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Past growth suppressions as proxies of fire incidence in relict Mediterranean black pine forests

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A B S T R A C T

Global warming and land use changes, contributing to landscape level fuel increments, could threaten Mediterranean pine forest resilience to wildfire disturbances. Reconstructions of historical fire regimes allow for the disentanglement of these two drivers by comparing the influence of climatic and anthropogenic variables on fire. Here we combine three sources of historical data: charcoal accumulation rates from a peat bog, detailed historical records of fire incidence and tree-ring width data from five relict black pine (*Pinus nigra*) forests with fire-scarred trees located in Sierra de Gredos (central Spain). We found growth suppression in 1893 and 1894 in all the sites which coincided with a peak of fire incidence in historical records and an increase in charcoal accumulation rates. The occurrence of these three synchronous events suggests increased wildfire incidence in the area which shaped the current stand structure of relict black pine forests. These late 19th century developments, we argue, can be mainly attributed to anthropogenic factors and contributing climatic drivers. We argue that the dissolution of the "Mesta", the biggest transhumance livestock organization in Europe lasting from the 13th to the 19th centuries, led to more extensive grazing and uncontrolled use of forests and grasslands which likely contributed to increased wildfire incidence. Additionally, 1893 was characterized by anomalously warm spring temperatures which may have facilitated vegetation flammability. Our approach couples human and climate systems as drivers of historical fire incidence in Mediterranean pine forests.

1. Introduction

Mediterranean pine forest ecosystems are known to be resilient to disturbances such as wildfire and drought (Naveh, 1974, Trabaud, 1987, Alfaro-Sánchez et al., 2015). However, two major global environmental changes may disrupt this resilience. First, climate warming is expected to increase the severity and frequency of heat waves and droughts which have been linked to increased wildfire risk (Piñol et al., 1998, Pausas, 2004, Cardil et al., 2014). Second, land-use changes driven by rural depopulation during the second half of the 20th century have increased the amount and homogeneity of landscape fuel beds leading to a greater frequency and size of fires in many Mediterranean countries since historical studies indicate that most fires were small and limited by fuel availability (Gil-Romera et al., 2010b, Pausas and Fernández-Muñoz, 2012, Molina-Terrén et al., 2016, Chergui et al., 2017). However, to understand if warming-amplified aridification, fuel build-up and human activities may be converging synergistically to trigger fire regime changes in Mediterranean pine forests we need long-term reconstructions of fire activity (Keeley et al., 2012). Applied historical fire ecology approaches are therefore needed for periods with abrupt land-use changes to discern the role played by humans on the fire regime (Swetnam et al., 1999; Abel-Schaad and López-Sáez, 2013, Sarris et al., 2014).

At millennial time scales, changing fire regimes have shaped Mediterranean pine forests throughout history as a function of climate-human feedbacks (Marlon et al., 2008, Gil-Romera et al., 2010a, Blanco-González et al., 2015, López-Sáez et al., 2017). Indeed, fire seems to have led to rapid structural and compositional changes in Mediterranean pine forests for at least the past 3000 years (Pyne, 2009, Carrión et al., 2010, Abel-Schaad et al., 2014, Leys et al., 2014). For instance, black pine (*Pinus nigra*) showed a long-term resilience to fire regimes characterized by frequent small fires and rare high-intensity fires, but recurrent anthropogenic crown fires linked to intensive land-use may have triggered their decline in the northern Iberian Plateau

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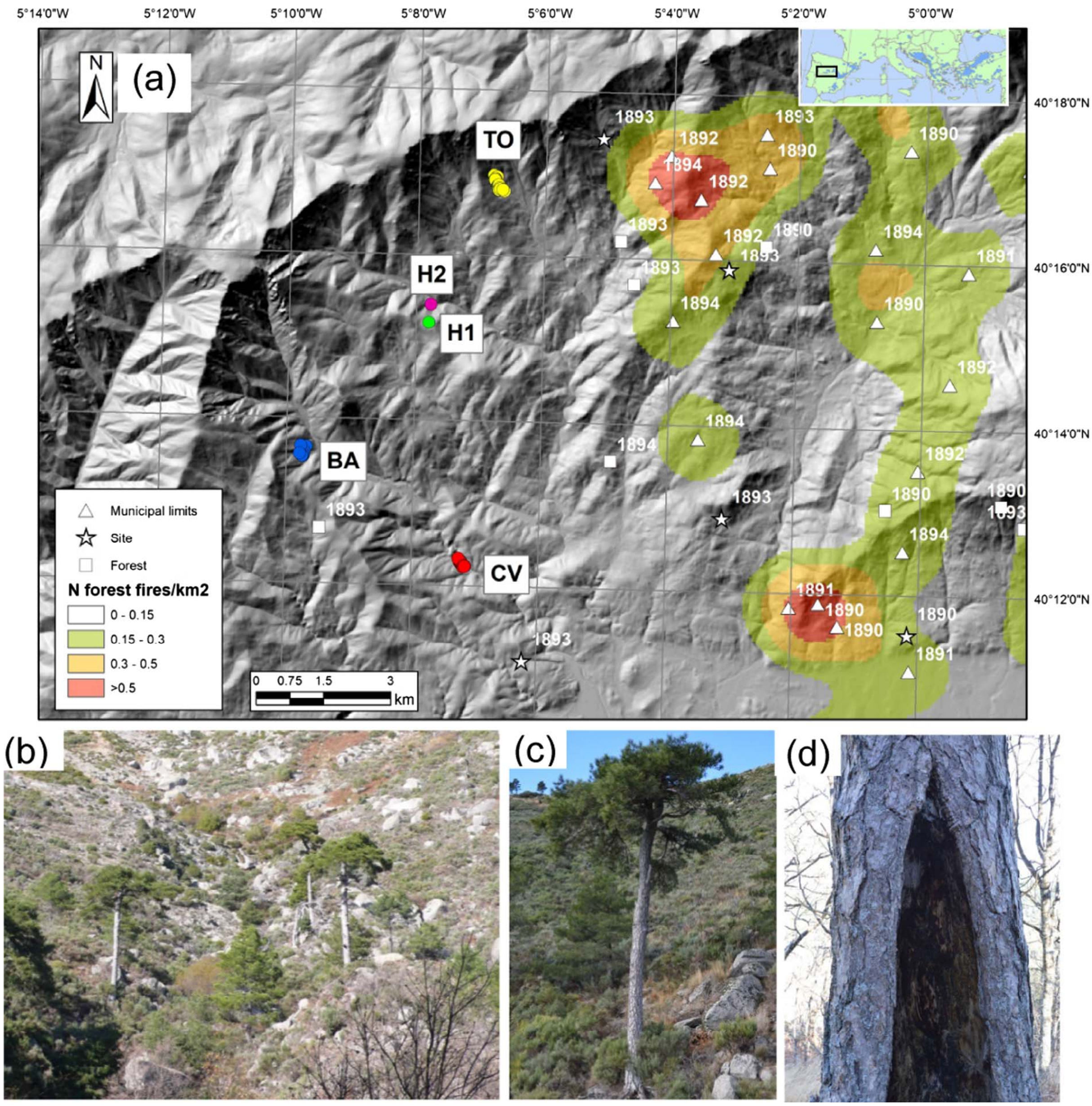

Fig. 1. Geographical situation (a) of the five black pine forests investigated in Sierra de Gredos (see Table 1; symbols show the locations of sampled trees and stands) and historical fire locations and estimated density of fire foci (color scale) during the 1890–1894 period when there was a peak in the number of forest fires recorded in the study area (Sierra de Gredos) based on documentary sources (three georeferenced historical fire levels are used: triangles, municipality; stars, sites without specified boundaries; and squares, forests or plots with precise limits of the property); views of an isolated relict stand (b), a sampled tree (c) and a living, fire-scarred tree (d) showing a cat face (triangular scar located at the base of the stem caused by fire damage). In the map the upper inset shows the distribution of black pine (*Pinus nigra*) in Europe and the location of the study area in central Spain (box). In the map of the study area (a), the shading represents the elevation gradient which ranges between low (700–900 m, down-right part) to high elevations areas (2000–2200 m, upper left part).

1400 years ago (Morales-Molino et al., 2017). Nowadays, this species forms relict populations in northern and central Spain, representing the south-western distribution limit of the species in Europe (Fig. 1), whereas it is abundantly distributed throughout eastern Spain (Barbéro et al., 1998).

Macrofossil evidence confirms that in central Spain, black pine was present from the mid-Holocene up to the present (Rubiales and Génova, 2015). The palynologic record has revealed that pine forests were more widespread in this area before the Middle Ages, when human pressure (fire, grazing) intensified leading to extensive deforestation from the 13th to the 15th centuries (López-Sáez et al., 2009, 2014, 2017; Robles-López et al., 2017). The beginning of this period coincides with the establishment of the "Mesta" transhumance grazing system, which was created in 1273 and was the major livestock organization in the Iberian peninsula until its dissolution in 1836 (Klein, 1920; Pascua-Echegaray, 2007). The end of "Mesta" activities in the 19th century represented a socio-economic shift with clearly negative impacts on forests because this organization regulated the controlled use and management of forests and pastures where sheep herds grazed (López-Sáez et al., 2017). It is therefore plausible that after the "Mesta's" dissolution unrestrained exploitation of mountain forests may have facilitated increased wildfire frequency (López-Merino et al., 2009, 2016a, 2016b).

Here we analyze the possible effects of the end of the "Mesta" on relict black pine forests in the Sierra de Gredos (central Spain) using dendrochronology to reconstruct growth patterns and past fire incidence. Previous dendroecological studies have provided long-term information on tree growth which is useful to preserve Mediterranean relict pine populations experiencing high human pressure (Todaro et al., 2007, Génova and Moya, 2012). For instance, it is necessary to characterize the climate-growth relationships in these relict stands so as to identify the major climatic constraints of tree growth and to differentiate growth reductions due to climate stress (e.g., droughts) from those caused by disturbances such as fires. However, information on historical fire regimes is limited for relict populations of Mediterranean pines though this type of retrospective data could inform their management (Fulé et al., 2008). For example, surface fire regimes are believed to have predominated historically in black pine forests because this species shows a poor post-fire regeneration (Tapias et al., 2004). A switch to frequent crown fires could then have led to the local extinction of some black pine populations (Pausas et al., 2004), and this fire regime change could explain the current relict status of black pine in the Sierra de Gredos. To explore these ideas, in this study we: (1) quantified the radial growth of relict black pine forests across an altitudinal gradient; (2) characterized the climate-growth relationship in these forests; and (3) reconstructed fire incidence by combining tree-ring width analyses, historical fire records (archival sources) and palaeoecological data (charcoal). We hypothesize that growth in these trees is highly sensitive to drought during the growing season leading to the formation of narrow rings, but that the formation of atypical multiple narrow rings is a consequence of intense fires damaging the crown. To test this hypothesis we compare the reconstructed growth data (five forests, 80 trees) with a database of fire records obtained from historical documents covering the last 200 years (Montiel-Molina, 2013), as well as with charcoal data (López-Sáez et al., 2017).

2. Materials and methods

2.1. Study area and tree species

The study area is located in the Sierra de Gredos, central Spain (5° 07′ 50″ W, 40° 14′ 41″ N, 1045 m a.s.l.; see Table 1). The climate of this mountain range is Mediterranean and continental, characterized by cold-wet winters and warm-dry summers. At the "Arenas de San Pedro" meteorological station (5° 5′ 28″ W, 40° 12′ 31″ N, 510 m a.s.l.) mean annual temperature is 14.5 °C, (December and July are the coldest and warmest months with mean temperatures of 5.1 °C and 25.1 °C, respectively), and total annual precipitation is 1483 mm (February and July are the wettest and driest months with precipitations of 226 mm and 6 mm, respectively). Drought may last from May to September, i.e. the period with negative climatic water balance.

The vegetation of the area includes oaks (*Quercus ilex* subsp. *ballota* (Desf.) Samp., *Quercus pyrenaica* Willd.) between 600 and 1600 m, and shrublands (*Cytisus oromediterraneus* Rivas Mart.) above 1600 m. The resin tapping industry has favored extensive pine (*Pinus pinaster* Ait.) woodlands at low to mid elevations, but scattered *Pinus sylvestris* L. appear at high elevations forming the tree line at ca. 1800 m (López-Sáez et al., 2013). The lithological substrate is dominated by granites, and soils are moderately deep (Gallardo et al., 1980).

In the Sierra de Gredos, pine woodlands, which produce a very flammable litter, have burnt disproportionately more than other vegetation types since the 1970s (Moreno et al., 2011). This pattern is consistent with what has been reported for other locations in the Mediterranean Basin where pine forests situated near densely populated areas are more susceptible to wildfire (Syphard et al., 2009). However, before the 1970s fire occurrence was closely associated with grazing practices which favored small controlled fires (Viedma et al., 2006).

Black pine (*Pinus nigra* subsp. *salzmannii* (Dunal) Franco) forms isolated and fragmented relict populations at mid to high elevation across the Sierra de Gredos (López-Sáez et al., 2016c), often located in rocky outcrops near creeks and surrounded by stands dominated by younger *P. pinaster* individuals. Black pine is a long-living, thick-barked, non-serotinous species which can survive low-severity surface fires forming fire scars (Keeley and Zedler, 1998, Tapias et al., 2004).

2.2. Climate and land-use data

To calculate climate-growth relationships we obtained a long-term (period 1901–2016) and homogeneous monthly mean temperature and precipitation record from the CRU climate dataset (Harris et al., 2014) accounting for the following climate variables: mean annual temperature (Luterbacher et al., 2004), annual precipitation (Pauling et al., 2006), and the Palmer Drought Severity Index (PDSI) from the Old World Drought Atlas (Cook et al., 2015). Additionally, we also obtained the reconstructed fraction of pasture land from the global land cover database (Ramankutty and Foley, 1999). This is a historical reconstruction of cropland extension based on national inventories and a land-cover model so it may be inaccurate for some regions and periods experiencing rapid changes in land use. All the aforementioned data were downloaded at a 0.5° spatial resolution (coordinates 5.0–5.5° W and 40.0–40.5° N) using the Climate Explorer webpage (https://climexp.knmi.nl/).

2.3. Field sampling and forest structure data

Due to strict conservation measures of relict Mediterranean pine forests, we discarded obtaining partial or complete cross-sections from living trees showing cat faces, i.e. triangular scars located at the base of the stem caused by fire and posterior axe incisions made by humans to obtain resinous tinders (Fig. 1d), and the quantitative reconstructions of

Table 1
Characteristics of the study sites. Values are means ± SE. Different letters indicate significant ($P < .05$) differences in tree size (DBH, diameter at breast height; height) between trees without or with fire scars within each site based on Mann-Whitney *U* tests. The last column shows the wildfires recorded in historical sources and located less than 2 km away from each sampled forests.

Site	Code	Longitude W	Latitude N	Elevation (m a.s.l.)	Slope (°)	DBH[a] (cm)		Height[a] (m)		No. trees (No. radii)	No. trees with fire scars	Fires recorded in historical sources
						Trees without fire scars	Fire-scarred trees	Trees without fire scars	Fire-scarred trees			
Charco Verde	CV	5° 07′ 13″	40° 12′ 19″	550	130	48.8 ± 2.4a	66.6 ± 4.9b	29.4 ± 1.0	30.8 ± 1.3	20 (38)	10	1893, 1921
La Bardera	BA	5° 09′ 41″	40° 13′ 36″	1027	65	63.1 ± 6.2a	107.2 ± 10.9b	20.0 ± 2.1	22.8 ± 1.2	10 (24)	5	1886, 1889, 1894, 1980
El Hornillo Alto	H1	5° 07′ 46″	40° 15′ 21″	1120	30	52.5 ± 10.2		8.6 ± 0.9		10 (20)	0	1894, 1895
El Hornillo Bajo	H2	5° 07′ 46″	40° 15′ 22″	1180	30	53.8 ± 10.2		8.7 ± 0.9		20 (49)	0	1882, 1886, 1894, 1974
Arroyo de los Torneros	TO	5° 06′ 46″	40° 16′ 49″	1350	148	76.1 ± 3.6a	100.1 ± 7.1b	21.1 ± 2.0	23.2 ± 1.5	20 (40)	4	1882, 1893, 1897, 1980

[a] Tree DBH and height are separately presented for trees with or without fire scars in sites with fire-scarred stems (cat faces).

the fire regime by cross-dating fire scars using dendrochronology is not feasible (e.g., Baisan and Swetnam, 1990). In low-severity fire regimes, fire scar analysis is an adequate technique to reconstruct fire history (Agee, 1993), while for high or mixed-severity fire regimes age-class analyses can be also applied (Johnson and Van Wagner, 1985). Taking cross-sections from the cat-face edge increases the susceptibility to stem breakage and the likelihood of mortality in sampled trees (Rist et al., 2011; but see Heyerdahl and McKay, 2017). In addition, a fire may not leave a record (scar) in every burned site, so random or stratified sampling of trees may be more robust to accurately estimate fire frequency than the biased sampling of trees showing fire scars (Johnson and Gutsell, 1994, but see Swetnam and Baisan, 2003). Finally, in intensively used anthropogenic cultural landscapes, such as Mediterranean pine forests, some scars may correspond to axe incisions caused by shepherds to remove resinous wood for kindling campfires (Fulé et al., 2008).

In the field, we selected dominant and living trees and sampled them in a ca. 0.5 ha large area. All dominant trees showing fire scars in the main stem, particularly those presenting cat faces, were sampled (Fig. 1d). Cat faces can be defined as deep, triangular scars located at the base of the stem (Agee, 1993). Dendrochronology was applied to cross-date the tree-ring width series (Fritts, 1976). For each tree, 2 cores were taken at 1.3 m above the base perpendicular to the maximum slope and also to the main scar face using a Pressler increment borer (Barrett and Arno, 1988). Their diameter at breast height (DBH) and tree height were measured with tapes or clinometers, respectively. In the field, bark thickness was measured at 1.3 m in each side of the stem where cores were taken using a Swedish bark gauge. Then, a mean bark thickness of the tree was calculated and related to DBH using linear regressions. Size variables were compared with trees not showing conspicuous fire scars in the stem (cat faces) using the Mann-Whitney *U* test.

2.4. Tree-ring data: processing and analyses

The cores were air-dried, glued onto wooden supports and polished with a series of successively finer sand-paper grits. The wood samples were then visually cross-dated using marker years based on consistently narrow rings (Yamaguchi, 1991). Tree-ring widths were measured to the nearest 0.001 mm using a binocular scope and a LINTAB measuring device (Rinntech, Heidelberg, Germany). Tree-ring cross-dating was checked using the COFECHA program (Holmes, 1983).

The tree-ring width series were individually detrended to remove non-climatic biological growth trends (Cook and Kairiukstis, 1990). A power transformation was applied and then a cubic smoothing spline with 50% frequency-response cut-off was fitted to the individual records to calculate ring-width indices. These indexed series were subjected to autoregressive modelling to remove most first-order autocorrelation so as to obtain residual ring-width indices. Finally, site chronologies were obtained by averaging the residual ring-width indices on a yearly basis using a bi-weight robust mean. A regional chronology was obtained by averaging all site chronologies. These procedures were performed using the ARSTAN software (Cook and Holmes, 1984).

The percentage growth change filter of Nowacki and Abrams (1997) was applied to identify abrupt decreases in radial growth. First, we calculated the ring-width medians of subsequent 5-year periods along all the growth series. Second, we defined M1 and M2 as the preceding and subsequent 5-year ring-width medians, respectively. The percentage of positive negative growth changes (NGC) was calculated as:

$$NGC = [(M1-M2)/M2 \cdot 100]$$

Therefore, NGC quantifies the relative difference in growth between preceding and subsequent 5-year periods for each annual tree ring. Suppressions were defined as those years with NGC > 75%. To assess changes in relative growth reduction we calculated mean curves of NGCs for each site.

We were particularly interested in detecting abrupt growth reductions or negative pointer years (Schweingruber et al., 1990) which could be potential markers of fire occurrence. First, ring-width data were normalized in a moving window of 4 years to obtain the number of standard deviations in tree growth in individual years deviating from the window average. Second, a negative pointer year was considered when the 75% of series showed a negative growth change higher than 40%. Prior to the calculation of event years, a 13-year weighted low-pass filter was applied (Fritts, 1976). To detect negative pointer years we used the package *pointRes* (van der Maaten-Theunissen et al., 2015) from the R Software (R Core Team, 2017).

To quantify the climate-growth relationships we calculated Pearson correlations between the five site residual chronologies and monthly climate data (mean temperature, total precipitation). The window of analysis spanned from October to September of the year of tree-ring formation. To quantify potential instabilities in the climate-growth relationships, we related the chronologies to the reconstructed summer precipitations (1850–2015 period; Pauling et al., 2006) considering moving 20-year long intervals.

2.5. Historical fire records from archival sources

We gathered historical fire records from a systematic and intensive research in national (National Historical Archive, General Archives of the Administration, Archives of the former Ministry of Agriculture, Spanish Military Police Archive, Spanish National Library), regional or provincial (Province Historical Archives, Forestry Administration Archives, private archives) and municipal archives, to reconstruct the complete fire history for the Spanish Central System (n = 3515 records) since the year 1497 until 2013. Going beyond the data provided by forest administration sources just for public woodlands and for the limited period 1830–1868 (Valdés, 1999), we have considered three different types of historical archival sources: administrative documents (coming from all the administrations with fire uses regulation and land management power since the 16th century); judicial and police sources (court registers and police reports since the 17th century) and printed press (official journals, newspapers, books) (Montiel-Molina, 2013). This research effort allowed us building up a reliable historical fire database with comprehensive information including 62 data fields (date, location, land ownership, land cover/use, burnt area, fire duration, fire cause, suppression resources, losses, etc.) Furthermore, the historical fire records were georeferenced with three different spatial levels of increasing accuracy (municipality, site or area without specified boundaries, and forest or plot with precise limits of the property), depending on the historical source precision.

Based on this historical fire georeferenced database, we estimated the density of historical fire foci in the study area (n = 1499 records) for the period 1890–1894 by transforming the point fire-foci data into fire-foci density data considering a 2-km search radius and using a kernel density function in Spatial Analysts, ArcGis (ESRI, 2012). We focused on the 1890s, when fire activity peaked (López-Sáez et al., 2017).

2.6. Palaeorecord of fire history

To reconstruct fire history we obtained charcoal accumulation rates (hereafter CHAR) obtained from a site (Serranillos), situated at ca. 12 km from the study sites, where a peat sediment core was obtained, analyzed and dated (dating uncertainty was ± 38 yrs. for the period 1800–2000) (see López-Sáez et al., 2017). This is a mountain peat bog (1700 m), where in the last two millennia there was a *P. sylvestris* forest that disappeared ca. 500 cal. yr BP (López-Merino et al., 2009; López-Sáez et al., 2009).

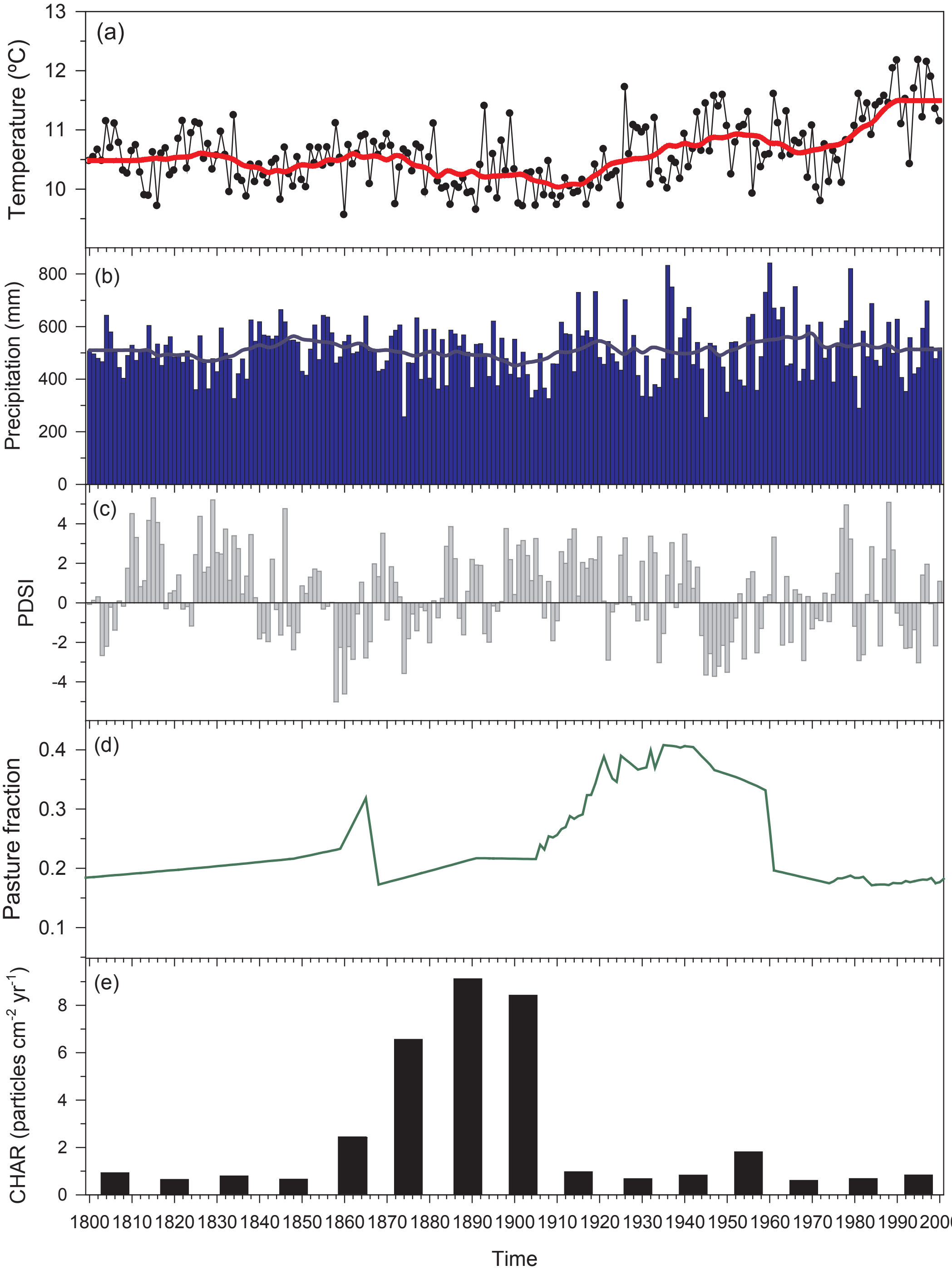

Fig. 2. Climatic (a, b, c) and land cover (d, e) reconstructions in the study area since 1800 (a, mean annual temperature; b, annual precipitation; c, Palmer Drought Severity Index; d, estimated pasture fraction; e, CHAR, charcoal accumulation rates).

3. Results

3.1. Long-term changes in climate, land use and fire history

According to climate reconstructions, the transition from the 19th to the 20th centuries was characterized by cold and humid conditions (Fig. 2a–c). In the 1860s, pasture surface peaked, briefly decreased then resumed its growth during the late 19th century until it reached its maximum value in the 1930s (Fig. 2d). From the 1870s to the 1890s, the CHARs peaked (Fig. 2e).

3.2. Structure, growth variability and negative pointer years

We detected trees with fire scars in three sites (CV, BA and TO). Half of the sampled trees presented scars in the low-elevation CV site (Fig. 1, Table 1). The thickest stems were sampled in BA, H2 and TO sites, whereas the tallest trees were found in the CV site (Table 1). In sites CV, BA and TO fire-scarred trees had significantly ($P < .001$) thicker stems (larger DBHs) than trees without fire scars, but tree height was similar between the two classes of trees. The DBH and bark thickness were positively and significantly ($P < .01$) related at all sites with the exception of CV (Appendix, Fig. S1).

The oldest dated non-scarred and fire-scarred trees were found in

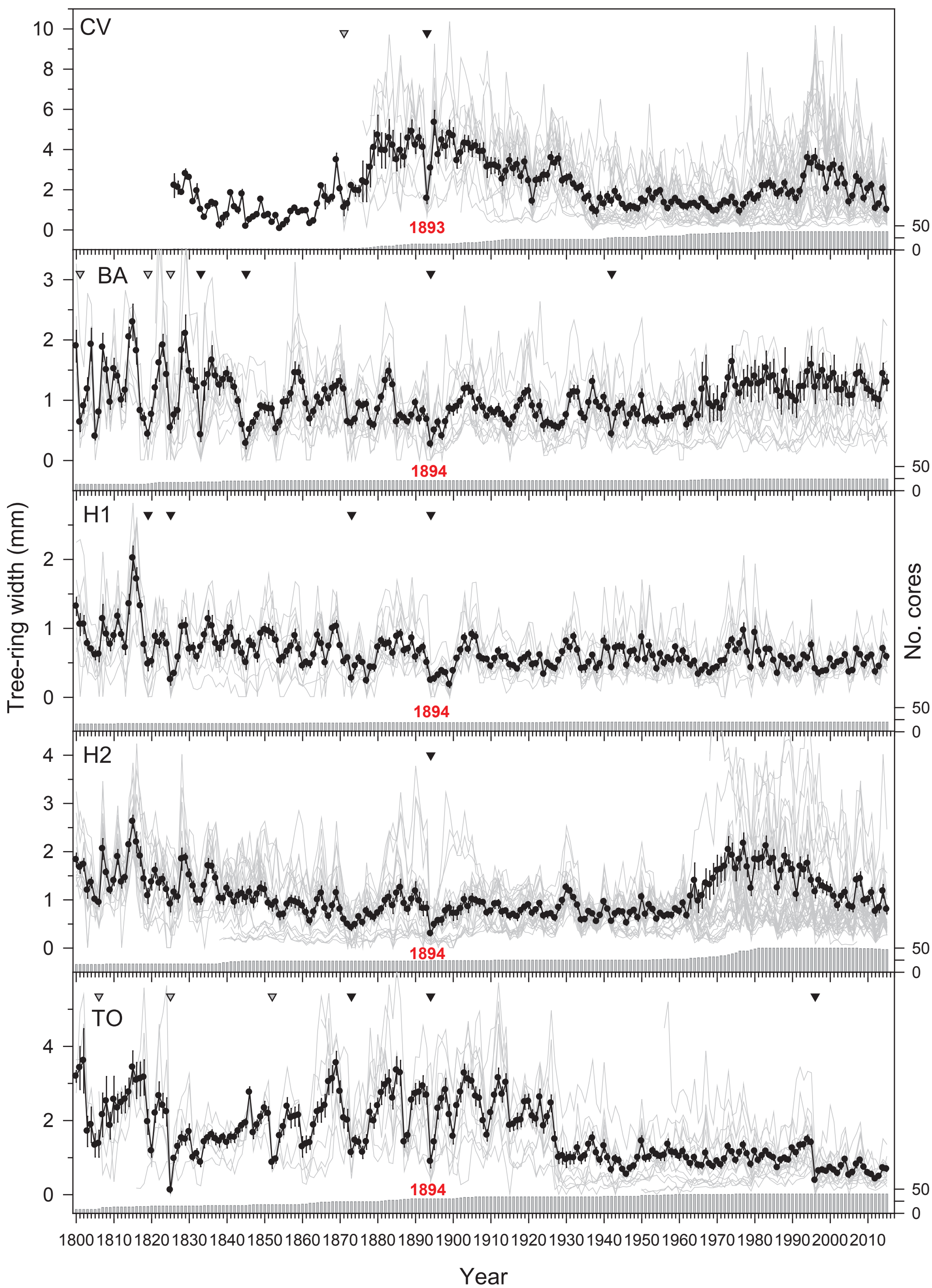

Fig. 3. Growth variability of black pine in the five study sites. The downward triangles indicate negative pointer years considering less (grey-filled triangles) or more (black-filled triangles) than 50% of sampled trees in each site, respectively. Gray lines show measured radii (sample depth is shown as bars and indicated in the right *y* axes) and black lines and symbols show the mean values (error bars are standard errors). The 1893–1894 years were detected as negative pointer years in all sites.

H1 and BA sites, they were 400 and 274 years old, respectively. Several trees became established during the 1960s to the 1970s in the CV and H2 sites explaining the increase in growth at those sites (Fig. 3), and the highest mean ring-width and first-order autocorrelation at site CV where young trees were abundant (Table 2). The recent growth increase peaked during wet-cool decades, such as in the 1970s, but the trend was interrupted due to sharp growth declines related to severe drought episodes, such as the one that took place in 1996 (a negative pointer year) at site TO (Fig. 2c and 3). In the BA site, another drought-related negative pointer year was detected in 1942, while three sites presented negative pointer years from the 1820s to the early 1870s (1871, 1873) though only the 1840s and 1850s were dry decades (Fig. 2c). This decoupling between drought and abrupt growth reduction in the 19th century suggests that other factors probably caused negative pointer years.

Drought-induced growth reductions cannot explain why two

Table 2
Descriptive growth statistics calculated based on raw chronologies. AC = first-order autocorrelation, MS = mean sensitivity, r_{bt} = mean correlation between trees, EPS = expressed population signal.

Site	Time-span (years)	Tree-ring width ± SD (mm)	MS	AC	r_{bt}	Period EPS > 0.85
CV	1816–2015	2.05 ± 1.51	0.34	0.79	0.54	1826–2015
BA	1742–2015	1.11 ± 0.64	0.35	0.67	0.55	1757–2015
H1	1617–2015	0.90 ± 0.66	0.37	0.72	0.61	1676–2015
H2	1703–2015	1.16 ± 0.61	0.30	0.71	0.57	1706–2015
TO	1766–2015	1.54 ± 1.07	0.33	0.74	0.62	1776–2015

marked negative pointer years were observed in 1893 and 1894 at all sites since that period was not as dry and warm as the 1940s and 1990s decades (Figs. 2 and 3). In the CV site, 1893 was identified as a negative pointer year, whereas 1894 was detected in the remaining sites. For instance, at site CV this represented a 44% reduction of radial growth passing from a mean tree-ring width of 1.8 mm in 1892 to 1.0 mm in 1893. The narrow rings formed in 1893 and 1894 did not show any conspicuous anatomical anomaly (more resin ducts, collapsed tracheids) which could be ascribed to fire damage to the cambium. Furthermore, these findings are robust because all site chronologies were well replicated from 1825 until 2015 showing a high mean correlation between the growth series of trees (r_{bt} = 0.58; see Table 2).

The abrupt growth reduction in 1893–1894 was also reflected in the highest values of mean negative growth changes (Fig. 4a) and the lowest mean ring-width indices of the site residual chronologies and the regional chronology which was below the −1.96 SD threshold (Fig. 4b). Those negative pointer years coincided with a peak in the historical fire records which reached high frequency in 1886, 1881, 1887, 1895, 1980, 1893 and 1974 (Fig. 4c). The estimated historical fire-foci density showed low-elevation hotspots of fire initiation near CV, TO and BA sites (Fig. 1).

3.3. Climate-growth relationships

Black pine growth was enhanced in response to warm February and warm-dry March conditions and by colder weather in the previous and current October (Fig. 5a). Wet June and July conditions improved growth at all sites except in CV where warm and wet prior-winter (December, January) conditions were associated with wider rings. Regarding the moving correlations between ring-width indices and summer precipitation, they peaked from the 1960s to the 2000s in all sites but showed negative associations in the early 1890s, 1920s and 1940s, particularly at the BA and CV sites (Fig. 5b).

4. Discussion

We found a higher frequency of negative growth changes (narrow rings) in the late 1890s at all study sites, and particularly at sites with more fire-scarred trees and a higher density of historical fire record foci. This coincided with an increase in CHARs in a nearby peat bog, and a peak in the historical record of wildfires in the study area. These changes preceded an increase in pasture lands during the first half of the 20th century (Ramankutty and Foley, 1999). The observed 1890s growth suppression was not a response to drier weather conditions usually associated with growth reduction in Iberian black pine forests (Génova et al., 1993, Génova, 2000, Camarero et al., 2015, Touchan et al., 2017). Therefore, these parallel datasets seem to support our hypothesis that the severe growth reduction in the studied trees was a consequence of widespread fires, possibly damaging part of the pine crowns, which, in turn, likely shaped the current structure of these relict Mediterranean black pine forests.

The fires of the 1890s decade constituted a coupled regime shift in the ecology and management of the studied forests since it coincided with the end of the "Mesta", and the transition from a regulated transhumance-based use of forests and grasslands to a more intensive and unrestrained exploitation of natural resources (Ruiz and Ruiz, 1986). For instance, during the period when the "Mesta" rules were applied, transhumant cattle was shepherded through specific mountain passes, while after the "Mesta" dissolution sheep herds used multiple passes, some of them located near the study sites (López-Sáez et al., 2017, 2018). The cessation of "Mesta" transhumance allowed local populations to exploit formerly protected or not intensively used mountain forests and woodlands, which in all likelihood were cleared using fire (Ruiz and Ruiz, 1986; Blanco-González et al., 2015; Silva-Sánchez et al., 2016). According to historical fire records, in the late 19th century fire frequency and extent increased reaching a maximum value of burnt surface area in 1893 (Montiel-Molina, 2007, 2013). Our reconstructions of tree growth and fire occurrence illustrate the tight connections between changes in socio-economic and ecological systems (Seijo et al., 2017).

This shift from transhumant sheep herds to increasingly local grazing activities by cattle in the mid to late 19th century is also reflected in several palaeoecological records from the Sierra de Gredos which showed peaks in CHARs and coprophilous fungi suggesting more intensive land use by shepherds and widespread wildfires (López-Merino et al., 2009, López-Sáez et al., 2009, 2016a, 2016b, 2017; Robles-López et al., 2017). Our data suggests that the transition from the 19th to the 20th centuries indicates a peak in livestock activities in the Sierra de Gredos, which would be corroborated by the rise in pasture fraction (López-Sáez et al., 2009). The end of the 19th century also coincides with the final stages of the Little Ice Age (LIA) which lasted until 1850 when a more humid, cold and climatically unstable phase started (Manrique and Fernández-Cancio, 2000). In fact, the 1890s were among the warmest decades of the 19th century coinciding with the end of the LIA (Luterbacher et al., 2004). In 1893 the warmest spring for the 1500–1960 period was recorded in the study area. These warm conditions further support the fire-related growth suppression we argue took place in the 1890s since warm spring seasons are not significantly related to a reduced growth in black pine, though they increase the wildfire hazard in Mediterranean forests (Piñol et al., 1998). In fact, spring is the season when most anthropogenic burning of grasslands occurs in the Sierra de Gredos (Viedma et al., 2006). Moreover, no circularity conflict can be attributed to these conclusions arguing that the climate reconstructions used here were based on tree-ring data (e.g., Pauling et al., 2006), since the presented chronologies have been developed later and in sites or species not considered in those reconstructions. Lastly, the fires of the 1890s caused a decoupling between growth and summer precipitations, particularly in fire-prone stands, which casts doubt on the value of those tree-ring proxies for deducing long-term climate reconstructions. Overall, our dendrochronological approach, combined with a multiproxy dataset (historical records, charcoal analysis), confirms that the fires of the 1890s were probably triggered by very warm spring conditions and facilitated by increased anthropogenic pressure on forests.

Fire-surviving trees forming relict stands usually had a large size (DBH) and occupied rocky outcrops, often near humid enclaves such as creeks or small rivers (e.g., CV site), where fire intensity could be lower than on steep and drier slopes (Moreno et al., 2011). The larger DBH of scarred fire survivors, as compared with neighboring trees, was also observed in a Rocky Mountain forest (Margolis et al., 2007). In that

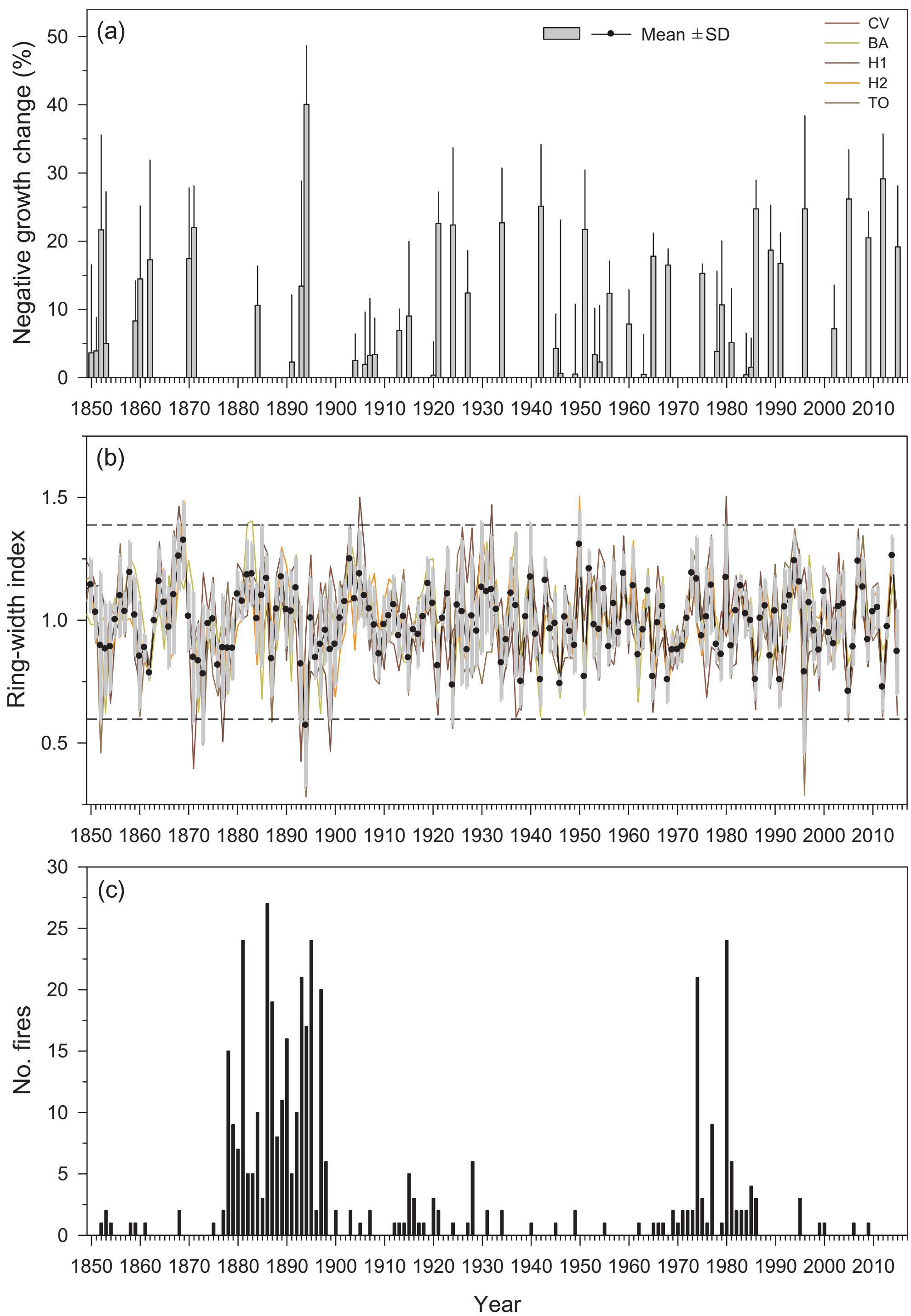

Fig. 4. Mean negative growth changes (a) detected at the five study black pine forests, (b) ring-width indices, and (c) number of forest fires recorded in the study area (Sierra de Gredos) from documentary sources. Thin lines show individual sites and bars (a) or thick lines (b) show the mean values of all sites (error bars are standard errors). In the uppermost plot (a) site values were omitted for the shake of clarity. In (b) the dashed lines indicate the ± 1.96 SD thresholds.

study it was shown that bigger trees tend to produce a thicker and more fire-resistant bark, and their high crowns allowed them surviving surface fires. We observed a tight relationship between DBH and bark thickness thus seemingly confirming this hypothesis which consequently suggests that currently dominant trees had a bark thick enough in the 1890s to survive the extensive fires that took place during that period.

Fire damage to crowns leads to canopy disturbances which may create specific tree-ring width signatures that can be used as proxies for fire histories (e.g., Veblen et al., 1991). The observed pattern in black pine (growth suppression in 1893 and 1894) agrees with the marked reduction of growth caused by fire damage described by Barrett and Arno (1988) in their report on scar-boring cores, though in our study missing rings were not detected. Post-fire survivor trees show either growth releases or suppressions as a function of the degree of damage to the crown and the cambium. However, mixed responses can also be found (Peterson et al., 1994). In the first class of studies, growth increases on the surviving trees in the early years following wildfires have been explained by the release from competition for water, especially in semi-arid and arid forests, as well as the increased availability of

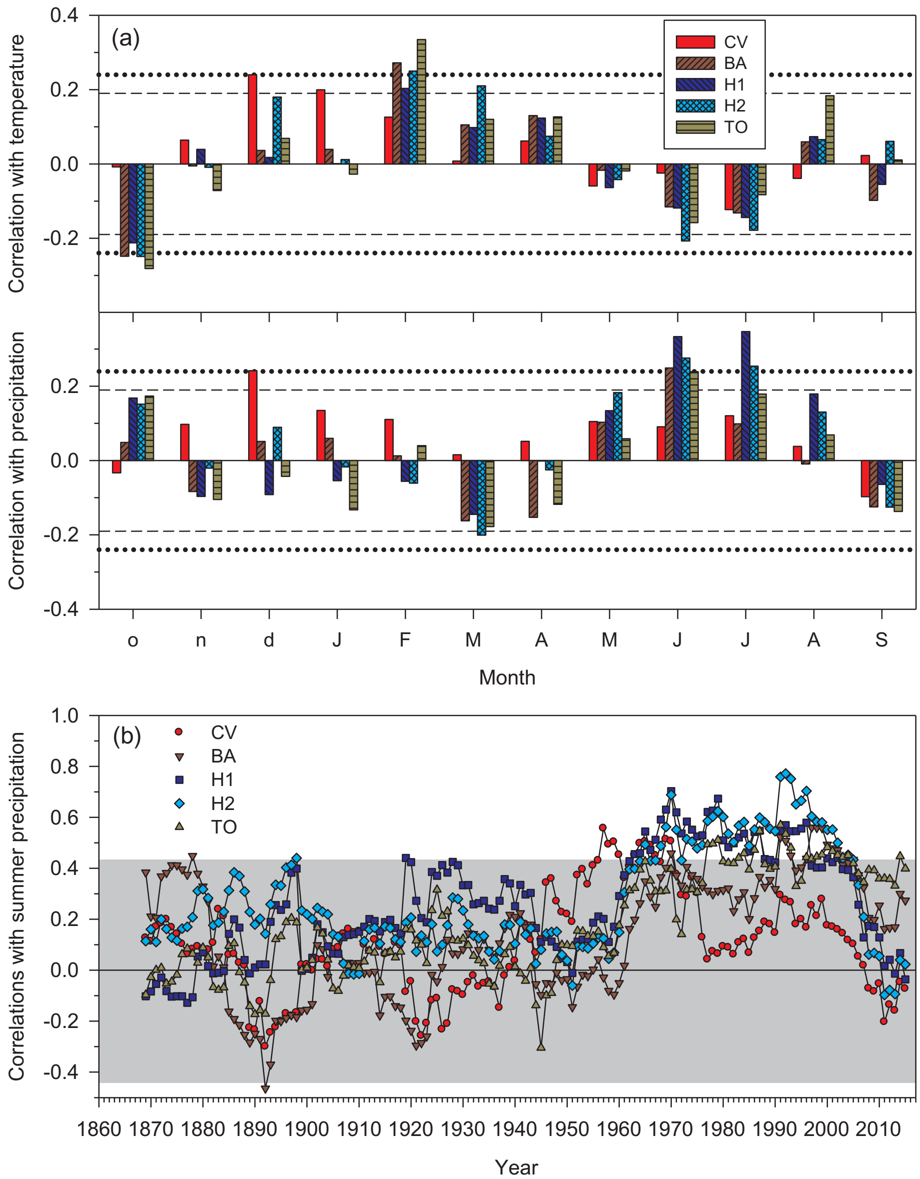

Fig. 5. Climate-growth relationships in the five study sites calculated either for (a) fixed intervals (period 1901–2015, CRU climate data) or based on (b) moving correlations. In (a) correlations were calculated between ring-width indexed chronologies and climate data (mean temperature, total precipitation) from October of the previous year (months abbreviated by lowercase letters) up to September of the year of tree-ring formation (months abbreviated by uppercase letters). Significant levels are indicated by dashed ($P < .05$) and dotted ($P < .01$) lines. In (b) moving correlations were calculated considering 20-year long intervals between chronologies and the reconstructed summer precipitation (Pauling et al., 2006) for the 1850–2015 period. Symbols are placed at the end of each interval (e.g. the symbol placed in 1869 corresponds to the 1850–1869 interval). Values located outside the grey box are significant ($P < .05$).

nutrients (Mutch and Swetnam, 1995, Lageard et al., 2000, Py et al., 2006, Margolis et al., 2007). Such abrupt growth increases are very pronounced and cannot be related to improved climatic conditions. However, our study seems to confirm the findings of the second class of studies which reported growth reductions either related to the amount of forest litter consumed by surface fires (Elliott et al., 2002) or to crown fires which reduced growth proportionally to the amount of crown scorched (McInnis et al., 2004, Rozas et al., 2011). In the fire-adapted *Pinus canariensis* species, surface fires did not negatively impact growth because they barely burned the crown, while crown fires leading to almost completely scorched crowns did cause short-term and abrupt growth reduction (Rozas et al., 2011). In south-eastern USA pine-oak mixed forests high-severity fire events also led to marked growth reduction in surviving pines (Guiterman et al., 2015). These findings suggest that the 1890s growth suppressions were probably responses to widespread surface wildfires affecting the relict black pine forests in our study area.

Some of our studied relict forests (CV, BA and TO sites) presented attributes consistent with a fire-resistant evolutionary strategy (Keeley et al., 2012) such as an open, multi-aged structure with large, thick-barked trees forming high crown bases and growing in relatively humid microsites prone to low severity fire behavior. However, the observed 1890s' growth suppression would be consistent with fires partially affecting the crown, a disturbance regime change which in all likelihood contributed to the decline of black pine in the northern Iberian Plateau (Morales-Molino et al., 2017). This development contrasts with the regime of repeated surface fires which was shown to affect a relict black pine forest studied in eastern Spain (Fulé et al., 2008). That forest was located in a drier site (almost half the precipitation than in the Sierra de Gredos), and therefore its long-term dynamics may differ from the relic stands here described whose fire regime may depend on human effects as well as climatic conditions.

At the local scale, this study offers a robust replication of negative pointer years in relict black pine stands which are potentially linked to fires in the late 19th century and to other causes (droughts in the 1940s and 1990s) more recently. Since black pine can be fully defoliated after pine processionary moth outbreaks this insect could also cause a severe growth reduction but that signal should be more local or, in any case, would have led to the formation of two consecutive narrow rings (Sangüesa-Barreda et al., 2014). Sharp growth reductions were also observed in other black pine populations from the Sierra de Gredos during the late 19th century but the variability in growth between coexisting trees was too high, challenging their cross-dating and suggesting the influence of other local level disturbances such as resin tapping, logging or fires (Génova et al., 1993).

Other reconstructed fire histories using dated fire scars also found a high incidence of fires during the mid to late 19th century in several Mediterranean countries including Greece (Touchan et al., 2012, Christopoulou et al., 2013, Sarris et al., 2014), Spain (Vega, 2000, Fulé et al., 2008) and Algeria (Slimani et al., 2014). After those dominant pre-19th century anthropogenic fire regimes - often characterized by high frequency and low intensity surfaces wildfires - subsided; land-use changes and new conservation laws regarding forest resources may have led to a sharp reduction in fire frequency. In Greece, most fires occurring in the late 19th century and 20th century seem to be associated with either anomalously dry or warm conditions. More recent fires, however, occurring between the late 20th and early 21st centuries were characterized by both dry (below normal precipitation) and warm (above normal maximum temperatures) conditions (Sarris et al., 2014). It would be therefore interesting to reconstruct and compare different fire regimes in the 19th and 20th centuries using multiples proxies (fire scars, growth suppressions, historical records, palaeoecological data) to disentangle the role played by humans and climate on those historical fire regime transitions.

Regarding forest management, the increase in fire frequency and size observed during the late 20th century in Spain as a consequence of more fuel availability occurred despite improved fire extinction technologies and budgets (Seijo, 2009). From the point of view of conservation and restoration, low-intensity burns could be tested in the field so as to ascertain whether a more frequent, low-severity fire regime improves the dynamics of relict black pine populations currently forming patches within other vegetation types which are very flammable as *Pinus pinaster* forests. These dense stands, formerly used for resin tapping, surround relict black pine forest groves in Gredos and can experience medium to high severity crown fires which may cause black pine forest decline (Génova and Moya, 2012, Robles-López et al., 2017). Ancient, monumental black pines should be preserved and used to improve the reconstruction of fire history by studying their fire scars once they die or are felled.

To conclude, three coherent lines of evidence support the existence of widespread fires in the western Sierra de Gredos during the late 19th century affecting relict black pine stands: severe growth reductions in 1893 and 1894, an increase in fire frequency as shown by historical documents, and a peak in charcoal accumulation rates. The late 19th century increase of fire incidence was mainly explained by the dissolution of the “Mesta” system, the major transhumant livestock organization in European history, which was followed by a more intensive and widespread use of forests and grasslands aided by extensive anthropogenic wildfires. The late 19th century’s complex fire history contributed to shape the current structure of relict black pine forests and may inform future management strategies based on prescribed burning to recreate pre-19th century disturbance regimes associated with a greater abundance of those forests.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2018.01.046.

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