CBS (highest site)	NAV	PMB
NAV	*r*: 0.67 *t*: 10.00 *GL*: 77.5 % $P_{\mathrm{Gl}} < 0.0001$		
PMB	*r*: 0.62 *t*: 8.75 *GL*: 77.8 % $P_{\mathrm{Gl}} < 0.0001$	*r*: 0.77 *t*: 13.35 *GL*: 84.3 % $P_{\mathrm{Gl}} < 0.0001$	
LIN (lowest site)	*r*: 0.45 *t*: 5.61 *GL*: 67.5 % $P_{\mathrm{Gl}} < 0.001$	*r*: 0.66 *t*: 9.77 *GL*: 77.5 % $P_{\mathrm{Gl}} < 0.0001$	*r*: 0.72 *t*: 11.55 *GL*: 80.2 % $P_{\mathrm{Gl}} < 0.0001$

Temperature at the end of previous summer/early fall (previous August to October) was closely related to tree growth at all elevations, as inferred from the results of the correlation functions. However, response functions identified this effect only for previous September to October at the highest site (CBS) and for previous September at the mid-elevation site NAV, whereas PMB and the lowest site LIN did not appear to respond to this factor. Correlation to mean temperature for the whole period from previous August to October was highly significant at the mid-elevations and the upper site ($P < 0.0001$) and weaker at LIN ($P < 0.01$). Growth response to late winter/early spring temperature (February–March current year) was strong and highly significant at all sites ($P < 0.001$ for mid-elevation sites and $P < 0.0001$ for the highest and the lowest site). Highly significant correlations ($P < 0.0001$) and response function coefficients were found for February at all sites; this relationship was also maintained for March, except for the lowest site (LIN) where correlation became insignificant, and was stronger at mid-elevations, with significant response function coefficients for both NAV and PMB. The other responses observed were not shared by all sites, but showed variations along the gradient. High temperature in current June–July appears to be negative for growth, but its effect on growth seems to be weaker than the role of temperature in late winter/early spring and previous late summer; response function analysis identified this factor only for LIN in May, and simple correlations, though significant at all sites, yield a low significance level ($P < 0.05$ to $P < 0.01$).

Growth response to precipitation was not as clear as to temperature. In general, relationships appeared to be

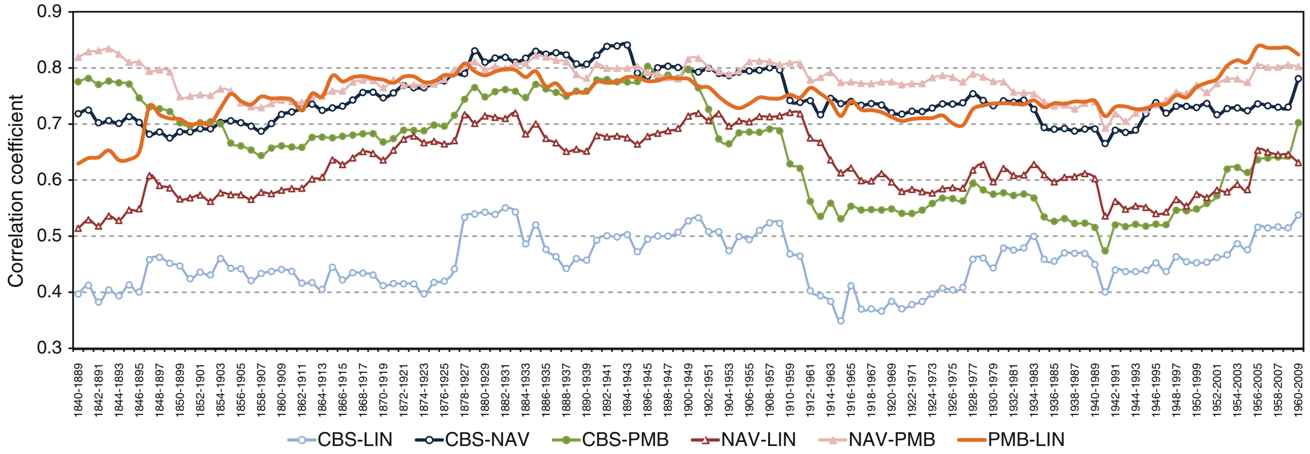
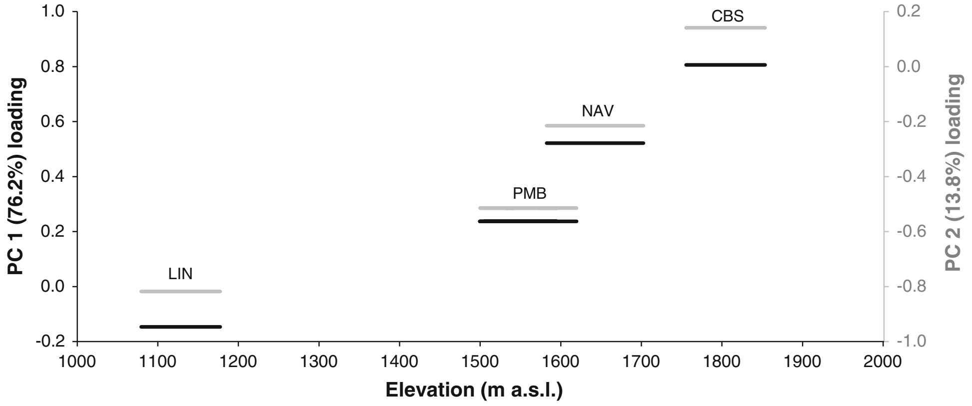


Fig. 3 Temporal variation of the correlation between the computed Cazorla chronologies for the common period 1840–2009

Fig. 4 Loadings of each chronology on the first and second varimax-rotated PCs in relation to elevation. Horizontal lines indicate the elevation ranges for all trees sampled at each site



weaker and more diffuse along the gradient. Correlation functions showed that precipitation had a significant effect at all elevations only in previous September (positive) and March (negative, especially significant at NAV, where $P < 0.0001$). But response functions only indicated the positive relationship at CBS and PMB in previous September and at LIN in May, and the negative response at NAV in March. The lowest elevation site (LIN) seemed to be the most sensitive one to precipitation, as significant positive correlations ($P < 0.05$ to $P < 0.001$) appeared for previous October and current January, May and July as well. Positive relationships also showed up at PMB in previous January and May, whereas at the high-elevation site (CBS), this factor has a significant positive effect in previous July ($P < 0.05$) and current June ($P < 0.01$).

Spatiotemporal variability of climate–growth relationships

Moving correlation functions showed a predominant response to temperatures than to precipitation (Fig. 6), although this trend has been changing since halfway the twentieth century mid- and high elevations, where response to February–March precipitation has been taking increasing relevance. We observed negative correlations with previous August to October temperatures, which remained significant along the whole century at the mid- and high-elevation sites, whereas the response to this variable was not as strong at LIN. CBS presented a quite stable pattern in the response to temperatures throughout the twentieth century, showing a stronger response to previous August–October temperatures than to current February–March. At NAV and PMB, the response to previous August to October temperatures increased during the first half of the century, turning into a steady decrease during the second half of the century. The positive correlation with late winter temperature (February–March) followed a similar pattern at mid-elevation, becoming less significant toward the third quarter of the century, but increasing in the last decades. At the lowest site, response to temperature was less intense than elsewhere, but the pattern for current February–March temperatures was similar; this site seemed more sensitive to current June–July and, particularly, previous August–October temperatures. At mid- and high

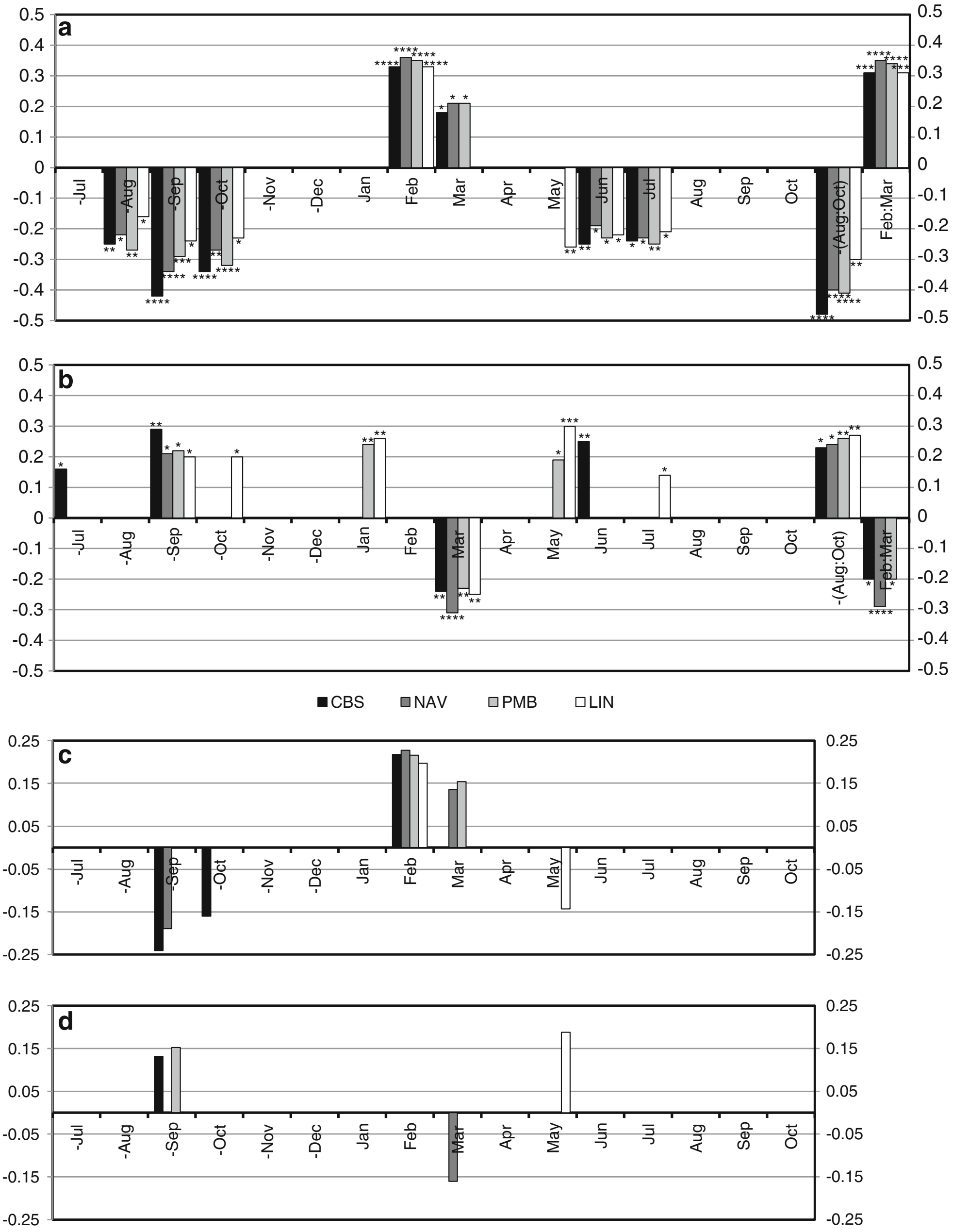


Fig. 5 Bootstrapped correlation functions between the residual chronologies and monthly temperature (**a**) and precipitation (**b**), for the period 1902–2009; and response functions for temperature (**c**) and precipitation (**d**) for the same period. All calculations were performed for a 16-month window (July previous year to October current year); correlation functions also include calculations for the intervals August–October previous year and February–March current year. Only significant results are shown (*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$, ****$P < 0.0001$)

elevations, negative correlations to June–July temperatures became non-significant by the second quarter of the twentieth century and so remained until present.

The role of precipitation on tree growth was very unstable through time (Fig. 6). At LIN, we found no clear response to precipitation. At the mid- and high-elevation sites, the response to current June–July precipitation became non-significant already in the first half of the twentieth century. More remarkably, the response to February–March precipitation increased steadily, reaching highly significant negative correlations toward the last quarter of the twentieth century. This response reached the highest values at NAV, although it seemed to stabilize in the last two decades at both mid-elevation sites, whereas it still followed an upward trend at CBS for the end of the studied period. Response to previous August–October precipitation was very similar at all elevations, fluctuating slightly along the boundary of positive significant correlations during the twentieth century.

Teleconnections

When considering the whole length of the Cazorla chronologies attaining an EPS > 0.85, the highest similarities were found between the mid-altitude chronology NAV and black pine chronologies from the center and east of Spain

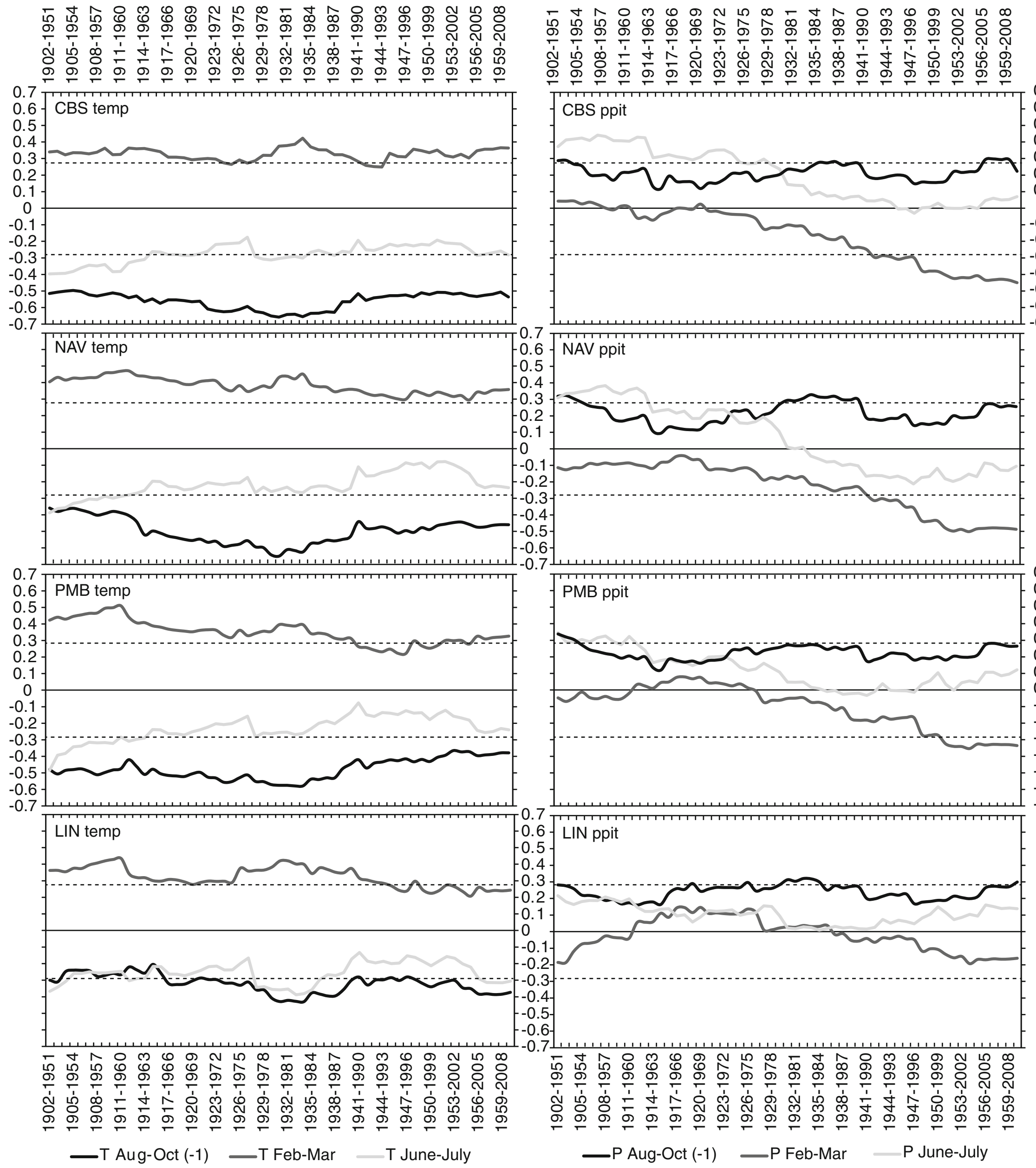


Fig. 6 Evolution of growth responses to temperature and precipitation at the four study sites of the Cazorla Mountains for the period 1902–2009, calculated by moving correlation functions (50-year period shifted 1 year). Dashed horizontal lines indicate a significance level of $P < 0.05$

(*t* values higher than 8) (Fig. 7). Lower, although highly significant, similarities also existed with chronologies of this species located further away (including a black pine chronology from Corsica) and with other pine species (*P. sylvestris* L., *P. pinaster*, and *P. mugo* subsp. *uncinata* Ramond ex DC.). NAV also showed strong heteroconnections with a chronology of *Abies pinsapo* Boiss. from the south of Spain and another chronology of *Cedrus atlantica* Manetti from Morocco. The other mid-altitude chronology (PMB) was also similar to a broad number of black pine chronologies. More remarkable are the heteroconnections obtained between this chronology and other pine species, as well as with the *A. pinsapo* chronology from Spain and with four *C. atlantica* chronologies from Morocco. CBS, the chronology from the altitudinal limit of the species in Iberia, provided highly significant agreements with a broad range of chronologies, including some from black pine, *P. sylvestris*, *P. pinaster* and *P. mugo* subsp. *uncinata*, the *A. pinsapo* chronology from south of Spain, and two *C. atlantica* chronologies from Morocco, although the *t* values were lower than the ones for the mid-elevation chronologies (most of the matches

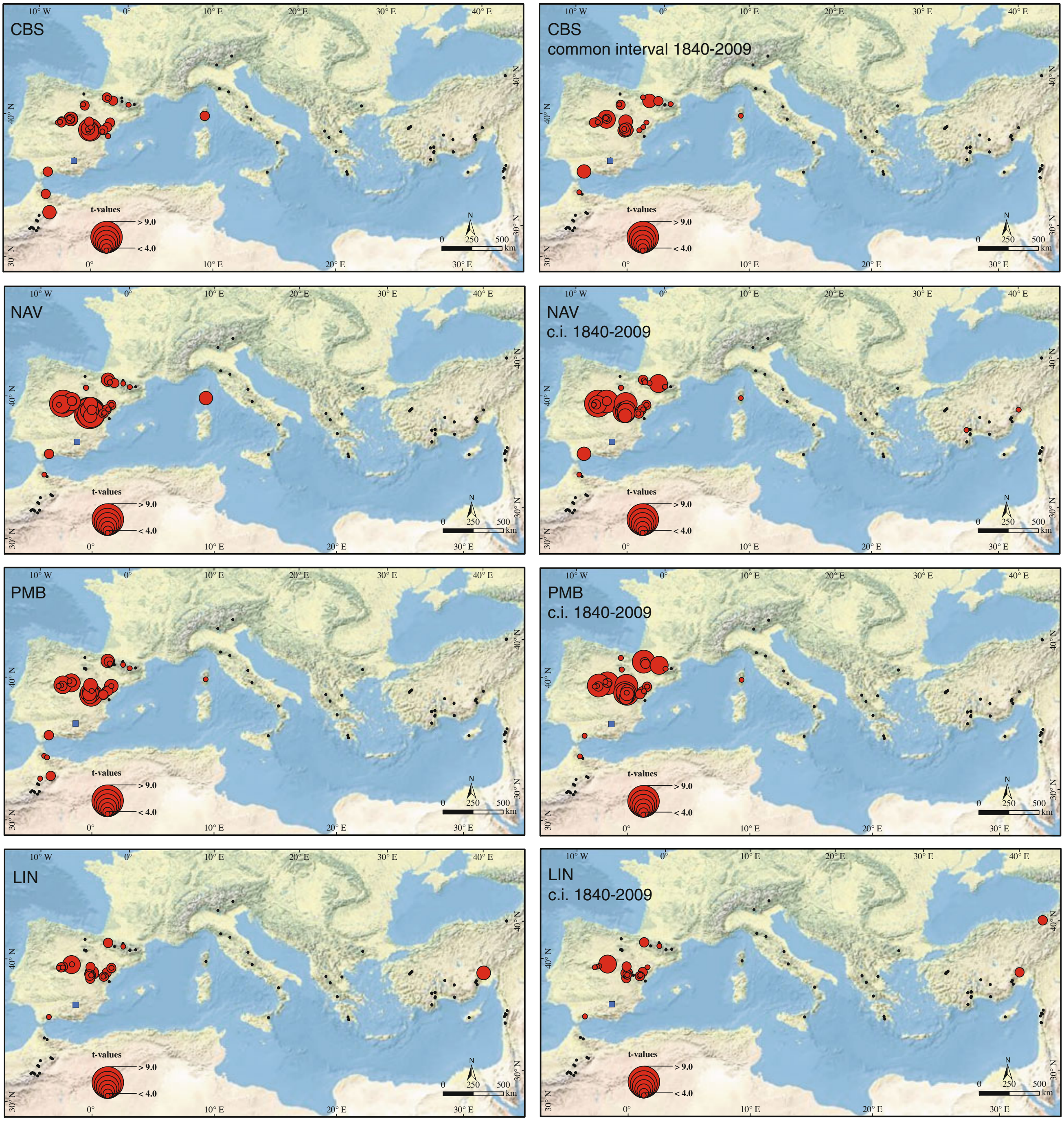


Fig. 7 Maps presenting tele- and heteroconnections between the Cazorla chronologies and a selection of chronologies from the Mediterranean basin, for the period with EPS > 0.85 (left graphs) and for the common interval 1840–1974 (*right*). Only *t* values over 3.0, with a *GL* higher than 55.0 % and $P < 0.01$, are presented. *Black dots* indicate chronologies used in the comparison that did not produce results above those values

ranged between 3 and 4). The best teleconnections for CBS (*t* value higher than 6) were found with three *P. nigra* chronologies from the center of Spain, whereas the best heteroconnections (*t* value between 5 and 6) were obtained with two *P. sylvestris* chronologies from Spain and a *C. atlantica* chronology from Morocco. The chronology from the lowest site (LIN) provided a very good match ($t = 6.9$) with a *P. nigra* chronology from the center of Spain, and lower, but still highly significant teleconnections with other Spanish chronologies of the same species. A high and significant agreement ($t = 5.22$) was obtained with a *P. nigra* chronology from southern Turkey.

Tele- and heteroconnections for the common interval 1840–1974 (135 years) delivered similar results. In general, correlations were found with same chronologies, but the degree of similarity decreased in some cases (especially for the upper site) as the statistics calculated are dependent on the length of the compared period. The Cazorla chronologies from mid-elevation maintained high agreements with numerous chronologies of *P. nigra* and *P. sylvestris*. Surprisingly, matches were still found between LIN and NAV and *P. nigra* chronologies from Turkey, although the statistical matches were rather weak (t value between 3.2 and 4.6). Similarities with *C. atlantica* chronologies from Morocco declined for all four Cazorla chronologies in the compared period (t values between 3.0 and 3.6). However, the agreement of CBS with the *P. mugo* subsp. *uncinata* from the Pyrenees increased when considering the common interval ($t = 5.34$), as also did the *A. pinsapo* chronology ($t = 5.2$).

The multivariate analysis on the crossdating between Cazorla and the chronologies from the reference data set clearly indicates the importance of altitude within the study area (Fig. 8), as the ordination along the two principal components corresponds to this variation. This analysis, which explains nearly 95 % of variance, separates the low-elevation site (LIN) from the highest elevation (CBS), while both sites at mid-elevation remain intermediate, but considerably closer to CBS, regardless of the statistic used for the comparison (correlation coefficient or test of parallel agreement).

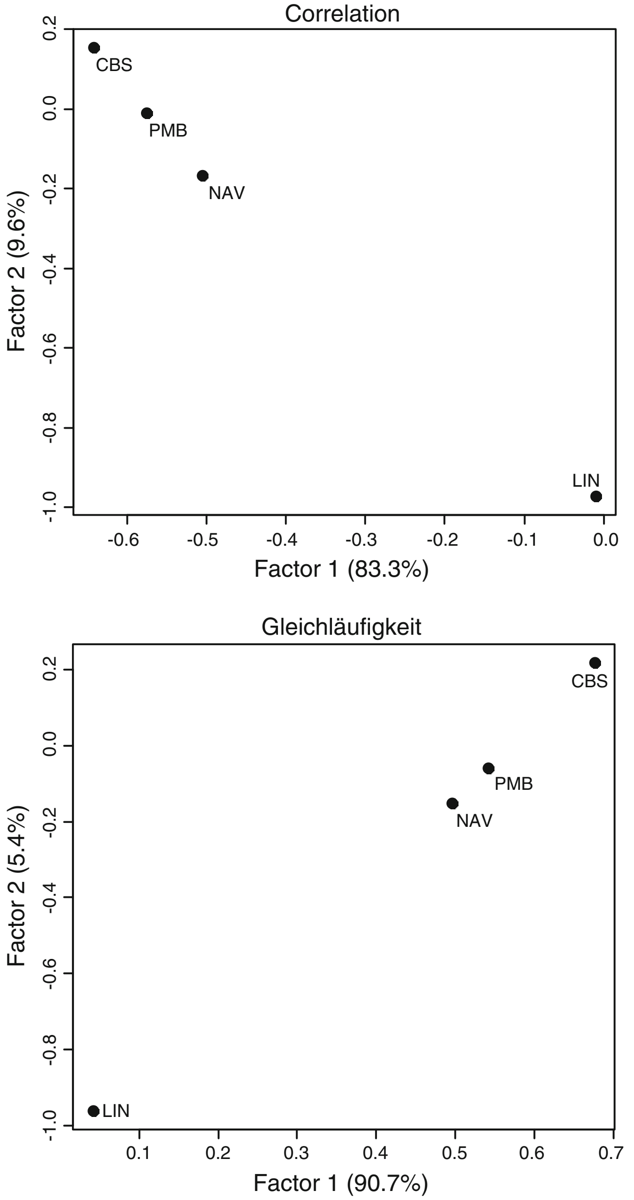


Fig. 8 Principal component analysis of the comparison between the Cazorla chronologies and their crossdating to other Mediterranean STD chronologies, considering correlation coefficients and percentage of parallel variation

Discussion

In this contribution, we developed four well-replicated chronologies along an almost 1,000-m elevation gradient to understand crossdating potential and radial growth responses to climatic factors of black pine, and their variability through time, as well as the connections between the black pine from the Cazorla Mountains and other conifer species in Iberia and the Mediterranean basin. Black pine in the Cazorla Mountains occurs within an elevation range from ca. 1,000 up to almost 2,000 m a.s.l.; hence, differences, both in age of the trees (due to different access possibilities for logging) and in growth responses to climatic factors, were expected along the gradient. Such differences have been confirmed by our results.

Chronology quality and inter-site variability

The developed ring-width chronologies considerably differed in their time span, with trees several centuries older at the upper site. Although the variation of site factors has been reported to affect lifespan of trees as inversely related to growth rates (Di Filippo et al. 2012), we cannot assess this relationship, given the human impact on both stand structure and history at our sites. In fact, age structure appears to reflect the history of intense logging activities carried out well up to the nineteenth century in the most accessible lower part of the mountains (De Aranda y Antón 1990, 1999; Araque Jiménez 2007; Ruiz García 2010). At the upper part, a well-replicated chronology reaching back to AD 1331 was obtained, followed by a chronology of considerable length (466 years) at the mid-elevation site PMB, but a long chronology was not possible at the lowest altitude as a result of such activities. However, trees at each site showed a strong common response despite the differences in age classes, as demonstrated by the rbar values and the low number of trees needed to achieve an EPS $>$ 0.85. This indicates a high quality of the collected material not only for ecological research (Briffa 1995) but also for dendroarcheological purposes, as it shows a high potential to crossdate series from single trees (as opposed to object tree-ring mean curves representing several trees) with chronologies from the same elevation. Such situation can be of great importance if the construction of a well-replicated mean curve from historical material is not possible due to limited sampling options (e.g., when investigating historical wooden artifacts such as furniture, sculptures or string instruments).

Crossdating patterns among different chronologies can vary through time due to changing sample size or variations in the conditions that constraint growth (Briffa and Jones 1990; Wilson and Elling 2004; Andreu et al. 2007), and consequently, it is important to compare them in different time periods. In this study, moving correlations among chronologies through the common interval 1840–2009 showed in general a high degree of analogy. The similarity between site chronologies was mainly determined by the elevation pattern, but several periods were more synchronous than others, especially from the 1970s onward (synchronous upward trend). Since common variance in tree growth is most likely caused by climate (Fritts 1976), such synchronous patterns seemed to point at periods of increased common signal within sites, and also along the gradient, hence suggesting that climate became more limiting at all elevations in a similar way, particularly for the last four decades. These results agree with those reported by Andreu et al. (2007) for several pine species on sites at different elevations in the eastern half of Spain.

Despite the existence of a common pattern to all sites, our results also indicate that the affinity among the created chronologies is clearly dependent on elevation. The strong statistical results found between the lower and the upper sites are restricted to 1840–2009, a period with a high sample depth for all chronologies, but they cannot assure whether they could be extrapolated to previous periods. Using the CBS chronology (upper site) to date low-replicated object mean curves from fifteenth- to seventeenth-century artifacts or structures, made of wood from the lower part of the mountains, does not guarantee to yield any satisfactory results. Consequently, dendrochronological dating of historical wood from the Cazorla Mountains may result as challenging as dating *Picea abies* or *Abies alba* from different elevations happened to be in the south of Germany (e.g., Wilson and Hopfmueller 2001; Dittmar et al. 2012). Therefore, sampling strategies for the development of long-span reference chronologies should focus on the acquisition of a dense tree-ring data set from different elevations before trying to systematically date historical objects.

Radial growth responses to climate

As climate is the main driving force that determines year-to-year variation of tree rings (Fritts 1976), tree-ring responses to climate should explain the main sources of variation for the crossdating among sites. In the present work, despite the existence of a common pattern to all sites, growth responses to climatic factors also differed along the studied elevation gradient, as has been observed in other studies along gradients (e.g., Di Filippo et al. 2007; Wilson and Hopfmueller 2001; Dittmar et al. 2012). Overall, the developed data set contains a strong temperature signal, with trees from the mid and upper sites having a very strong inverse relationship to temperature in previous late summer, and weaker to current year summer, as well as a mild positive response to current year February. These results are consistent with those found by Dorado Liñán et al. (2012) for adult and old black pines in the same area, which should be expected, as their PN-S site overlaps with our upper site (CBS). However, Dorado Liñán and others used climatological data from local stations, whereas we used CRU data. This demonstrates that both sources of data lead to the same results regarding growth responses in this area.

The negative effect of previous year August–September temperature coupled with the positive effect of precipitation has also been reported by other studies on conifers growing at mid- and high elevations in eastern and north-eastern Spain (Richter et al. 1991; Andreu et al. 2007), as well as in the Alps (e.g., Büntgen et al. 2006). As suggested by Andreu et al. (2007), conditions in previous late summer would probably modulate the amount of carbohydrates available for the following season, so that a prolonged growing period in the previous year would lead to a narrower ring in the current year, as a result of the consumption of the available photosynthates instead of their storage.

Relationships (negative to precipitation and positive to temperature) were also strong at the end of winter, that is, the quiescent period when winter rest can be broken if environmental factors are favorable. Therefore, such responses appear to be related to the resumption of growth, that is, moist and cold conditions prolong winter dormancy and thus result in a narrower ring.

Some responses were also observed during the current early summer, namely tree rings negatively related to temperature. Under such Mediterranean climate, summer precipitation is greatly reduced, and soil water reserves from winter and spring should be fundamental for summer growth, so that we hypothesize that temperature is probably modulating water loss by evapotranspiration. In fact, our results indicate that tree growth mostly occurs during spring, and the responses obtained determine the available reserves within the tree (previous summer) and the extension of the growing season by anticipating its beginning (warm late winter) or prolonging spring growth (mild early summer).

At the lowest site, differences were more remarkable than among the three other sites; among these, we found a response to water availability in spring (negative to May precipitation, positive to temperature), which is probably related to the anticipation of the summer drought characteristic to Mediterranean environments. According to Fritts (1976), tree-growth is more susceptible to variations for species living at their ecological limits. This could explain the differences between LIN and the upper sites, which are exposed to different prevailing limiting factors. In addition, LIN is made out of considerably younger trees, which may retain a different climatic signal than the older trees from the upper sites (Fritts 1976; Briffa and Jones 1990). Dorado Liñán et al. (2012) found homogeneous growth responses to climate among adult and old black pines in the upper part of the Cazorla Mountains, concluding that age did not affect climate–growth responses. However, given the considerable young age of the trees from our low-elevation site (not more than 170 years), those results cannot be extrapolated. For dendrohistorical studies, the observed variations in climate–growth responses between the upper and lower sites could be limiting for crossdating, but the mid-elevation chronologies, which attain a longer span, may serve as bridge, helping dating historical timbers from lower sites.

Dynamic growth–responses through time

The strong responses found at the mid- and upper elevation sites to temperature imply important consequences for the historical and climatological usefulness of these series, since they should greatly facilitate crossdating ring-width series from historical timbers from the same altitude. Similarly, a composite chronology developed from living trees and historical timbers from the mid- and high-elevation sites should serve as a high resolution proxy for the study of past environmental conditions in the western Mediterranean (see results of Richter and Eckstein 1990). However, our results also show that these growth responses are dynamic, presenting a marked shift in the strength of the response to previous year late summer temperatures toward the mid- twentieth century at the mid- and high-elevation sites, as well as an increasing effect (negative correlation) of precipitation from current February–March as the century progressed, becoming highly significant after the 1970s. At the lower site, response to current February–March temperature had practically lost significance since the 1970s, whereas response to previous August–October precipitation seemed to have gained increasing relevance for the last two decades. This could be related to the considerable increase in February and March temperatures observed for the last decades in the climatic data used in this work (not shown).

Such shifts in growth–response to climatological variables are not easy to interpret, as they could be triggered by several factors (see Büntgen et al. 2012). However, the influence of changing climatic variables at a regional scale is a plausible explanation, as episodes of increased spring and winter temperatures, as well as fluctuating precipitation regimes in the late nineteenth century have been reported for the area, together with an increase in summer temperatures for the second half of the twentieth century (Linares and Tíscar 2011). Changes in radial growth responses to climate have been reported not only in central Europe and Scandinavia (e.g., Mäkinen et al. 2002; Carrer and Urbinati 2006; Büntgen et al. 2012), but also in the Mediterranean region, for example, eastern Spain, (Andreu et al. 2007) for different conifer species at various elevations and using different standardization methods and meteorological records, hence supporting the non-stationary character of growth responses to regional climatic factors as suspected by Carrer and Urbinati (2006).

However, this considerable limitation for dendroclimatological research should not necessarily be a handicap for historical purposes, as long as the variations in responses to climate along time are similar among sites. This seems to be the case for our study, since the trend of the changing responses to temperature and precipitation had a similar pattern among the sites regardless of the elevation.

Teleconnections and the supra-regional climatic signal

In general, drought is considered to be the most limiting factor for tree growth in the Mediterranean basin (Specht, 1981), being dry summers and a high interannual precipitation variability unfavorable factors for plant growth (Mitrakos, 1980). Therefore, tree-growth response of conifers is expected to be homogeneous over large areas in the southeast of the Iberian Peninsula Richter et al. (1991). But our results indicate that this macroclimatic signal is not constant through time and also that variations in regional climatic factors may induce different responses along with elevation. Such situation can hamper crossdating of tree-ring series, which should be taken into consideration for dendrohistorical studies.

The similarities we found between the Cazorla chronologies and other black pine chronologies from Spain are consistent with the results reported by Richter et al. (1991) and Andreu et al. (2007), who found that pines of different species growing at similar altitudes and exposures presented highly similar growth variations. As previously stated by those authors, this evidences the existence of a common climatic signal over the western Mediterranean and encourages the development of a regional black pine master chronology for this area. Furthermore, the high similarities between these chronologies and some chronologies of *P. sylvestris* from the Iberian Peninsula would also justify the combination of both species into a regional master chronology, although the effects of such mixture of species on the statistical dating of historical timbers should be carefully evaluated. Likewise, high similarities between the mid-elevation Cazorla sites with the *A. pinsapo* and the *C. atlantica* chronologies from northern Morocco indicate that the common climatic signal is consistent along a latitudinal gradient (from northern Morocco to northeastern Spain). However, the decreased agreement with the *C. atlantica* chronologies when restricting the compared period to a common interval of 135 years could indicate that the signal captured by both species is a low-frequency (i.e., multi-decadal to multi-centennial) signal. If this is the case, the construction of hetero-chronologies, including *C. atlantica,* is not advisable, as the high-frequency signal needed for dating historical timbers would not be enhanced, but reduced.

Highly significant teleconnections with black pine chronologies from the eastern Mediterranean (especially between sites at mid- and low elevations) could indicate the existence of a macroclimatic signal reaching both ends of the basin. Nevertheless, the underlying reason for these connections should be properly identified and described, as the western Mediterranean (unlike the eastern part) is strongly influenced by the North Atlantic Oscillation, which affects winter precipitation and may have an influence on growth responses to February precipitation (e.g., Zorita 1992; Hurrel 1995), whereas this effect diminishes toward the eastern part of the Mediterranean basin.

Future perspectives and concluding remarks

The construction of well-replicated black pine ring-width chronologies along the ca. 1,000-m elevation gradient of this species in the Cazorla Mountains revealed significant differences in climate–growth relationships along the gradient and through time. Such differences seem to be triggered by regional climatic fluctuations and adaptive responses of trees, and they may hamper crossdating of historical data derived from low-elevation trees with the long chronology obtained at the high-elevation site. To overcome this obstacle, the chronologies from the mid-elevation sites may act as crossdating bridges, as they show more similarities to the lower site than to the upper chronology.

To achieve a well-replicated set of reference chronologies for dating cultural heritage originating from this geographical region, further strategies for tree-ring data compilation should be directed at sites along the elevation gradient, as well as across the latitudinal and longitudinal gradients of the Cazorla Mountains and the rest of the Baetic System, covering all possible niches of black pine in the south of Spain. To improve the replication of the earlier centuries and extend the chronologies back in time, sampling of roof structures from buildings is recommended, although their selection should be preceded by historical research, in order to acquire as much information a priori as possible in what regards the origin of the historical wood.

Our results indicate that tree growth is influenced by a combination of factors, which has multiple implications for environmental studies. Notwithstanding this, trees at mid-elevations seem to capture a stronger macroclimatic signal than trees at the upper site. The observed shifts in responses to climatic factors through time should be further explored, and potential age effects on the climatic signal should also be assessed. For the time being, the use of these ring-width chronologies for climatic reconstructions is not advisable; we recommend the assessment of the temporal dynamics of climate–growth responses before climatic interpretations and reconstructions are made.

The common signal found with chronologies of black pine and other conifer species in Iberia, northern Morocco and Turkey, especially among mid-elevation sites, indicates the existence of a macroclimatic signal in stands at similar elevations. This signal should be better understood, as it may lead to supra-regional chronologies for the Mediterranean basin, which could be used for historical and climatological purposes.

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