

Increasing extremes of heat and drought associated with recent severe wildfires in southern Greece

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Abstract Mountains of the northern Mediterranean basin face two major threats under global change. Aridity and available fuel are both expected to increase because of climatic and land-use changes, increasing fire danger. There may already be signs of such effects in the case of the *Pinus nigra* and *Abies cephalonica* forests on Mt. Taygetos (southern Greece). We reconstructed climate (mid- to late-fire-season drought) using tree-rings for the last 150 years and compared it with the mountain's fire history reconstructed from *P. nigra* fire scars. Seven, out of the ten, large fires Mt. Taygetos experienced were associated with below-normal precipitation (P) or above-normal maximum temperature (T_{\max}). The largest fires occurred in late summer of 1879, 1944, 1998, and 2007. However, only

the recent fires (1998 and 2007) had both low P and high T_{\max} , also confirmed from long-term meteorological data. The synergy between climate and fuel availability may explain the very high intensity of 1998 and 2007 fires that burned mostly as stand-replacing crown fires. The other two large fire events (1879 and 1944) most likely occurred under reduced availability in burning fuel and were related to above-normal T_{\max} . Our findings are among the first based on long-term and site-specific empirical data to support the prediction that Mediterranean mountainous areas will face a very large threat from wildfires in the twenty-first century, if socioeconomic changes leading to land abandonment and thus burning fuel accumulation are combined with the drought intensification projected for the region under global warming.

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Introduction

As global warming is predicted to intensify within the twenty-first century and aridity predicted to increase for the northern Mediterranean basin (IPCC 2007), the region is projected to suffer even more from forest fires (Schröter et al. 2005; Moriondo et al. 2006; Giannakopoulos et al. 2009), as is the case in other regions in the world with similar climate (Westerling and Bryant 2008). In particular, an additional month of fire risk in summer is expected over a great part of the basin by mid-twenty-first century (2 °C of global warming; Giannakopoulos et al. 2009), whereas the area burned by wildfire can be expected to increase by a factor of 3–5 at the end of the twenty-first century compared with present (Dury et al. 2011). In addition to forest fires, the impacts from water shortages, northward shifts in the distribution of typical tree species, and losses of agricultural potential make the Mediterranean area the most vulnerable to global change among all European regions (Schröter et al. 2005).

During the fire season of summer 2007, Greece experienced the worst natural hazard in its modern history, the worst year in the country's fire records, and one of the worst in the Mediterranean. The fire disaster was consistent with fire model projections for such regions under global warming scenarios; 280,000 ha (ca. 2 % of Greek land surface) of forests, bush, and agricultural areas were burned, claiming more than 60 human lives, leaving thousands of people homeless, and damaging the local economy (Founda et al. 2008). Peloponnesus, in southern Greece, was the region most affected with 189,952 ha burnt area (ca. 1.5 % of Greek land surface; 117,188 ha of forests and forested areas burnt; Koutsias et al. 2012).

The causes behind this disaster are a subject of intense investigation. Climate is one factor that may have played a key role (Founda and Giannakopoulos 2009; Koutsias et al. 2013; Sarris and Koutsias 2014), while a synergy of land-use changes and climate is also likely (Koutsias et al. 2012). Changes in these factors with similar dramatic effects have been recorded both in the Mediterranean basin (Pinõl et al. 1998; Pausas 2004; Moreira et al. 2011; Pausas and Fernández-Munõz 2012) and in other places (Westerling et al. 2006; Flannigan et al. 2009).

However, for many areas of the Mediterranean local records of climate, land use and fire statistics are limited to the last 40–50 years. For example, for fire-affected areas of Peloponnesus, the nearest long-term climate data

(covering the entire twentieth century) are available from a ca. 150 km distance, at the station of the National Observatory of Athens (Koutsias et al. 2013). This is the only approach when no other data are available. Nevertheless, in investigating long-term climate–fire interactions at a regional or even local scale, providing both long-term and on-site evidence provides better data for explaining fire behavior.

Reconstructions based on tree-rings (dendrochronology) are a valuable tool in investigating past fire occurrence and spread (Baisan and Swetnam 1990; Brown et al. 1999; Fulé et al. 2008; Farris et al. 2010) as well as past climate (Briffa et al. 1992; Touchan et al. 1999; Briffa et al. 2001; Esper et al. 2007; Nicault et al. 2008). In the absence of actual measurements, using these proxies in examining causality can be vital for identifying co-occurrence of extreme climate and fire events.

Christopoulou et al. (2013) provided recently the only available reconstruction at landscape scale of fire history from Peloponnesus based on Mt. Taygetos. Using fire-scarred *Pinus nigra* trees the reconstruction spans back to the 1850s. These records offer a valuable tool for looking into the long-term fire history of this particular Mediterranean region.

According to the local Forest Service, the burnt area on Mt. Taygetos was ca. 8,800 ha in 2007 (ca. 5 % of all burnt area and ca. 8 % of all forested land burnt in Peloponnesus in 2007). The fires of 2007 and 1998 (in 1998 ca. 3,600 ha was burnt on the mountain; the 3rd most severe year in Greek fire history; Koutsias et al. 2013), appear as two of the most extensive fire events for Mt. Taygetos since 1850s (Christopoulou et al. 2013).

The aim of this paper is to reconstruct, by using tree-rings from old trees on Mt. Taygetos, the on-site climatic conditions during which the most important fires occurred on the mountain within the last one and a half century. The historical relationship between climate conditions and fire events provides a useful context to understand whether or not recent large fire events have been climatically extreme at a scale of centuries. We hypothesize that if future projections for increased fire damages in this region under global warming are valid, there should also be evidence for such associations between drought and fire within the last 150 years.

Methods

Tree-ring sampling

For dendroclimatological reconstruction of summer drought conditions on Mt. Taygetos during the last two centuries, we selected two tree species *Abies cephalonica* Loudon

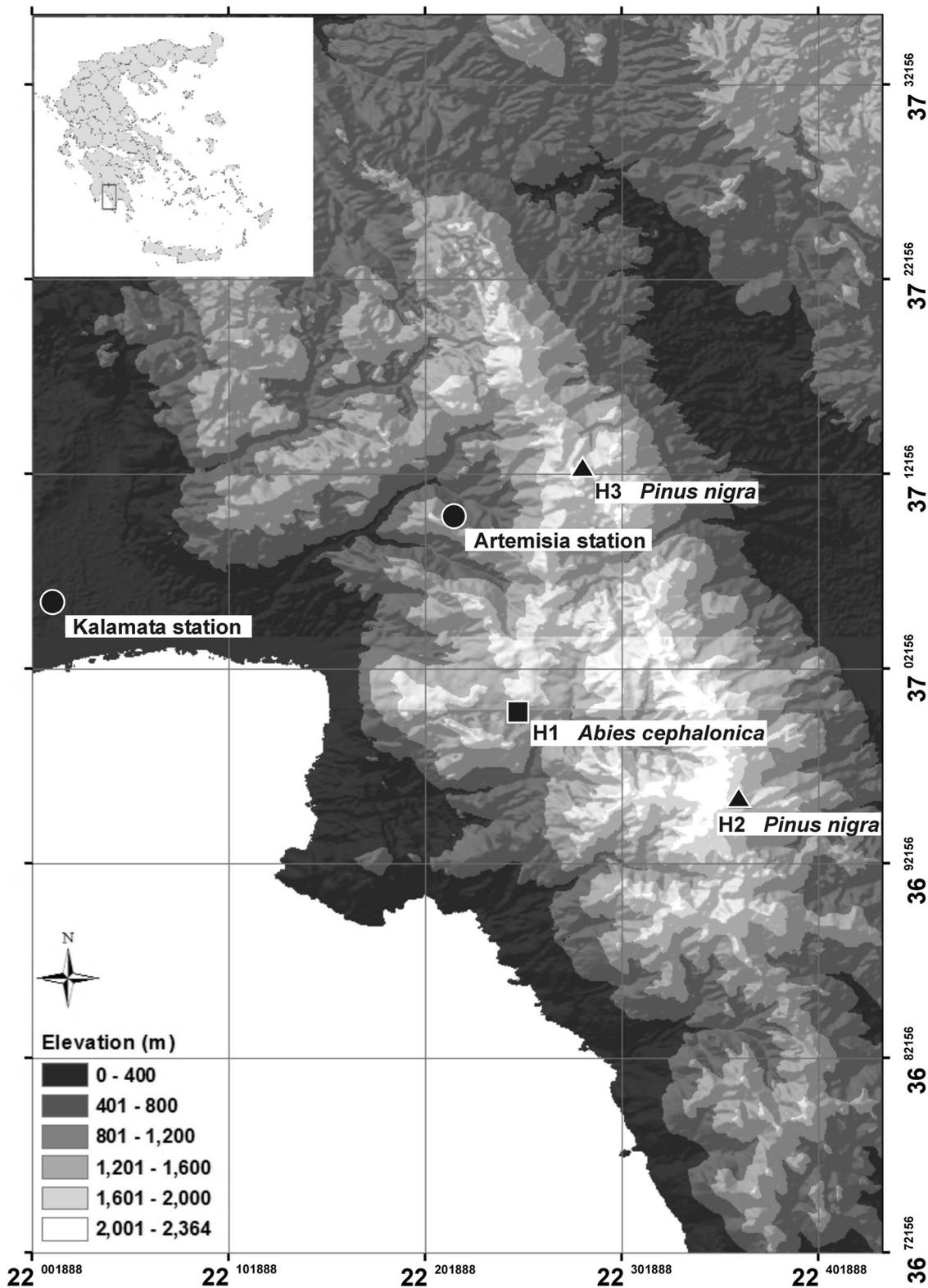


Fig. 1 Map of Mt. Taygetos with locations of sampling areas and meteorological stations

(Greek fir) and *P. nigra* Arnold (Black pine); these are the longest-living tree species on the mountain (Brandes 2007). Both species are suitable for dendroclimatological studies

(Schweingruber 1996), producing clear tree-rings. Specific forest habitats were selected to find trees whose tree-ring width would be determined by summer climate

(precipitation and/or temperature). Actually, secondary growth at the lower altitudinal distribution range of a tree species (xeric margins) is more likely to be determined by precipitation, while at the opposite side of its range at higher altitude (thermal limits), temperature is likely to be the main limiting factor driving growth (Sarris et al. 2011). For *A. cephalonica*, the selected habitat (H1) was at ca. 1,000–1,050 m a.s.l., lat 37°00'N, long 22°15'E (close to the species xeric limits), whereas for *P. nigra*, two similar habitats were selected (H2 and H3) at higher elevation (ca. 1,600–1,750 m, close to the species highest distribution range on the mountain; H2, lat 36°57'N, long 22°22'E; H3, lat 37°07'N, long 22°17'E; Fig. 1). The fir habitat was on a south to southwest facing slope, while those for pine faced north to northeast. Slopes varied from 10° to 30° mostly, while the bedrock was limestone, exposed at times because of erosion (soils were no deeper than ca. 30 cm). All sites above were free from fire occurrence (did not possess trees with evident fire scars, nor had any fires in their recent history) to avoid disturbances of fire on tree-rings and their recorded climatic signal.

Using a standard 5-mm-diameter increment borer, 20 *A. cephalonica* trees were cored at ca. 1.2 m height from the base of the tree, while for *P. nigra*, 24 and 15 trees were cored per sampling area (H2 and H3) during 2010–2012. At least two cores per tree were taken from opposite sides of the stem (the sides that were 90° to the ground level) that were compared to check for compression wood (the result of tree leaning at some part of its life causing disturbance in the relationship between tree growth and climate). Our sampling strategy was to sample the most dominant trees based on trunk circumference (CR) and height (HT) and then expand to trees of all available trunk sizes around them (for pines, the maximum CR and HT were ca. 4.5 and 16–18 m, respectively; the minimum CR and HT were ca. 0.4 m and 7–8 m, respectively; similarly for firs but with maximum CR of ca. 2.5 m) within the habitat. Selected trees were not suppressed, e.g., growing under shade and did not show signs of damage; trunks were not bent, and we avoided sampling trees next to stumps or dead trees. The understory vegetation varied from site to site, mostly consisting of *Juniperus oxycedrus* and *Pteridium aquilinum*. In the lower elevation, dry site shrubs such as *Quercus coccifera*, *Erica manipuliflora*, and *Cistus creticus* were also present, while *P. aquilinum* was absent.

Dendrochronological analysis

After drying, sampled tree-ring cores were mounted on channeled wood and polished with sandpaper for precise dating and tree-ring width measurement. Measurement of annual increments was conducted to the nearest 0.01 mm, from bark to pith by a computer-linked measuring table

(LINTAB 5) and a software package (TSAP-Win software, version 4.63; Rinn 2005). In cases of the core not reaching the pith of the stem, the number of missing rings to the pith was calculated using concentric circles, representing growth patterns similar to those of the available early years of growth. After dating, the trees sampled were found to be from 34 to 185 years old for firs and from 56 to 362 years old for pines (in 2012). Since growth data from at least three fir trees were available since 1856, we used this year as the beginning year for reconstructing climate to be compared with fire events on the mountain (see below). The first 14 (for firs) and 19 (for pines) years of growth from the pith of the stem were not used, to avoid possible disturbances during the trees' establishment phase.

Single tree-ring curves were averaged into chronologies for each sampled habitat and used as reference chronologies for cross-dating the samples (more information on cross-dating is provided in Online Resource 1). Out of the 19 best cross-dating fir trees, six trees were from 34 to 80 years old (i.e., all 19 trees available since 1978), whereas eight trees were from 81 to 160 (i.e., 13 trees available since 1931) and five from 161 to 185 years old (i.e., 5 trees available since 1851). Out of the 24 selected pines, three were from 56 to 80 years old (i.e., all 24 trees available since 1956), five were from 81 to 160 (i.e., 21 trees available since 1931), seven were from 161 to 240 (i.e., 16 trees available since 1851), and nine were from 241 to 362 years of age (i.e., 9 trees available since 1771).

Moreover, tree-ring formation may reflect local habitat peculiarities. Some trees may be growing on more shallow soil and, thus, continuously produce narrower rings than other trees of the same habitat growing on somewhat deeper soil. To remove such microhabitat-related “noise,” we standardized each tree-ring series for habitat by dividing each annual ring width by the mean width of all rings from the particular series (mean for all years of tree growth). This transformed the original data into indices, which retained the year-to-year variation but permitted unbiased averaging across habitats.

In a second step, we standardized for age trends in tree-ring width. Effects of aging were removed by analyzing similar life (age) stages of trees following the age band decomposition (ABD) methodology (Briffa et al. 2001; Sarris et al. 2007, 2011). For the advantages of this methodology in retaining intact the signals of low-frequency climatic variability captured in tree-rings, compared to conventional detrending (curve-fitting), see Sarris et al. (2011). Ten-year-long age bands were used from 20–29 years through 160–169 years of cambial growth for firs and 20–29 years through 270–279 years for pines. In producing the age-detrended mean chronology per species, we averaged these age bands year by year so as to be able to reconstruct climate corresponding to particular years of fire.

The two resulting age-detrended tree-ring chronologies were checked for autocorrelation using the program ARSTAN (Cook and Krusic 2007). Current year's growth was found to be significantly correlated with past years' growth at a lag of up to 3 or 4 years. This autocorrelation was removed by ARSTAN. As a second step, the "stabilize variance" option in ARSTAN was used to correct for the gradual increase in the number of trees represented in the chronology from the 1850s up to the more recent years (see above). Two residual chronologies with stabilized variance were produced per tree species. The first by using the smoothing spline function in ARSTAN with a 33 % and the second with a 67 % cutoff. The original chronologies without variance stabilization were also retained and used to compare results with the "stabilized" chronologies under correlations with climate. We would expect that the chronologies with stabilized variance would produce improved correlations with climate compared to their non-stabilized counterparts.

Climatic data

Monthly precipitation (P) and monthly mean maximum temperature (T_{\max}) from the nearest station on the mountain (Artemisia meteorological station; lat 37°06'N, long 22°13'E, elevation 760 m; ca. 6 km to 20 km away from all sampling sites; Fig. 1) were used to determine the climate signal captured in tree-rings. However, this station provided complete monthly data for both climatic parameters from 1961 till 1987 and scattered readings thereafter (1998–2000 and 2002), which were corrected using the closest station with complete data during the recent period (Kalamata station; data for 1971–2008, lat 37°03'N, long 22°00'E, elevation 6 m; Fig. 1; more information is available in Online Resource 1).

As predictors for tree growth, we used 41 monthly and multiple-month integration periods (starting with the 12 calendar months separately and then moving to their 2–12-month integrations) for P and T_{\max} . This covered all possible integration periods within the spring to autumn growing season plus the influence of climate during the previous months (Table S1). As a further step for testing the influence of previous year's climate on current year's growth, these parameters were also shifted 1 year back in time, e.g., to test effects of 1963–2007 climate on 1964–2008 tree growth. The process was repeated up to a lag of 3 years (but statistics did not improve).

Dendroclimatological analysis

In identifying which climatic parameter can be reconstructed based on the two tree growth chronologies, we first tested their correlations with climate for 1964–2008 (the

period defined by the availability of climate data at lag 0). We used the different versions of each tree growth chronology (with and without stabilizing variance; see above) and selected the one that produced the best correlation. The climatic parameter found to best reproduce the variability of each tree growth chronology was normalized (z scores) by calculating the difference of this climatic parameter's value for a particular year from the 1964–2008 mean and then dividing this difference by the standard deviation of data for 1964–2008 (Nicholson 1983; Piervitali and Colacino 2003; Sarris et al. 2007).

Verification of climatic reconstructions with independent data establishes the reliability of the estimated climate using intervals outside the calibration period and can be approached in three ways (Fritts et al. 1979): (1) statistical verification with independent meteorological observations, (2) verification by proxy data, and (3) verification by historical observations and accounts. Following the first approach in reconstructing climate, we used the split sample verification method (Snee 1977; Cook et al. 1994; Esper et al. 2007) by calibrating the model on one half of the 1964–2008 data and verifying on the other half and vice versa.

As statistical tools for the verification process, we used the square of the Pearson's product-moment correlation coefficient (r^2 ; coefficient of determination), the reduction of error (RE; Fritts et al. 1979; Cook et al. 1994), and the even more demanding coefficient of efficiency (CE; Cook et al. 1994). Positive RE or CE values indicate a more reliable and accurate climatic reconstruction. Finally, we applied a running correlation analysis between the reconstructed climatic parameters and the actual meteorological data using 25-year "windows" to verify the stability of the reconstruction over the 1964–2008 data period. Such an analysis could spot the years where the model may not reproduce well the actual meteorological data (which may result to $CE < 0$). The final reconstruction of climatic parameters back to 1856 was performed using a linear regression model that significantly predicted ($P < 0.05$) climate during the calibration period (dependent data set) but also produced a $CE > 0$ during the verification period (independent data set).

To assess the long-term fire history on Mt. Taygetos, the data provided by the reconstruction of Christopoulou et al. (2013) were used. By analyzing fire-scarred *P. nigra* stems in an area of 3,370 ha on the mountain, 34 fires were detected during a 165-year period (1845–2010). By filtering out the small-scale fires, 11 major fire events were found (for more information related to the fire history reconstruction, see Christopoulou et al. 2013). Since 1856, when our climatic reconstruction begins, 10 such fire events were available. These 10 largest in spatial extent fire events on Mt. Taygetos were plotted together with the

Z scores of reconstructed climatic parameters. Note, however, that only four fire events (1879, 1944, 1998, and 2007) were large enough to affect more than 30 % of the studied area in Christopoulou et al. (2013).

A threshold of $Z > 0.25$ or $Z < -0.25$ was selected to represent the conditions of fires occurring during climate higher or lower than the mean, while $Z > 0.9$ or $Z < -0.9$ to represent the conditions of fires corresponding to climatic parameters much higher or much lower than the mean (Nicholson 1983; Piervitali and Colacino 2003; Sarris et al. 2007). In practice, this means that with $Z > 0.25$ or $Z < -0.25$ ca., 20 % of observations were excluded from the analysis as being close to the mean, while with $Z > 0.9$ or $Z < -0.9$, this exclusion increases to a little above 60 %.

Finally, we assessed whether the integration periods of climate that were reconstructed by the use of tree-rings can indeed be related to the fire extent (burnt area) not only for our area of focus but also for the wider region, i.e., the province of Messinia. Burnt area data for this province include most of the burnt area on Mt. Taygetos. Such data were provided by the Hellenic Forest Service and the Fire Brigade for 1985–2008. Thus, only field measurement data (not reconstructions) were used for this analysis.

Long-term climatic data

To test their accuracy, our climatic reconstructions were compared to the longest climatic series available in southern Greece. First, data from the National Observatory of Athens station (ATobs; coordinates lat 37°58'N, long 23°43'E, elevation 107 m) were used, located ca. 160 km northeast of Artemisia station (both P and T_{\max} available since 1899). Second, we used gridded climatic data for southern Greece (SGr; lat 35–40°N, long 20–25°E grid cell), i.e., the grid cell that includes the location of Mt. Taygetos (and ATobs). Monthly gridded precipitation (version 2) and mean monthly temperature (T mean; version 3; gridded T_{\max} not provided) were accessed from the GHCN-NCDC Web site (Peterson and Vose 1997; Lawrimore et al. 2011; both P and T available since 1900).

We assessed whether the climatic variability represented in these long climatic series could be significantly correlated to Artemisia station data for 1964–2008 (ARmet) and to its reconstructed climate back to 1899 (ARrec). Then, we investigated for any climatic similarities between reconstructed climate for Artemisia and these long climatic series during fire years on Mt. Taygetos.

Correlation analysis

The program SPSS for Windows was used for correlation analysis. As a basis for tests, our data were checked for

normal distribution with the Kolmogorov–Smirnov test and for homogenous variance throughout the series with the Levene's test. The Pearson's correlation coefficient (r) was selected as the standard coefficient for correlating normally distributed data except in correlations using fire data (burnt area). As the latter were not normally distributed, the Spearman's rank correlation coefficient (r_{sp}) was applied. Correlation coefficients with at least $P < 0.05$ were considered statistically significant (although in a few cases, results where $P < 0.1$ are given to mark correlations that tend to produce significant results).

Results

Precipitation reconstruction

The fir growth chronology (lower-elevation trees) produced the best correlations with August–October, August–September, February, and August precipitation (P) of the previous year during 1964–2008 ($r = 0.34$, $P = 0.02$, or $r = 0.33$, $P = 0.03$, $n = 45$; Table S2). In order for our fir chronology to correspond to current year's fire season and not to that of the previous year, it was shifted back in time by 1 year. This step shifted the ring width value of 2009 to the position of 2008 and that of 1964 to the position of the year 1963. As a result, the correlation with August–September P corresponding to 1964–2008 improved to a greater extent compared with the other variables ($r = 0.38$, $P = 0.01$, vs. $r = 0.33$, $P = 0.03$ for August–October and February and $r = 0.36$, $P = 0.02$ for August; $n = 45$).

Stabilizing variance for the fir growth chronology (using smoothing splines with a cutoff of 67 or 33 %) did not further improve the correlations with climatic variables (e.g., $r = 0.34$ and $r = 0.31$ for correlations with August–September P), so in this case, such a transformation of the ring width chronology was not used to reconstruct climate. In reconstructing normalized August–September P back to 1856 (Fig. 2), we applied a linear regression based on tree-ring width (X_a) and normalized climate data (Y_a) for 1964–1983 (model eq. $Y_a = 1.7061X_a - 1.7732$; $r^2 = 0.20$, $P < 0.05$; additional data on the reconstruction are given in Online Resource 1).

Temperature reconstruction

The pine growth chronology (higher-elevation trees) produced the best correlations with July–September T_{\max} of the previous year ($r = -0.51$, $P = 0.0003$, $n = 45$; Table S2). In order for our pine chronology to correspond to current year's fire season and not to that of the previous year, it was shifted back in time by 1 year and also each value was reversed ($1/X_b$; X_b = each year's tree-ring width

Fig. 2 Normalized late-fire-season precipitation from Artemisia meteorological station (1964–2008) and its reconstruction (1856–1963). $Z < -0.25$ and < -0.9 highlight rainfall lower or much lower than the mean, while $Z > 0.25$ and > 0.9 the opposite (horizontal broken lines). The 10 years with the largest extent fires on Mt. Taygetos are given (white circles)

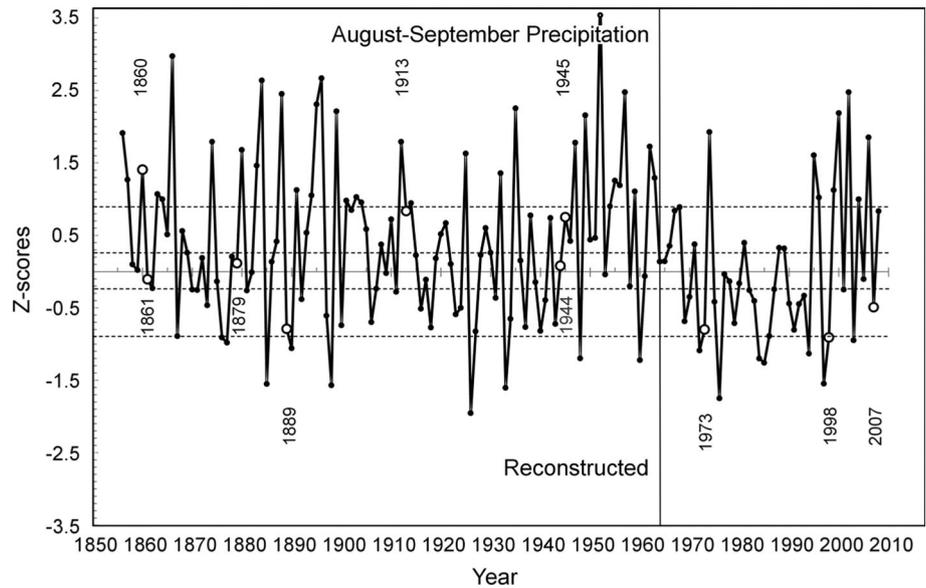
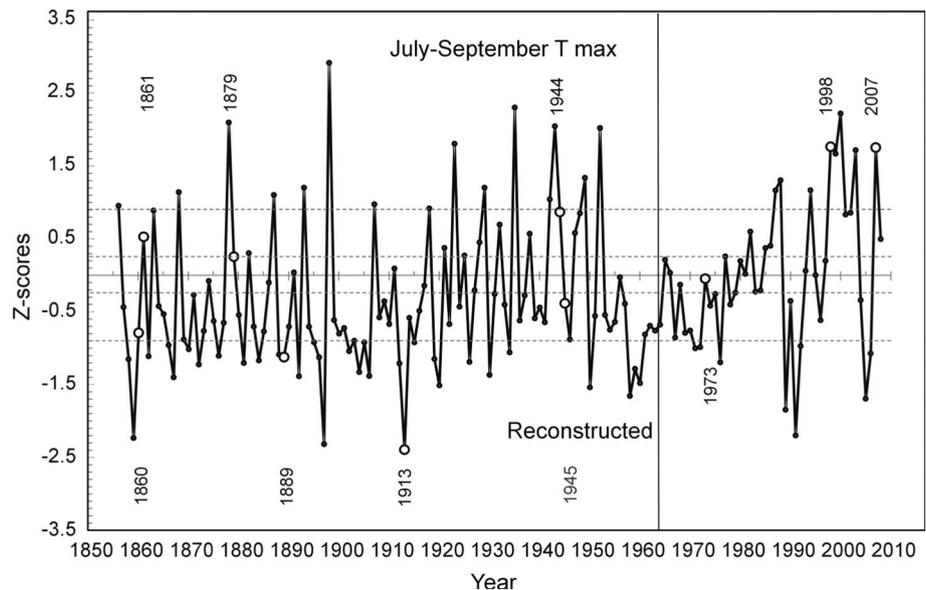


Fig. 3 Normalized maximum temperature for the mid- to late fire season from Artemisia meteorological station (1964–2008) and its reconstruction (1856–1963). $Z < -0.25$ and < -0.9 highlight T_{max} lower or much lower than the mean, while $Z > 0.25$ and > 0.9 the opposite (horizontal broken lines). The 10 years with the largest extent fires on Mt. Taygetos are given (white circles)



of the pine chronology) so that increasing values correspond to increasing T_{max} (as the original effect on T_{max} on tree growth was negative). This step again shifted the ring width value of 2009 to the position of 2008 and that of 1964 to the position of the year 1963. As a result, the correlation between the July–September T_{max} corresponding to 1964–2008 and the pine growth chronology slightly improved ($r = 0.52$, $P = 0.0002$, $n = 45$).

Stabilizing variance for the pine growth chronology (using smoothing splines with a cutoff of 67 or 33 %) further improved the correlations with climatic variables (i.e., $r = 0.58$, $P < 0.0001$ for a spline cutoff of 67 %; $r = 0.55$, $P < 0.0001$ for a spline cutoff of 33 %). Thus, the version of the pine growth chronology with its variance

stabilized using a smoothing spline with a cutoff of 67 % was used thereafter. In reconstructing normalized July–September T_{max} back to 1856 (Fig. 3), we applied a linear regression based on tree-ring width (X_b) and normalized climate data (Y_b) for 1964–1987 ($Y_b = 1.8496X_b - 2,125$; $r^2 = 0.25$, $P < 0.01$; additional data on the reconstruction are given in Online Resource 1).

Comparison between climate and fires

As a first step, we assessed whether the climatic parameters reconstructed can indeed be related to the fire extent (burnt area) not only for our area of focus but also for the wider region. Testing over the wider region, August–September

P produced a significant correlation ($r_{sp} = -0.47$, $P = 0.03$) with fire records of burnt area occurring in the province of Messinia (burnt area data for this province include most of the burnt area on Mt. Taygetos). Maximum temperature (T_{max}) for July–September also tended to produce a significant correlation with burnt area ($r_{sp} = 0.41$, $P = 0.06$). Thus, intense summer drought as a result of decreased late summer–early autumn P combined with increased midsummer–early autumn T_{max} can be related to large fires for the wider area around and including Mt. Taygetos (Fig. S1).

Out of the 10 largest reconstructed fire events on Mt. Taygetos since the 1850s, the fires of 1889, 1973, 1998, and 2007 (4/10) can be related to low rainfall within the fire season. The fire of 2007 coincides with lower than mean (i.e., $Z < -0.25$) August–September P , while those of 1889, 1973, and 2007 with much lower than mean (i.e., $Z < -0.9$) late-summer P (Fig. 2). The fires of 1913 and 1945 seem to have occurred during higher than mean late-summer P ($Z > 0.25$), while the event of 1860 appears to coincide with $Z > 0.9$, suggesting much higher than mean late summer–early autumn P .

Regarding July–September T_{max} , the fires of 1861, 1879, 1944, 1998, and 2007 (5/10) can be related to increased warming within the fire season. Three events, namely 1861, 1879, and 1944, corresponded with higher than mean warming (i.e., $Z > 0.25$; Fig. 3), while the fires of 1998 and 2007, with much higher than mean midsummer to early autumn T_{max} ($Z > 0.9$). On the other hand, the events of 1860 and 1945 seem to have occurred under lower than mean T_{max} ($Z < -0.25$), while the events of 1889 and 1913 were under much lower than mean midsummer to early autumn T_{max} ($Z < -0.9$).

Therefore, based either solely on precipitation or solely on temperature, it appears that out of the 10 largest fire outbreaks on Mt. Taygetos, seven fires (1861, 1879, 1889, 1944, 1973, 1998, and 2007) can be linked mid- to late-fire-season drought induced by P or T_{max} ($Z < -0.25$ for P or $Z > 0.25$ for T_{max}). However, only the fires of 1998 and 2007 appear to have been promoted by a combination of both lower than mean P and higher than mean T_{max} (Table 1).

Verification based on long-term climatic data

Correlations between ARmet July–September T_{max} and temperature for ATobs or SGr were very highly significant ($P < 0.000001$; $r = 0.66$ or 0.63 ; 1964–2008; Table S3), suggesting that despite local microclimatic peculiarities a common climatic signal exists among them. For August–September P , this signal was found somewhat weaker, with correlations being significant only between ARmet and SGr ($P < 0.01$; $r = 0.47$). The same pattern was observed when expanding correlations back to 1899 (or 1900 for P).

Table 1 Fire years coinciding with below-average precipitation ($z < -0.25$) or above-average T_{max} ($z > 0.25$)

Fire year	Prec. August–September	T_{max} July–September
1860		
1861		+
1879		+
1889	+	
1913		
1944		+
1945		
1973	+	
1998	+	+
2007	+	+

Note that for 1998 and 2007 both cases occur

Correlations between ARrec July–September T_{max} and temperature for ATobs or SGr were still very highly significant ($P < 0.00001$, $r = 0.44$ or $P < 0.001$, 0.32 ; 1899–2008; Table S3). For P , they remained statistically significant, again only between ARrec and SGr ($P < 0.05$; $r = 0.21$).

If above correlations were significant for 1964–2008 (i.e., during the period when only meteorological data were compared), but not significant during 1899–2008 or 1900–2008, it would indicate that our climatic reconstruction would be poor and not able to capture the general climatic trends of the region. However, this is not the case. Moreover, if the ARrec series is capable of reproducing the general climatic variability experienced in southern Greece at least during the twentieth century, it should be even more accurate in reproducing local climate on Mt. Taygetos.

Further on, we plotted the meteorological station data that produced the best correlations with ARrec (i.e., ATobs for T_{max} and SGr for P) together with the six major fire events reconstructed for Mt. Taygetos that occurred since the beginning of the twentieth century (fires of 1913, 1944, 1945, 1973, 1998, and 2007; Fig. S2 and Fig. S3). Even under this general assessment for climate in southern Greece, it appears once more that mid- to late-fire-season climate in 1998 and 2007 can be considered as the driest out of the six fire years (with simultaneous occurrence of reduced precipitation and increased temperatures).

Discussion

Connections between climatic dryness and large fires within the last centuries

Our reconstruction of late summer–early autumn P and of midsummer–early autumn T_{max} on Mt. Taygetos was found

to be related to large fires for the wider area around the mountain (Fig. S1). These two climatic parameters are not only very important for explaining burnt area at a local scale. According to national inventories, 85 % of the total burnt area in Greece occurs during the mid- to late fire season (July–September) (Tsagari et al. 2011). This comes to no surprise as July–September is the driest period of the year.

The reconstruction of fire history on the mountain provided results that arrive at the same conclusion. The intraring position of fire scars was found to be similar during the last 210 years, with most of the fires occurring during the summer xerothermic period and especially in the late summer (Christopoulou et al. 2013). Based on the same reconstruction, 34 fires occurred within the total area investigated with Black pine forests on Mt. Taygetos (3,370 ha) during the last 165-year period (1845–2010).

Out of these 34 fires, 10 were large enough to be worth investigating, whereas seven fires (1861, 1879, 1889, 1944, 1973, 1998, and 2007) can be linked to P - or T_{\max} -induced mid- to late-fire-season drought (Table 1). Furthermore, the events of 1879, 1944, 1998, and 2007 appear as the most widespread, standing out as the only one affecting more than 30 % of the studied area (32, 58, 36, and 84 %, respectively; Christopoulou et al. 2013). If there is indeed a strong connection between climatic dryness and burnt area on Mt. Taygetos, it should be most evident for these four largest fires. For 1879 and 1944, we found late-fire-season P to be within the normal range, while for 1998 and 2007, such rainfall was found to be below normal (Fig. 2). Mid- to late-fire-season T_{\max} , on the other hand, appeared above normal in all four cases (Fig. 3). Thus, mid- to late-fire-season drought either as a product of increased T_{\max} alone or in combination with reduced rainfall appears to have had a strong impact on burnt area on the mountain during the last ca. one and a half century.

Findings from Mt. Taygetos in support of future climate and fire projections

Climatic model projections under global warming scenarios for regions of the southern Mediterranean (which include our area of focus in southern Greece) suggest an increase by ca. 4–5 °C on average in summer temperature for the last 30 years of the twenty-first century compared with 1961–1990 (A2 IPCC emission scenario; extreme range CO₂ increase). Summer precipitation may vary from stable conditions to a decline of ca. 40 %. For winter precipitation, there is a general agreement on the decline, at a scale of ca. 30 % or more (Déqué et al. 2005; Gao et al. 2006; Somot et al. 2008; Giorgi and Lionello 2008).

For the province of Messinia (where most burnt area on Mt. Taygetos has occurred), a regional climate model

(RCM) driven by the medium-range IPCC emission scenario for CO₂ (A1B) projects by 20-day increase in the length of dry spell, by 15-day increase in the number of days above 35 °C and by 10 % decrease in winter precipitation for the period 2021–2050 (vs. 1961–1990; Giannakopoulos et al. 2011).

These conditions of reduced soil moisture in summer and more severe drought events are projected to profoundly affect wildfire frequency and intensity (Schröter et al. 2005; Moriondo et al. 2006; Giannakopoulos et al. 2009; 2011; Dury et al. 2011). In the Mediterranean, the area burned by wildfire can be expected to increase by a factor of 3–5 at the end of the twenty-first century compared with the present as a result of a dryer summer climate (A2 IPCC emission scenario), with Greece appearing as a typical example of such regions (Dury et al. 2011). This simulation was driven without the human impacts such as fire ignition and fire-fighting efforts. Arson, which is a common phenomenon in Greece, for example, may increase burnt area in dry years, with the opposite effect produced by effective fire prevention and suppression policies. For the province of Messinia, extreme fire risk (FWI > 30; van Wagner 1987) is projected to increase by ca. 15 days in 2021–2050 (vs. 1961–1990; A1B; Giannakopoulos et al. 2011). Our findings from Mt. Taygetos are consistent with such projections. In ca. 150 years of analysis, 2 out of 4 years with greatest increase in burnt area occurred in 1998 and 2007 (Christopoulou et al. 2013) when both above-average temperatures and below-average precipitation coincided during the mid- to late fire season, while the other two most extended fire events (1879 and 1944) occurred under above-average T_{\max} during the mid- to late fire season (Figs. 2, 3).

The climate of 1998 and 2007 can be linked to the climate projections under global warming that take the 1961–1990 climate period as a reference (see above), providing an opportunity to assess the possible future fire regime. In 1998, summer (June–August) or summer–early autumn (June–September) P in Artemisia station on Mt. Taygetos was –84 or –61 % below the 1961–1990 mean (reconstructed August–September P was similarly –44 %; ca. 50 mm mean for August–September in 1961–1990). T for summer or summer–early autumn was +4 °C compared with the 1961–1990 mean (as also for reconstructed July–September T_{\max} ; with its 1961–1990 mean at ca. 27 °C). Thus, the decline in summer or summer–early autumn P coinciding with the 1998 fire is even below the mean P projected for late twenty-first century for regions of the Mediterranean, while the observed summer temperature increase is in accordance with such projections.

On the other hand in 2007, apart from a very wet June (+74 %), mid- and late summer to early autumn (July–September and August–September) P was –17 %

compared with the 1961–1990 mean. However, T in summer (June–August) and summer–early autumn (June–September) were +7 and +5 °C (for reconstructed July–September +4 °C). These conditions are again within projections for the late twenty-first century, even exceeding those for temperature. However, they were not a local phenomenon. The summer of 2007 was exceptionally hot for southeastern Europe, the Balkan Peninsula and also part of the Asia Minor (Founda and Giannakopoulos 2009) as was the 2003 summer for Western Europe (Luterbacher et al. 2004). A number of heat waves hit the eastern Mediterranean area in summer 2007 (at the end of June, in July and also August), during which the national meteorological services reported all-time record-breaking temperatures at a number of stations (reaching up to 47 °C in some cases; Founda and Giannakopoulos 2009).

However, it is not only summer climate that can affect the fire regime. Sarris and Koutsias (2014) have shown for the province of Messinia (where most burnt area on Mt. Taygetos is classified) as well as for other Mediterranean regions that the entire hydrological year (dominated by winter precipitation) can also play an important role in fire extent (see also Dimitrakopoulos et al. (2011) for possible connections between annual drought and fire activity in Greece). For 2007, winter (December–February) P was –45 %, and P of the entire hydrological year (October–September) –22 % compared with the 1961–1990 mean of ca. 500 and 1,100 mm, respectively, placing again climatic conditions within projected climate under global warming scenarios. Once more, these conditions were not only observed on Mt. Taygetos. Winter precipitation in 2007 was very low over the entire Mediterranean (Luterbacher et al. 2007).

Hence, future work in reconstructing not only summer climate but also P for winter or the entire hydrological year would help in better understanding the historical evolution of other climatic parameters critical for fire spread. Low-elevation pines whose growth is mainly determined by annual P (Sarris et al. 2011) may prove useful tools for such an endeavor.

Although some effort has been made to study long fire history statistics that go before the twentieth century (Pausas 2004; Koutsias et al. 2013), we are not aware of any such work in the Mediterranean comparing both the fire and the climatic history from the same region in more than centennial scales. Replicating this approach may prove to be very useful in studying climate–fire interactions and in addressing uncertainties regarding their future fire regime in the Mediterranean under global warming by the use of past evidence.

However, finding tree sites and tree species that capture climatic signals explaining fire behavior is not an easy task. Another dendroclimatological study for Mt. Taygetos

based on high-elevation *P. nigra* trees, but from dry sites, was able to correlate tree growth with May–June rainfall (Brandes 2007). Despite our original tree sampling design, another two sites on the mountain, one with *A. cephalonica* at high elevation and another with *P. nigra* from lower altitude, were not used in this study as their growth was not found to be related to climatic signals suitable for explaining fire behavior, e.g., early spring T_{\max} and mid-autumn P . For reconstructing climate to assess its contribution to fire dynamics, our work also highlights ABD as a method that retains both the high- and low-frequency climatic variability in tree-rings (Briffa et al. 2001), a valuable tool for cases where the magnitude of changes in climate needs to be addressed.

The synergy between climate and land-use changes

Apart from a dry climate, increased burning fuel availability is another detrimental factor for fire suppression (Meyn et al. 2007; Koutsias et al. 2012). There is evidence to suggest that burning fuel availability has not remained stable on Mt. Taygetos during the last one and a half century. According to Papanastasis (2012), anthropogenic activity in mountains of the north Mediterranean basin (wood cutting, grazing, etc.) increased during the eighteenth and the nineteenth century because populations increased. The beginning of the twentieth century, however, marked the start of rural emigration from the mountains of northern Mediterranean countries that peaked after World War II, resulting in land abandonment and the remarkable increase in forest cover seen in recent years (see also McNeill 1992; Brandes 2007).

Thus, the large fires in recent decades on Mt. Taygetos (1973, 1998, and 2007) most likely have had more surface burning fuel to propagate compared with those in the nineteenth century because of (1) reduced harvesting of biomass and (2) longer periods of fire exclusion (during which burning fuel accumulated), both resulting from lower human activity (see Christopoulou et al. 2013 for more evidence on Mt. Taygetos; Körner et al. 2005; Koutsias et al. 2012 for other Greek regions). On the other hand, lower available biomass to burn could have somewhat masked the impact of dryness on fire spread in years such as 1861, 1879, 1889, or 1944 where there is evidence of either low precipitation or high temperature during the mid- to late fire season (Figs. 2, 3).

The synergy between climate and fuel availability may also explain the very high intensity of 1998 and 2007 fires on Mt. Taygetos that burned mostly as stand-replacing crown fires, a qualitative change in the fire regime with potentially very serious consequences for ecosystems (e.g., loss of old forests and land degradation), society, and climate. Although forest recovery in northern Mediterranean

mountains is a primary sink for CO₂, and especially old-growth tree stands, mega fires such as of 2007 in Greece were a primary source of greenhouse gases, thus creating a positive feedback for accelerating global warming processes. In 2007, the estimated total burned biomass in 11 northern Mediterranean and Balkan countries was 7.3 million tons, leading to the emission of more than 12.3 million tons of CO₂. The contribution from forest fires in Greece in that year to these total amounts was disproportionately high, estimated at ca. 37 % in both burned biomass and CO₂ (EFFIS 2007).

Conclusions

Although Mt. Taygetos has experienced fires coinciding with mid- to late-fire-season drought induced by P or T_{\max} in the past 150 years, the only time that climatic dryness was promoted by a combination of both lower than mean P and higher than mean T_{\max} was in 1998 and 2007. Thus, there is evidence to suggest that extreme climate has been behind the two out of the four largest in extent fires on the mountain. The 1879 and 1944 large fires, the only ones that are comparable to 1998 and 2007 during the last 150 years, are also related to higher than mean T_{\max} during the mid- to late fire season. This is despite the likely reduced availability in burning fuel of that time that could have masked such impacts. Thus, if the recent synergy between climate and burning fuel availability continues in the twenty-first century, burnt area should be expected to escalate in accordance with fire model projections under global warming scenarios for such regions, i.e., mid-latitude mountainous areas of the world where both aridity and available fuel are expected to increase. The latter factor in our case was a result of land-use changes permitting forests to reclaim former agricultural land.

Hence, for protecting northern Mediterranean mountains, their goods, and services, forest managers and policy makers will have to consider conditions of greatest fire danger because of the projected dryer climate, a phenomenon for which we may already have seen the initial signs in southern Greece. In such cases, developing fire risk assessment tools that enable long-term fire danger prognosis (Sarris and Koutsias 2014) and battling the accumulation of burning fuel should be a top priority to reduce fire spread, especially if rural depopulation further continues in northern mountains of the Mediterranean.

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