Forest Ecology and Management 518 (2022) 120296

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Multi-century spatiotemporal patterns of fire history in black pine forests, Turkey

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ARTICLE INFO

Keywords:
Climate change
Dendrochronology
Drought
Regime shift
Wildfire management
Fire history

ABSTRACT

In this study, we aimed to use tree-ring based fire reconstruction to understand the spatiotemporal patterns of past fires in different climate types of western Anatolia. We collected fire scarred wood samples from living trees as wedges and remnant woods from ten sites along a transect that represents a continental to Mediterranean climate gradient. We determined fire years and assigned seasonality of fires based on the intraring position of the fire scars. We calculated fire statistics and analysed fire-climate relationships. Breakpoints in our Anatolian regional fire chronology were estimated to determine the regime shifts. A decrease in fire frequency was recorded at most of the sites after the end of the 19th and the beginning of the 20th century. We observed two critical fire regime shift periods. The period between 1853 and 1934 is characterized by highly frequent (a total of 82 fires) and simultaneous fires occurring in multiple sites and this period overlapped with the longest and most severe drought period of the past 550 years. The fire frequency decline after 1934 coincided with the period of the first forest protection law in 1937. Dry, as well as prior wet conditions were main drivers of fires in the black pine forests in western Anatolia. We observed a decrease in fire frequency in the late 19th and early 20th centuries due to fire suppression activities. Continued fire suppression activities may cause fuel accumulation and pose a risk for more intense fires and thus a paradox for forests in the future. Based on future climate projections, we will face prolonged fire seasons as a consequence of increasing drought frequency, which may shift the fire regime from surface to crown fires with the accumulation of combustible material in the understory in black pine forests.

1. Introduction

Wildfire is an earth system process that has occurred since the first terrestrial plants emerged in the Silurian period (~420 million years ago) (Bowman et al., 2009, 2011; McLauchlan et al., 2020) and has been an important factor shaping plant evolution and the diversity of life (Keeley et al., 2012; McLauchlan et al., 2020; Kelly et al., 2020). Fire has also been used by humans throughout history for various purposes along (Bowman et al., 2011; Gowlett, 2016). In recent centuries, land use has increasingly created shifts in regional fire regimes in many ecosystems by altering the accumulation and structure of fuels, suppressing fires, and increasing ignitions (Liebmann et al., 2016; McLauchlan et al., 2020; Pausas and Keeley, 2021; Taylor et al., 2008).

Adaptive fire management should therefore include pragmatic approaches based on our understanding of past fire regimes. High-resolution, century-long paleofire records can enhance our understanding of fire regime dynamics and thus improve present and future fire management with more accurate information and effective ecosystem conservation strategies (Keane et al., 2009; Beller et al., 2020). Few fire history reconstructions were carried out with different species in the Mediterranean basin (Fulé et al., 2008; Touchan et al., 2012; Christopoulou et al., 2013; Fournier et al., 2013; Slimani et al., 2014; Molina-Terrén et al., 2016; Szymczak et al., 2020) and boreal regions (Östlund, & Linderson, 1995; Niklasson & Granström, 2000; Kharuk et al., 2013; Ryzhkova et al., 2020; Wang et al., 2021). Accordingly, a large number of tree-ring based fire history studies have

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https://doi.org/10.1016/j.foreco.2022.120296
Received 18 March 2022; Received in revised form 10 May 2022; Accepted 12 May 2022

contributed to our improved understanding of fire regime interactions with fire management strategies, climate types, or geographical gradients (Swetnam & Baisan, 1996; Farris et al., 2010; Trouet et al., 2010; Azpeleta Tarancón et al., 2018; and many others) with corroboration of empirical data (Caprio & Swetnam, 1995; Farris et al., 2010; Howard et al., 2021; Şahan et al., 2021). Understanding the variability and shifts of past fire regimes is specifically essential for regions at severe fire risk under a changing climate, such as the Mediterranean Basin (Turco et al., 2014; Şahan et al., 2021). Although fire is a natural ecosystem process in Mediterranean-type ecosystems (Slimani et al., 2014), it is predominantly driven by drought at the local and regional scales (Bekar et al., 2020; Forzieri et al., 2021), and burning probability, therefore, increases under anthropogenic climate change. Moreover, fuel accumulation in Mediterranean forests and shrublands has increased over the past decades as a result of fire suppression and the coincidence of fuel accumulation with the effects of climate change (e.g., heatwaves, elongation of a dry season, etc.) leads to the occurrence of recent megafires in Mediterranean ecosystems (Moreira et al., 2020). In particular, for populations of black pine *(Pinus nigra* JF Arnold), a long-lived coniferous tree adapted to low-intensity surface fires, the main future threat is a potential regime shift toward destructive crown fires (Christopoulou et al., 2013; Şahan et al., 2021). Such tree species are vulnerable to crown fires due to the lack of a specific adaptation termed serotiny (i.e., the formation of a canopy seed bank), which is present in many other pine species adapted to crown fire regimes (e.g., *Pinus halepensis* and *P. brutia*; Keeley et al., 2012).

Summer temperature and fire risk are projected to increase, and hydrological/ecological drought severity and frequency are expected to rise in the Mediterranean Basin under future anthropogenic climate change (IPCC, 2021). In 2021, Mediterranean forests in Turkey faced a series of major crown fires that left burned areas of record size (>160.000 ha, according to EFFIS data, https://effis.jrc.ec.europa.eu). The burned forested areas were predominantly covered by Turkish red pine (*Pinus brutia* Ten.), but a considerable amount of black pine forests were also affected by these crown fires. Black pine may thus be threatened by more intense fires due to accumulated fuels as a consequence of fire suppression and the increasing effect of anthropogenic climate change in the near future.

In this study, our goal is to understand the variability of spatiotemporal patterns of past fires throughout the main distribution areas of black pine forests in Turkey using tree-ring based fire reconstruction. We analysed ten sites along a latitudinal transect in western Anatolia that represents different climate types (continental to Mediterranean climates).

2. Materials and methods

2.1. Study area and climate

Black pine, growing primarily in elevation ranges between 400 and 2100 m in the mountains of the Black Sea, Aegean, and Mediterranean regions in the western part of the Anatolian Diagonal, is a widely distributed tree species in Turkey (Davis, 1965; Akkemik, 2020). Our sampling sites (37–41° N and 28–33° E) were selected roughly along a latitudinal transect extending from northern Turkey on the Black Sea to southern Turkey in the Mediterranean region to represent different climate types (Fig. 1). We collected 149 fire-scarred wood samples from living trees as wedges and remnant wood (e.g., stumps, snags, and logs) using a chainsaw. An additional 62 samples from three sites in Kütahya province that were previously published in Şahan et al. (2021) were also

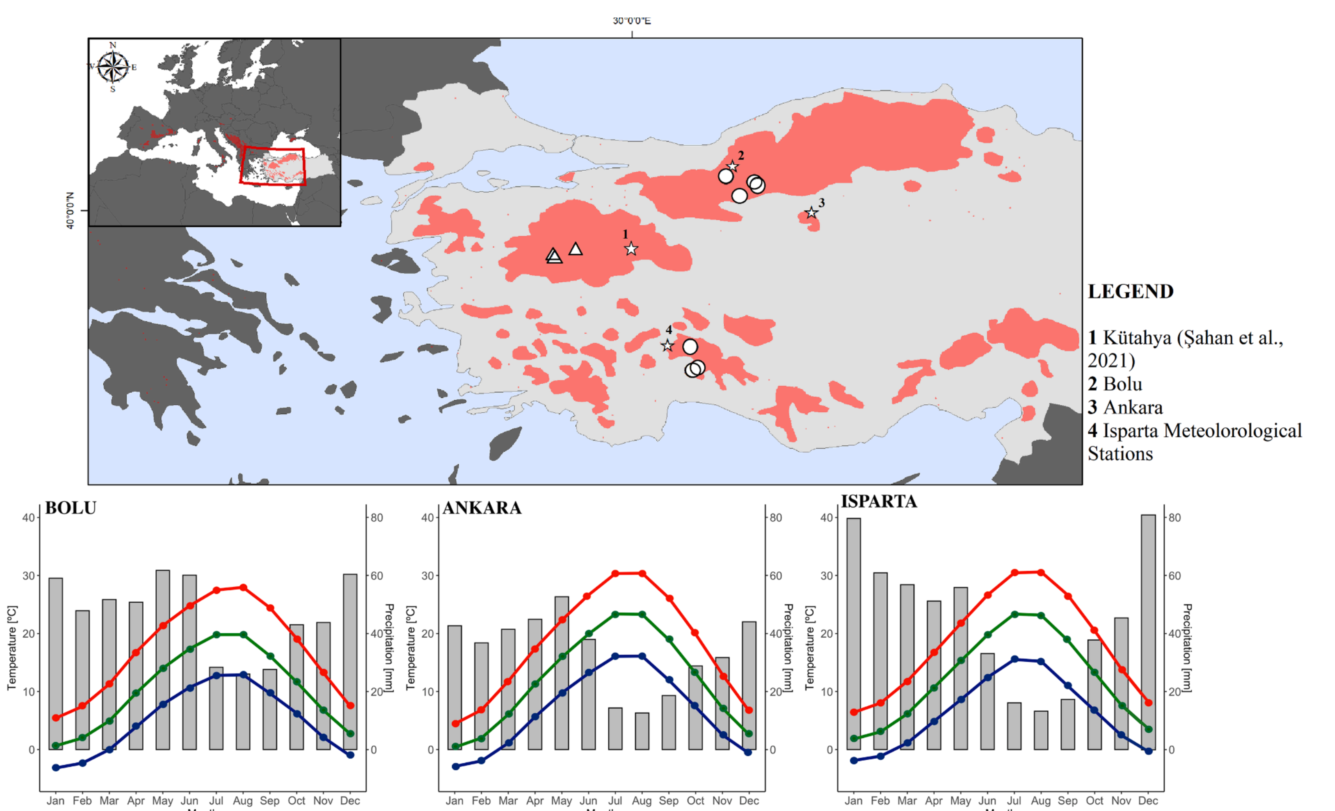

Fig. 1. A map of our 10 sample sites (top) and climatic diagrams of three meteorological stations representing study sites (bottom). Red areas of the map represent the distributional range of *Pinus nigra* in Turkey (data from EUFORGEN, 2004). Circles represent the sampling sites in this study, triangles show previously published sites (Şahan et al. 2021), and stars show the location of meteorological stations. In the climatic diagrams, bars indicate precipitation (mm), and red, green, and blue lines represent the maximum, mean, and minimum temperature (°C), respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

included in our analyses (Table 1).

The climate is typically the Mediterranean in our study area. However, the Mediterranean climate prevails more dominantly on the coast, while a more continental climate is dominant in the plateaus in the inner parts of the country (Bozkurt & Şen, 2009). Therefore, four dominant climate types, the Mediterranean, Black Sea, continental, and Marmara types, are observed in Turkey. We categorised our sites based on their climate type and Köppen classification (Table 1) in order to understand the spatiotemporal patterns of change in fire regime parameters. The climate in Depel (DEY) site in Ankara is the continental climate, while the three northern sites in Bolu (ARY, YRY, SEY) are in the transition zone from the Black Sea to the continental climate. The climate of three southern sites in Isparta (AKY, HAY, YUY), on the other hand, are the Mediterranean and Kütahya (CUY, ELY, KAY) is the Marmara transition climate conditions (Şensoy et al., 2016). The Aegean and Mediterranean coasts have cool, rainy winters and hot, moderately dry summers throughout the year. The Black Sea coast receives more rainfall throughout almost the entire year and summers are relatively cool, winters are warm in the coastal areas, snowy and cold in mountainous areas (Şensoy et al., 2016). The continental climate, on the other hand, is characterised by hot summers and cold winters with drought due to limited precipitation. Finally, the Marmara transition climate is cooler than the Mediterranean and warmer than the continental climate in winter, less rainy than the Black Sea, and not as dry as the continental climate in summer (Şensoy et al., 2016). According to the Köppen-Geiger climate classification, Isparta sites belong to the warm-cool summer Mediterranean climate (Csb), SEY and YRY in Bolu to the Humid Continental climate (Dsb), ARY in Bolu to the Oceanic climate (Cfb), and Kütahya and Ankara sites to the warm-cool summer Mediterranean climate (Csb) zones (Kottek et al., 2006; Öztürk et al., 2017). Additionally, according to the fire risk classification of the General Directorate of Forestry in OGM (2013), Ankara and Bolu sites are located in 3rd level fire risk, while Kütahya and the AKY and HAY sites in Isparta (YUY in 2nd level fire risk) are in 1st level fire risk area (the highest risk) (Table 1). This pattern can also be depicted through the Haines fire weather index (Tatlı and Türkeş, 2014).

2.2. Data analysis and fire history reconstruction

Cross-sections were first dried to avoid resin leakage, then mounted and polished using a belt sander and by hand. The samples were then scanned and tree-ring widths were measured based on standard dendrochronological methods with an accuracy of 0.01 mm using WinDENDRO software (Regent Instrument Inc, 2002). We first cross-dated visually then with the tree-ring width measurements and verified crossdating accuracy using COFECHA software (Holmes, 1986). We assigned fire years for each sample according to the formation of callus tissue on transverse sections (Schweingruber, 1988; Guyette and Spetich, 2003).

We determined the seasonality of fire scars (earlywood, latewood, or dormant; corresponding to spring, summer, or fall/winter fires) based on the intra-ring position of scars (Baisan and Swetnam, 1990). First, we created individual site level composite chronologies based on both regular fire years as years when a minimum of two samples recorded scars and major fire years as years when $\geq$ 25% of recording samples had fire scars, with a minimum of two samples. Then, we developed regional fire chronologies for Isparta (HAY, AKY, YUY) and Bolu (ARY, YRY, SEY) by combining the minimum 2-scarred fire years of individual sites, as well as major fire years. Finally, we built an Anatolian composite fire chronology by combining all minimum 2-scarred fire years of ten sites and determined major fire events as the years recorded in at least three of the ten sites simultaneously. We calculated mean fire interval (MFI), minimum and maximum fire return interval (FRI), Weibull median probability interval (WMPI), and standard deviation for both minimum 2-scarred and 25% filtered composite fire chronologies of each site. The MFI refers to the average period between fires, while WMPI represents a measure of central tendency (Sutherland et al., 2015). Then, we used the 'strucchange' package (Zeileis et al., 2002) in R software (R Core Team, 2020) to determine breakpoints in the time series of the number of sites recording fires in our Anatolian regional fire chronology. We decided on the optimum number of breakpoints based on the Bayesian Information Criterion (BIC) and by minimising the residual sum of squares (RSS) (Zeileis et al., 2002).

We applied Superposed Epoch Analysis (SEA) to investigate fire-climate interactions. We compared the major fire years in our site-specific fire chronologies, as well as the regional fire chronologies and Anatolian composite chronology with a gridded summer season (June, July, August) self-calibrating Palmer Drought Severity Index (scPDSI) reconstruction (1400–2012; Cook et al., 2015). We used two grid points in our analysis: 40.00–41.00 °N; 31.50–32.50°E for Ankara and Bolu, 37.00–38.00 °N; 30.50–31.50 °E for Isparta. The fire years of Kütahya in Şahan et al. (2021) were also included in the SEA of the Anatolian regional fire chronology. We used the 'burnr' package (Malevich et al., 2018) in R statistical software (R Core Team, 2020) to calculate descriptive statistics of the fire interval, create the fire charts, and for SEA (Haurwitz & Brier, 1981).

Lastly, this study was an incomplete part of the fire history studies on black pine forests in the Mediterranean basin. We, therefore, determined the common fire event years between our Anatolian regional fire chronology years and years that we obtained from fire charts of previously published literature in the Iberian Peninsula (Fulé et al., 2008) and the Balkan Peninsula (Touchan et al., 2012; Christopoulou et al., 2013) to compare regional climate conditions and influences.

Table 1
Characteristics of the sample sites.

	Site	Code	Latitude (N)	Longitude (E)	Elevation Range (m)	Aspect	Climate Types	Köppen Climate Classification	Fire Risk**
Ankara	Depel	DEY	40.24	31.71	1338–590	N-NW	Continental	Csb	3
Bolu	Ardıç	ARY	40.56	31.50	1346–1463	SW-E-NE	the Black Sea to continental transition	Cfb	3
	Yarbaşı	YRY	40.41	32.00	1634–1673	S-SW		Dsb	3
	Serke	SEY	40.47	31.95	1398–1433	SW		Dsb	3
Isparta	Akçal	AKY	37.37	30.96	1288 1445	W, SW, NE, NW, S, E	The Mediterranean	Csb	1
	Hacıaliler	HAY	37.78	30.95	1336–1551	E			1
	Yuvalı	YUY	37.74	30.94	1237–1486	W, SW			2
Kütahya *	Çukurçayır	CUY	39.36	29.09	1508–1558	S - SW	The Marmara transition	Csb	1
	Elmaalanı	ELY	39.28	28.73	1427–1484	W - NW			1
	Karagöl	KAY	39.24	28.76	1404–1456	E - SE			1

* Three sites from Kütahya were presented previously in Şahan et al. (2021).
** Fire risk classification from 1 to 5 (high to low risk, respectively), which is based on the average number of fires from the forestry administration in OGM (2013).

3. Results

3.1. Composite fire chronologies and fire statistics

We developed ten site-specific fire chronologies that extended back to between 1467 CE (AKY, Isparta) and 1810 CE (CUY, Kütahya) (Fig. 2). The earliest recorded major fire year was 1726 in Ankara, 1686 in Bolu, and 1547 in Isparta. We found two major fire years (1720 and 1763) that occurred simultaneously in Isparta (HAY, AKY) and one (1954) in Bolu (ARY, SEY). For sites in Isparta (AKY, HAY, YUY), major fire years were present in many of the sampled trees (Fig. 2). At the three sites in Bolu (ARY, YRY, and SEY), on the other hand, recorded fires were much less common between trees, representing more patchy fire events and a more humid climate (Fig. 2). By combining the fire years of the 10 sites in one regional black pine composite fire chronology for Anatolia, we found 13 major fire years from the 18th century onwards (1793, 1822, 1828, 1840, 1853, 1879, 1886, 1887, 1890, 1893, 1894, 1954, and 2005), which were recorded in at least three of the ten sites.

To understand the effect of climate type on fire regime, we calculated fire statistics of site-level minimum 2-scarred and major fire year composite fire chronologies organised by climate type (Fig. 3). MFIs for the site chronologies did not significantly vary by climate type, but the major fire years' statistics showed differences. Calculated MFIs were higher in relatively northern sites in Bolu (the Black Sea-continental climate transition) and Ankara (the continental climate) (16.3 for the YRY, 21.3 for SEY, 24.5 for ARY, and 39 years for DEY sites). Relatively shorter MFIs were calculated for Kütahya sites (from 9.8 to 16.3) under Marmara transition climatic conditions. The highest minimum FRIs were calculated for the DEY (nine years) in Ankara and for CUY (eight years) in Kütahya. The regional variability of maximum FRIs of major fires was similar to that of maximum FRIs of two scars, the lowest maximum FRIs were observed in Kütahya and YUY in Isparta (from 17 to 36 years). WMPIs showed similar variability to MFIs among sites for both site composites of min 2-scarred and major fire years.

In the most recent century(ies), a decrease in fire frequency was recorded at most of the sites, at the end of the 1800s in Isparta (except YUY, 1922) and at the beginning of the 1900s in Ankara (DEY) and in Bolu (YRY). A similar decreasing trend over the past century was observed in Kütahya (Şahan et al, 2021) in a tree-ring based fire history as well as written documents (also see Fig. 2). We verified these visually observed frequency changes in the site-specific fire chronologies statistically in the Anatolia-wide regional fire chronology, to answer the question whether there is a change in the frequency of fires throughout the Anatolian black pine forests. Our Anatolian composite fire chronology shows three regime shifts, in 1734, 1852, and 1934, which are associated with differing fire regimes from 1467 to 1734, 1735–1852, 1853–1934, 1935–2019 (Fig. 4). This regime-shift analysis highlights the period of 1853–1934 CE as the period when black pine forests burned most frequently, and simultaneous fires occurred in many sites in the same year. The decreasing trend over the past century, observed at most of the individual sites, occurred after 1934 in the Anatolian composite chronology with low fire frequency and fewer sites recording fires simultaneously.

3.2. Fire seasonality

We were able to determine the seasonality of fire scars for most of the samples (82.7%) and found that the majority (87.1%) of fire scars occurred in the latewood across all sites, reflecting late summer and fall fires, with fewer fires in the dormant season (6.7%) (Fig. 5). The percentage of fire scars in the earlywood was low, with most of those occurring in the mid-earlywood (3.8%).

3.3. Climate-fire relationships

We found no significant ($p < 0.05$, based on bootstrap simulations) association between major fire years and drought for individual sites, except for the SEY site in Bolu, which is the only site that showed substantial fire activity into the twentieth century (Fig. 2) (Fig. 6). Major fire years in Bolu also showed a significant relationship with dry years. Fire years of the Isparta regional fire chronology, on the other hand, occurred two years after significantly wet conditions (Fig. 6). Finally, major fire years of the Anatolian regional fire chronology showed a strong and significant relation with concurrent drought in western Anatolia.

This influence of drought on region-wide fire occurrence in Western Anatolia was further confirmed when plotting a 50-year low-frequency Hanning filter value of the mean summer scPDSI reconstruction against the Anatolian regional fire chronology (Fig. 7A). The 1853–1934 CE period with the most frequent and simultaneous fires overlapped with the longest drought period of 50-year filtered mean summer scPDSI reconstruction.

We further plotted the gridded summer scPDSI reconstruction (Cook et al., 2015) during the 13 major fire years of the Anatolia regional chronology, to indicate the spatial extent of the drought for these fire years (Fig. 7B). The majority of the fire years coincided with a drought affecting the whole of western Anatolia, except for the years 1886 and 2005. The highest number of sites recording simultaneous fire events was observed in the years 1853, 1879 (five sites), and 1890 (four sites), which all occur in the longest dry period as well as in the most frequently and simultaneously burned period (Fig. 7A; B).

3.4. Spatial and temporal pattern comparison with other fire-history studies from the Mediterranean Basin

Our results complement existing fire-history studies across the Mediterranean Basin both in Spain (Iberian Peninsula) and Greece (Balkan Peninsula) (Fulé et al., 2008; Touchan et al., 2012; Christopoulou et al., 2013). We visualised the severity of drought conditions across the Mediterranean basin to understand the effect of drought and the number of common fire years (Fig. 8). Across the Basin, extensive fires are recorded in fire scars in the 19th century. Frequent fires continued during the 20th century in Greece (Christopoulou et al. (2013)), even though no fire years between 1891 and 2000 were found in Touchan et al. (2012). In the fire record from Spain (Fulé et al. (2008)), on the other hand, there is no evidence that the number of fires decreased in the 20th century because a significant part of the fire record was erased from the catfaces by cutting. We found more (18) common fire years between Anatolia (combining site-level min 2-scarred fire years) and the fire-history sites in the Balkan Peninsula (1727, 1818, 1830, 1845 1860, 1868, 1879, 1880, 1890, 1891, 1913, 1930, 1945, 1958, 1962, 1973, 1977, 2007), which is also located in the eastern Mediterranean than with the sites in the Iberian Peninsula (1866, 1868, 1892, 1902, 1918, 1934, 1945, 1953, 1957, 1963, 2003), which is located in the western Mediterranean Basin (Fig. 8). We found the year 1945 to be a common fire year in all three regions in the Mediterranean basin which was a very dry year.

4. Discussion

We provide a half-millennia-long fire history of black pine forests in Anatolia to improve our understanding of how the fire regime components differ between climate types and whether climatic changes are the trigger for recent changes in fire regimes. Although a 553-year western Anatolian regional chronology developed, it is necessary to consider the sample depth increased after the beginning of the 1700s. Fire statistics showed that black pine forests in Anatolia have experienced fires at a minimum of one year and a maximum of 105-years intervals (Fig. 3) over the past 553 years. This variability in FRIs was mainly due to the difference among study areas. MFIs of regular fire events showed similarities in the sampled black pine forests of Anatolia under different climatic conditions. On the other hand, we calculated lower MFIs of

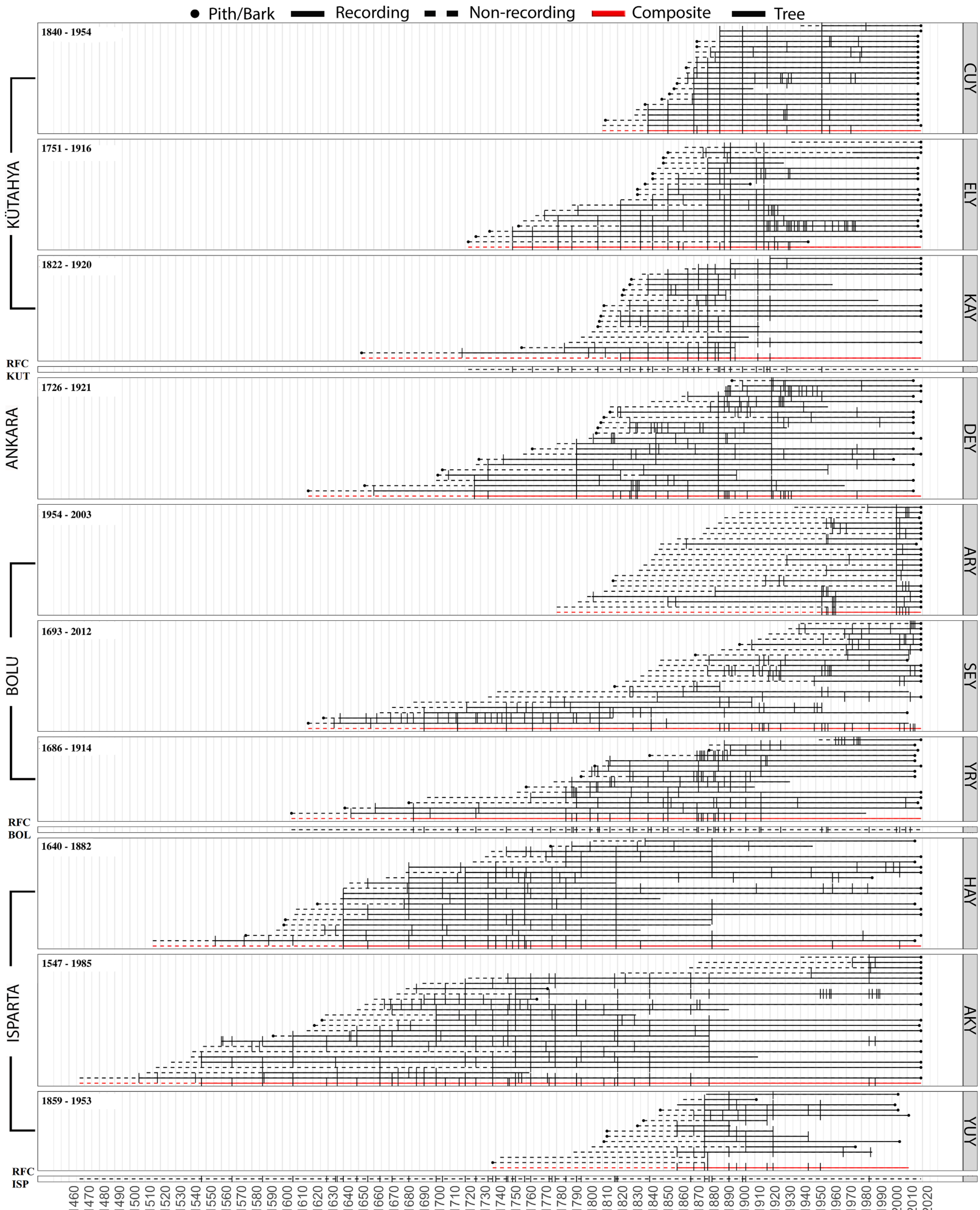

Fig. 2. Fire chart for 10 sites in western Anatolia. Red horizontal bars highlight the site-level composite chronologies and regional fire chronology (RFC) with a minimum of 2-scarred trees. The horizontal lines represent individual samples in each site, while the vertical lines represent the fire years. Data and graph of three sites in Kütahya were taken from Şahan et al. (2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

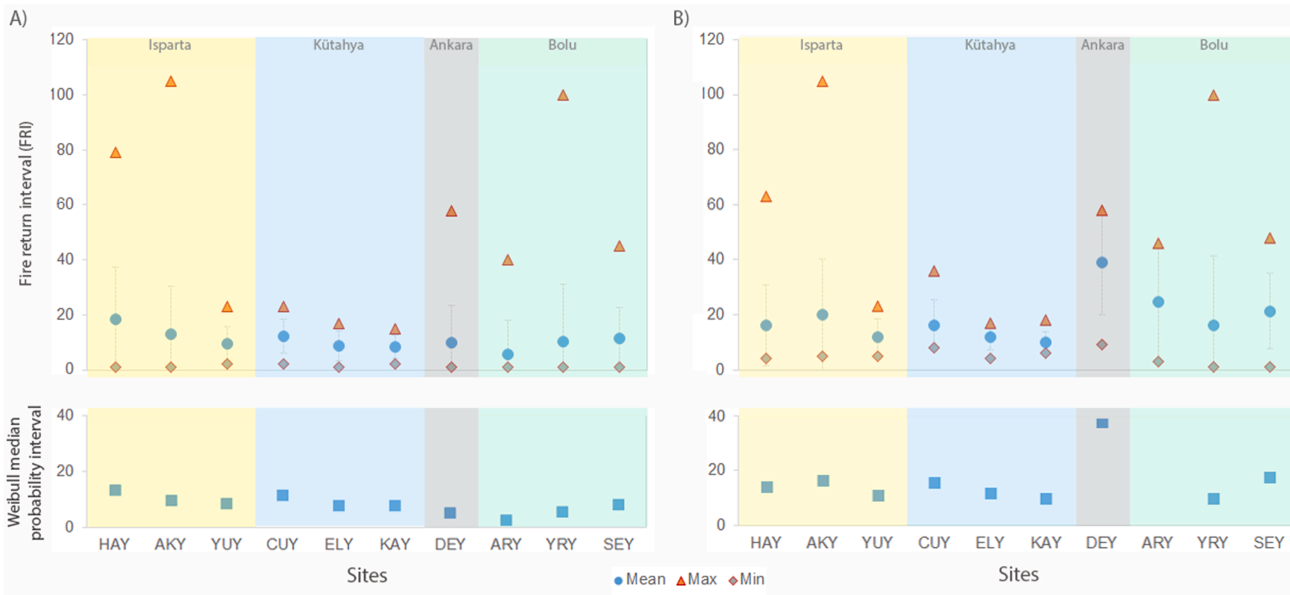

Fig. 3. Measures of central tendency of fire interval distributions (fire interval distributions and WMPI) at A) all sites with regular and B) major fire years. Different climate types are indicated by different colours (yellow: Isparta; Mediterranean climate; blue: Kütahya; the Marmara transition climate; grey: DEY; Ankara, continental climate; green: Bolu; Black Sea to continental climate transition). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

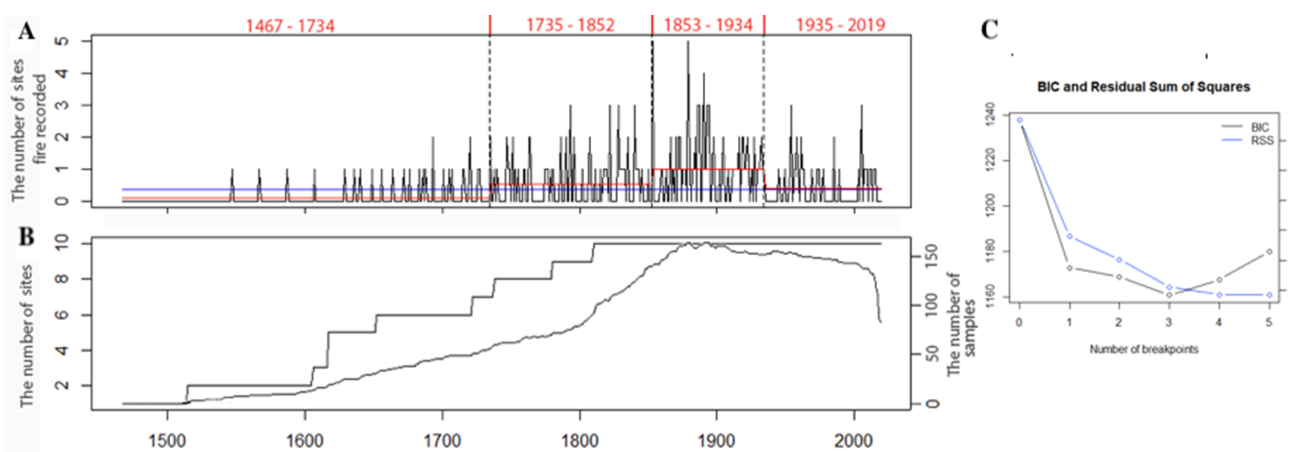

Fig. 4. A) The number of sites recording a minimum of two fire scars in western Anatolia (1467–2019) with the segments described by estimated break dates, B) number of chronologies and sample depth, and C) minimum BIC partition.

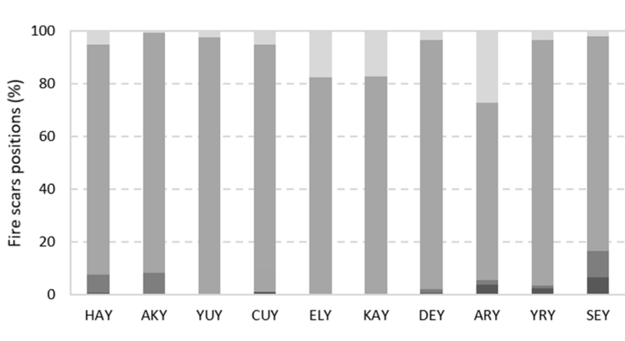

Fig. 5. Percentage of fire scar positions for each site.

major fire events for sites in the drier Mediterranean and Marmara transition climates (Kütahya and Isparta) but found relatively high MFIs for sites in the wetter Black Sea-continental climate transition and the continental climate (Bolu and Ankara). According to the forest fire risk map of Turkey (OGM, 2013), Kütahya and Isparta, where lower MFIs of major fire events were observed, are in the high fire risk areas, whereas Bolu and Ankara with relatively higher MFIs, are classified in the medium fire risk areas (Table 1). Maximum FRIs are the main parameter that distinguishes the sites from each other. The maximum FRIs of major fire years are very large in Bolu and this result confirms that the fire risk in this region is low. Maximum FRI is the highest in Bolu, Isparta (AKY, HAY), Ankara and lower in Kütahya, and YUY (Isparta), which shows Kütahya and YUY experience more frequent fires than other sites.

The sites in Bolu showed different fire patterns compared to the other regions. At the Bolu sites, we observed many fire scars in individual trees that did not correspond in time to fire scars in other trees from the same site (Fig. 2). This limited within-site synchrony could be caused by human-induced fire activities (or combination of both human activities

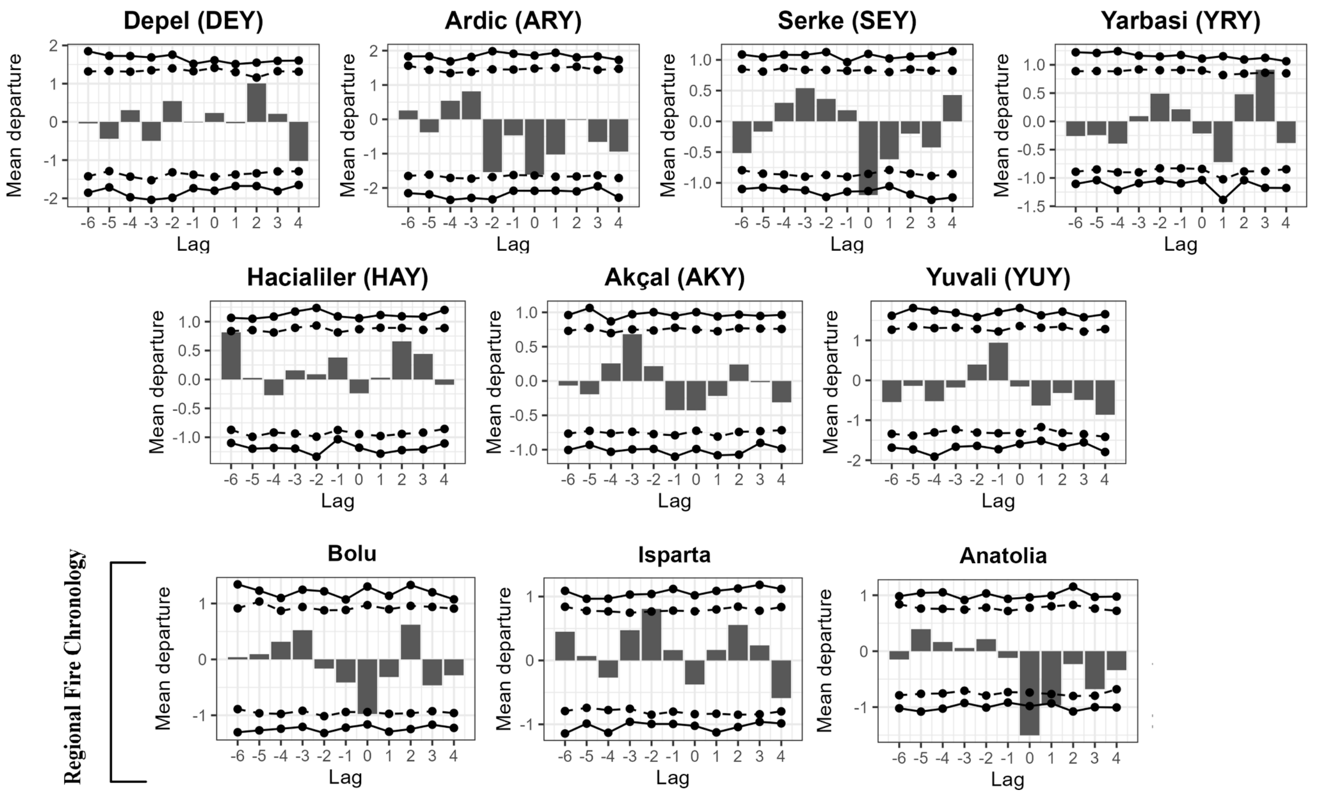

Fig. 6. Site level SEA results for the major fire years with the gridded scPDSI reconstruction, Ankara (DEY), Bolu (ARY, SEY, YRY), and Isparta (HAY, AKY, YUY). Regional level SEA results with major fire years of regional fire chronologies for Bolu, Isparta, and Anatolia (bottom). The dashed line represents 95% and the solid line represents 99% confidence intervals based on a bootstrap simulation with 1000 iterations.

and climate), for instance, due to occupational burning by pastoralists (Fulé et al., 2008), but could also be related to the relatively humid conditions. Bolu receives significant amounts of rainfall throughout the year, even in the driest months for other study sites. Such humid conditions are not conducive to the initiation and combustion process of fire and may prevent the growth of fires by affecting the humidity of the combustible material. This is also reflected in the 'medium fire risk' designation for Bolu in the fire risk map of Turkey (OGM, 2013). Despite the weak intra-site synchrony at Bolu, major fire years in Bolu are strongly associated with drought (significant for SEY and regional fire chronology of Bolu) (Fig. 6), which weakens the hypothesis of human-induced fire activities as the cause of limited within-site synchrony.

In Isparta, however, even at the site where sampling was the most widely spatially distributed (AKY), major fire events burned the majority of individual trees, indicating that the fire extent of individual fires is large. This occurrence of widespread fires in the low-elevation sites of Isparta (between 1230 and 1440 m) is in line with the higher likelihood of major fire events at lower elevations compared to higher elevations (lower elevations ~ 1600 m in Caprio & Swetnam, 1995).

Most fire scars in our Anatolia record occurred in the latewood, which is formed from August to October in the Mediterranean black pine forests (Guada et al., (2016)). This result is in line with other black pine forests of the Balkan Peninsula (Touchan et al., 2012; Christopoulou et al., 2013), but differs from those in the Iberian Peninsula, where the dormant period is the primary fire season (Fulé et al., 2008).

The discrepancy between this primary fire season (August-October) and the seasonality of the available regional scPDSI reconstruction (June-August) may explain the generally weak fire-climate relationships we found at the site level. Nevertheless, we found that major fire years were anomalously dry in two of our western Anatolian regions, Bolu and Kütahya (Fig. 6; Şahan et al., 2021). Major fire years in Isparta, on the other hand, followed two years after wet years. This can be explained by the wet conditions in previous years affecting the growth of the understorey plants in the forest and likely causing the accumulation of biomass (combustible material) (e.g., Swetnam & Brown, 2011; Cerano-Paredes et al., 2021; Stambaugh et al., 2021 and many others). Similar to our results, in the eastern Iberian Peninsula, the burned area has a negative relationship with the summer rainfall in the year of fire and a positive relationship with that of two years before the fire, which can be attributed to the increased fuel loads due to high rainfall in years before the fire events (Pausas, 2004).

Major fire years combined from all ten sites also showed a significantly strong relationship with dry years. Black pine forests in western Anatolia are thus regionally affected by drought and future drought conditions might lead to a change in the fire regime.

At all sites, surface fires occurred frequently until the early 20th century (late 19th century in Isparta) and widespread major fire activity mostly peaked throughout the 18th and 19th centuries (Fig. 2). We found the maximum number of fire years in the 1700s in Isparta and in the 1800s in the other regions (Fig. 2). The number of major fire years has decreased in all sites since the end of the 19th and beginning of the 20th century, but small-scale fires still occurred throughout the 20th century in many sites. This is a globally known trend for surface-fire ecosystems (e.g., Chavardès et al., 2018; Marlon et al., 2008), including Mediterranean black pine forests (Camarero et al., 2018; Şahan et al., 2021), and is mainly related to the start of fire suppression efforts. The suppression of fires both of natural and anthropogenic origin changed fire regimes drastically in Europe, Asia, and North America over the past century (Taylor et al., 2016) and has a significant contribution to the global decrease in the burned area over the same period (Marlon et al., 2008; Andela et al., 2017).

We estimated a regime shift in the year 1934 (Fig. 4) and a serious decrease in fire frequency after this year. This was probably due to the increase in human-induced fire suppression with the enactment of Turkey's first forest protection law in 1937 with the aim to protect forests and organise effective fire suppression efforts. The dominance of

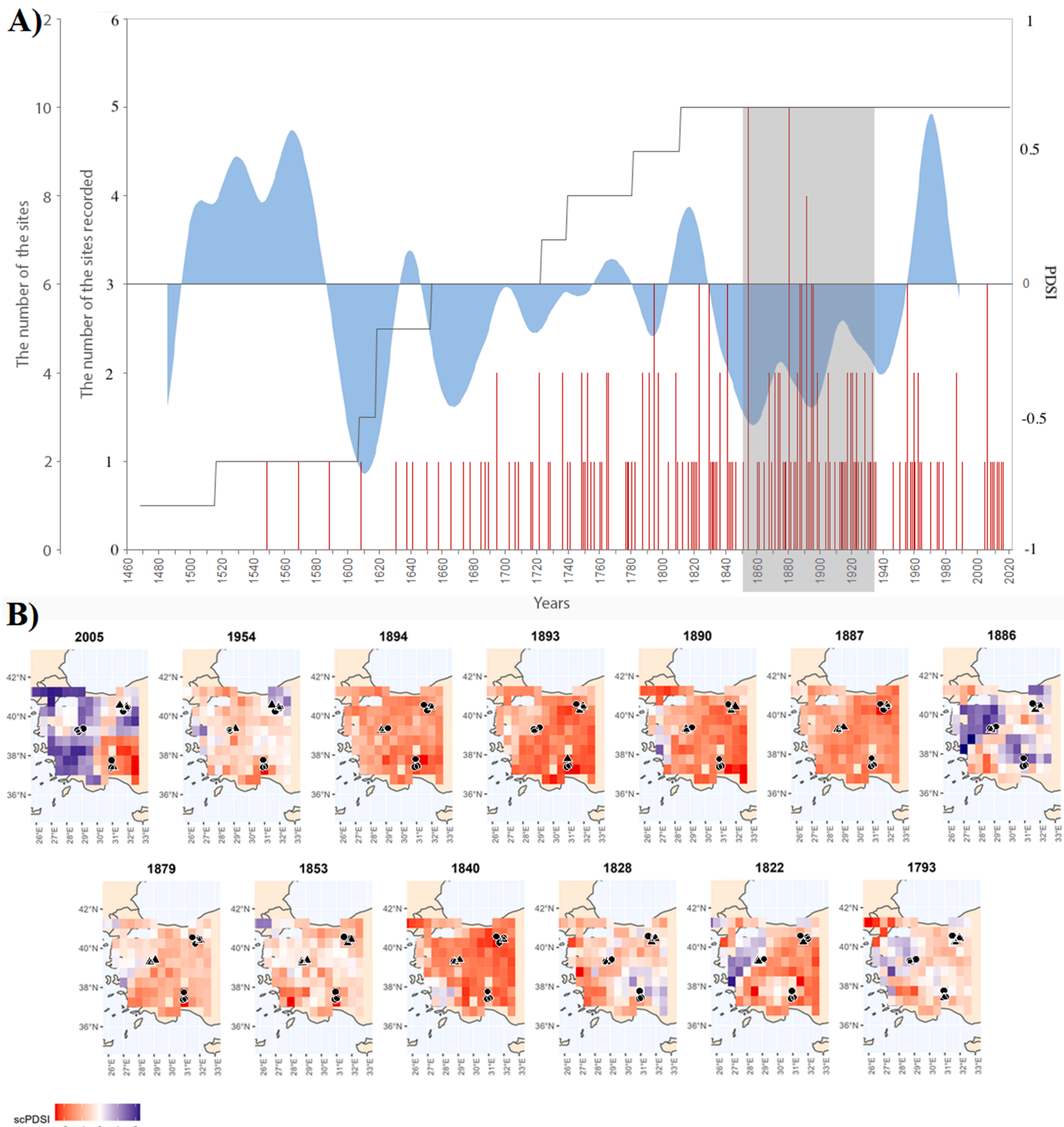

Fig. 7. A) The number of sites recording minimum two fire scars in western Anatolia (1467–2012) with 50-year low-frequency Hanning filter value of the summer scPDSI reconstruction (Cook et al., 2015). The grey box highlights the dry period (1853–1935) when frequent and simultaneous fires were recorded in the Anatolia regional fire chronology. B) Triangles show the sites where fire was recorded in a particular fire year and circles show that there was no fire that year.

individual-tree fire scars in the 20th century in black pine forests of Anatolia (Fig. 2) may be an outcome of the relative ease of reaching and suppressing small fires in a suppression-active environment. However, long-term and detailed historical fire information is lacking for western Anatolia. History of forestry records of the Ottoman Empire in the 19th century regarding fire suppression strategies and land-use changes are incomplete in terms of specific spatiotemporal information, which limits the extent of our interpretation. This decrease in the number of fires supports the idea of Turco et al. (2016) on increased effort in fire management, based on the consideration of both effective fire prevention and exclusion as the main causes for this observed change. The most important development in the forestry of the Ottoman era was the 1870 Forest Regulation, which was issued with the influence of French experts. These experts considered that the forests in Turkey were destroyed at an astonishing rate and that fires were the primary factor in this destruction (Dursun, 2007; Kılıç, 2020). The interventions were first initiated in 1850 when dispatches were sent to the local governments in order to protect and prevent burning forests to open up agricultural areas (e.g., Fowler and Konopik, 2007) (Dursun, 2007). After 1880, a large number of warnings were issued to the local authorities to protect the forests and to ensure the fining of people who burned the forests (Dursun, 2007). The forest order created by this regulation was

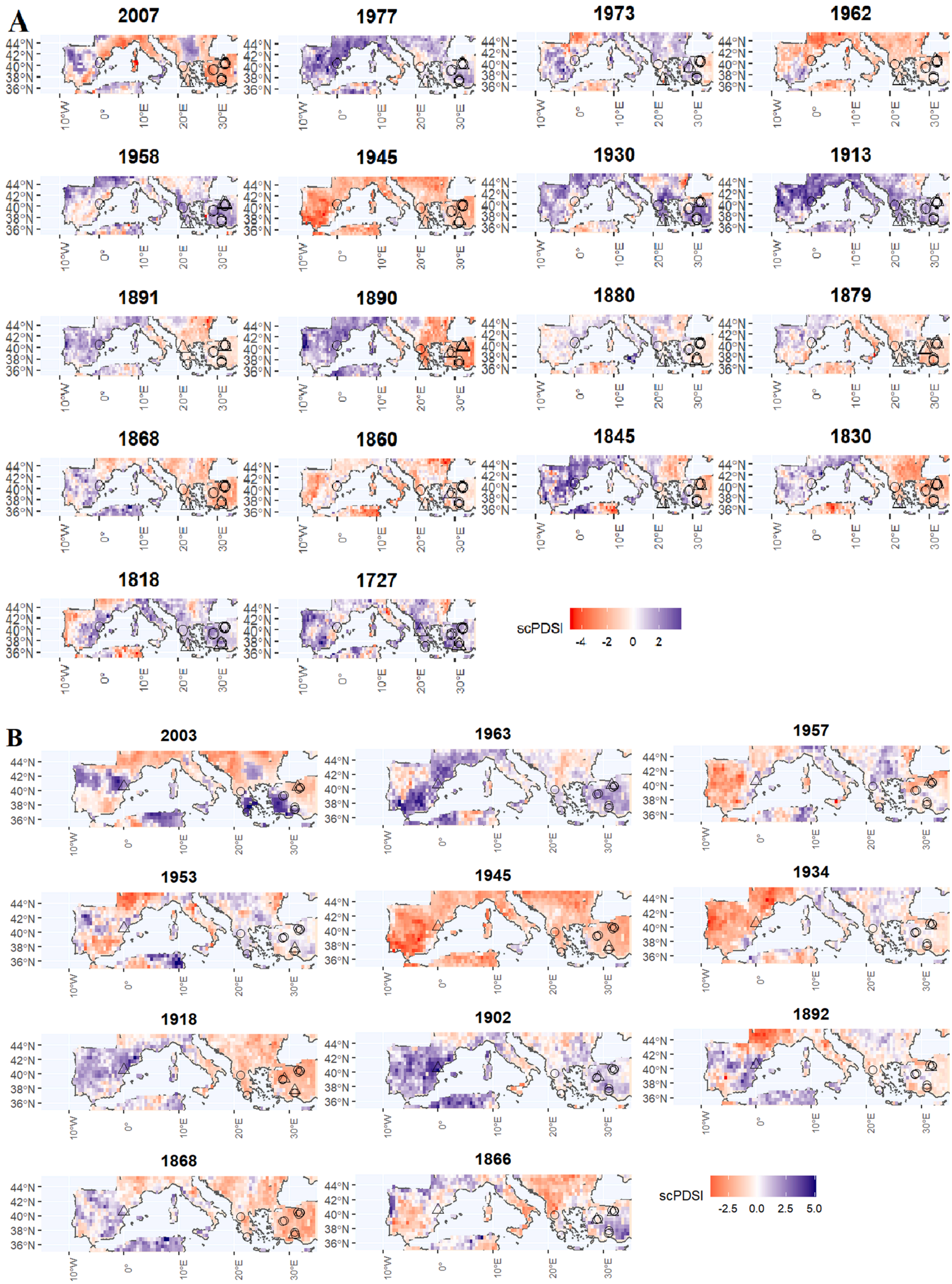

Fig. 8. Maps representing the geographic extent and severity of drought conditions based on a gridded scPDSI reconstruction (Cook et al., 2015) for common fire years between western Anatolia and A) the Balkan Peninsula and B) the Iberian Peninsula. Triangle symbols indicate the sites that burned in a given year and circles show that there was no fire that year. The year 1945 is a common fire year for Balkan, Iberian Peninsula and Anatolia.

abolished by the forest protection law published in 1937.

The period between 1853 and 1934 is prominent with highly frequent and simultaneous fires occurring in multiple sites (Fig. 7). These fires occurred in the longest and most severe drought period of the past 550 years. Our study thus shows that drought leads to higher fire risk not only at the annual level but also at decadal scales (Fig. 7).

We found more common fire years with studies in the Balkan Peninsula, compared to the Iberian Peninsula. In addition to geographical distance, the differing climate conditions of the eastern and western Mediterranean due to frontogenesis or depression activity (higher annual total precipitation in the western Mediterranean) (Allen, 2001) might explain this difference in common fire years (Fig. 8). The year 1879 was the most extensive fire year in the Balkan Peninsula in the 19th century (Christopoulou et al., 2013) and it was also a common widespread fire year in Anatolia. On the other hand, the distinct decrease in fire frequency that was recorded at our sites in Turkey was not observed in the sites in the Balkan Peninsula. The year 1945 is the only common fire year observed in all three Mediterranean regions. Christopoulou et al. (2013) stated that the fire in 1945 was spatially large and might be associated with the increase in the number of battles during the Second World War. However, our results showed that the fires in 1945, observed simultaneously in Anatolia, Balkan and Iberian peninsulas, occurred in the most severe and widespread drought among the spatially visualised common fire years (Fig. 8).

Our results support the projection that increased future severity, length, and frequency of drought will lead to increased area burned in the Mediterranean Basin (IPCC, 2021). The accumulated combustible materials due to long-term fire suppression have increased and may drive more frequent megafires under future climate change in Mediterranean forests (Moreira et al., 2020; Pausas & Keeley, 2021). A similar pattern can be true for the fire regimes of black pine forests, and a regime shift from frequent low-intensity surface fires to infrequent high-intensity crown fires is expected (Christopoulou et al., 2013; Şahan et al., 2021).

In forests with surface fire regimes, an increase in fire frequency can be expected with anthropogenic climate warming and the associated increased occurrence of mega-droughts (Conedera et al., 2006). Such mega-droughts will cause weather conditions more favourable to the spread of wildfire, which may result in novel fire regimes, including a shift from low-intensity surface fires toward high-intensity crown fires (Fyllas and Troumbis, 2009; Christopoulou et al., 2013). Therefore, fire suppression policies appear to disrupt the historical fire-climate relationships and buffer the expected increased fire activity due to climate change (Chavardès et al., 2018; Wahl et al., 2019; Moreira et al., 2020).

In many parts of the world, the fire management strategies of national forest services are based solely on the suppression of fire, which results in the accumulation of fuel in the understory and litter layers of forests during prolonged fire-free periods. This suppression-oriented approach to increasing the amount of fuel makes forests over time more prone to larger and more intense fires driven by extreme fire weather (Moreira et al., 2020). This 'fire paradox', with prolonged fire suppression efforts eventually leading to larger fires, is possibly true for the black pine forests in western Anatolia that have experienced no major fires in the past century. Traditional methods are still highly used for preventing and suppressing fire, however, new approaches should be developed by considering integrated multi-stakeholder, multi-variable, and multi-scale problems (Fernandes et al., 2011). The aim should be to minimise the damage and maximize the benefit for future management approaches. There are various silvicultural practices based on the structure and components of the forest, such as canopy, mid-story, ground-level vegetation, and forest floor treatments to control the spread of fires from the surface into the canopy or reduce the amount of ground-level vegetation (Graham & Jain, 2005). It is one of the most common forest floor fuel treatment methods recommended to be used the prescribed fires to reduce accumulated combustible material (Rego et al., 2010). Immediate actions other than fire suppression, such as fuel treatments, thinning, and/or prescribed fires are needed for the management of black pine forests to increase their resistance and resilience to novel fire regimes under a changing climate.

5. Conclusion

We studied the 553-year-long fire history of black pine forests in western Anatolia and the drivers of those fires in different climatic regions. This fire history information offers important suggestions for future management plans. We found that drought is the main driving factor of fire in some sites and prior-year wet conditions in other sites. Our fire history chronologies further document a decrease in the number of fires in the late 19th and 20th century due to widespread fire suppression activities. These continued fire suppression activities may cause fuel accumulation and pose a risk for more intense fires and thus a paradox for forests in the future. This increased fire risk in a warmer, drier future is further supported by the fact that the most frequent and simultaneous fires occurred in the longest dry period in the past. Taking the increased drought frequency under projected future climate change into account, which will prolong the fire season, climate conditions highly suitable for more frequent fires are projected. Combined with the accumulation of combustible material in the understory of the forest, the fire regime change towards crown fires may occur in black pine forests in the near future.

Drought due to anthropogenic climate change will affect future fire regime parameters. The forest fires in the year 2021 (more than 200 fires in July and August 2021) taught an unforgettable lesson in Turkey about how wildfires can be destructive and that it can be difficult to prevent the negative impacts with the increasing effect of the ongoing climate crisis. Thousands of people were evacuated from hundreds of villages and towns as the fires spread to the settlements. Therefore, additional studies are needed to appropriate wildfire management activities and to guide and support ecosystem management programs. More detailed analysis is necessary to comprehensively understand fire regime parameters separately for the behaviour of fire and the change in forest structure after the fire (i.e., post-fire regeneration). For instance, weekly observations of cambial activity in burnt areas can be used to determine fire seasonality in different ecosystems (e.g., Rother et al., 2018). Especially the catastrophic fires of 2021 showed us that we need to work towards managing fire regimes, rather than fires (e.g., Cochrane & Bowman, 2021; Pausas & Keeley, 2021). This will involve pragmatic approaches for both fuel and silvicultural management strategies on ground level vegetation, and forest floor treatments to control the spread of fires based on different species' characteristics and future climatic conditions. Each species behaves differently to the fires under different climatic conditions. Therefore, the role of fire might be also understood by supporting long-term dynamics of different forest ecosystems with forest succession and disturbance studies. The conservation and management plans and pragmatic approaches should be considered not only for the fires but also for the fire regime parameters.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Evrim A. Sahan reports financial support was provided by Scientific and Technological Research Council of Turkey. Nesibe Kose reports financial support was provided by Scientific and Technological Research Council of Turkey. Evrim A. Sahan reports financial support was provided by Council of Higher Education of the Republic of Turkey.

Acknowledgements

We would like to thank the staff of the Regional Directorate of Forestry, Kütahya, Isparta, and Bolu for helping us during the fieldwork. We express our gratitude to Kenan Akduman, Sibel Korkmaz, Fahri

Kaya, Özgür Müftüoğlu, and Mehmet Bozkurt for their valuable contributions and efforts for this project. Evrim A. Şahan acknowledges the financial support of the 100/2000 doctoral scholarship by the Council of Higher Education of Turkey (CoHE). This research was funded by the Scientific and Technological Research Council of Turkey (TÜBİTAK) (Project number: 118O306). We are grateful for two anonymous reviewers who helped us to improve this manuscript.

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