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PALEOFIRE DYNAMICS IN CENTRAL SPAIN DURING THE LATE HOLOCENE: THE ROLE OF CLIMATIC AND ANTHROPOGENIC FORCING

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ABSTRACT

The use of fire and, consequently, its severity and incidence on the environment have grown steadily during the last millennia throughout the Mediterranean. This issue can be assessed in several mountain ranges of central Iberia where changes in the management policy on anthropic activities and exploitation of high-mountain environments have promoted a remarkable increase on fire frequency. Our research focuses on fire dynamics throughout the last 3,000 years from three peat bog charcoal records of the Gredos range (central Iberia). Our aim is to reconstruct past fire regimes according to forest vegetation typology (*Castanea sativa*, *Pinus pinaster*, and *Pinus sylvestris*). Charcoal influx shows low values between 3,140 and 1,800 cal. year BP when forests were relatively dense in both high and mid-mountain areas. Fire appeared synchronous between 1,800 and 1,700 cal. year BP for Lanzahíta and Serranillos and around 1,400–1,240 cal. year BP for the three sites, suggesting anthropogenic fire control between the Late Roman and Visigothic periods that can be related to the cultivation of olive trees in the valleys and a greater human impact in high-mountain areas. By contrast, during the Muslim period (1,240–850 cal. year BP), fire dynamics becomes asynchronous. Later, fires turn again coeval in the Gredos range during the Christian period (850–500 cal. year BP) and can be also correlated with drought phases during the Late Medieval Warm Episode. In short, our study demonstrates that fire activity has been enormously variable during the late Holocene in response to both short-term and long-term regional and global climate, vegetation dynamics, and land use changes. Copyright © 2017 John Wiley & Sons, Ltd.

KEY WORDS: fire history; charcoal analysis; climate variability; human impact; Gredos range; Iberian Peninsula

INTRODUCTION

Undoubtedly, the Mediterranean region is among the most impacted by land degradation (Brandt & Thornes, 1996). Its Mediterranean climate, characterized by dry summers, rough topography, weak lithology, and high fire incidence have been cited as main drivers of such alterations (Vannière *et al.,* 2010; Keeley *et al.,* 2012; Marlon *et al.,* 2013; Molinari *et al.,* 2013). Nonetheless, fire has been identified as the main destabilizing element of Mediterranean terrestrial ecosystems, among human activities triggering a profound impact on this region throughout history (Le Houérou, 1973; Pausas *et al.,* 2008). In addition to natural fires, intentional burning of the forest was one of the usual management techniques employed by prehistoric societies (Naveh, 1975). In fact, it could be said that humans and fire constitute a coevolutionary system in Mediterranean high-mountain areas (López-Sáez *et al.,* 2014; Montiel & Galiana, 2016). Fire intervals are frequently <100 years in dry biomes such as the Mediterranean region and can even be <30 years (Leys *et al.,* 2013). Although Mediterranean forests are able to withstand and evolve against a high fire frequency, alterations in the fire regime could have generated important consequences for past Mediterranean ecosystems (Pyne, 2009), where the role of fire has been a key factor directly affecting the distribution, structure, composition, and vegetation history (Pausas, 1999; Carrión *et al.,* 2010).

High-resolution paleoenvironmental records are required to properly understand the role of fire on the configuration and temporal dynamics of current Mediterranean landscapes, at both regional and local scales, in order to reconstruct fire regimes and predict their natural or anthropic origin (Turner *et al.,* 2008). For instance, charcoal records from peatlands or lakes have allowed to study the temporal trend of fire frequency on millennial scales, relating it to changes in vegetation and the amount of available biomass, as well as understanding its linkages to climatic variability and human impact (Conedera *et al.,* 2009; Blarquez *et al.,* 2015; Ruiz-Fernández *et al.,* 2016; Vannière *et al.,* 2016). In fact, the use of macroscopic charcoal (Ø > 150 μm) has provided more accurate fire event reconstructions at high temporal and spatial resolution (Clark, 1988, 1989; Lynch *et al.,* 2004). Several experimental studies have shown that macrocharcoal analysis is a useful tool to determine local scale fires (500 m–1 km) because its potential transport from long distances does not alter the relationship between local fires and the sedimentary macrocharcoal record at the coring

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site (Clark *et al.,* 1998; Lynch *et al.,* 2004; Higuera *et al.,* 2007; Peters & Higuera, 2007).

Recent studies from the Mediterranean region have shown a clear connection between climatic shifts and millennial-scale fire regimes, particularly from the early to the mid-Holocene (11,700–5,000 cal. year BP; Vannière *et al.,* 2011; Burjachs & Expósito, 2015). In contrast, during the last 3,000 years, fire regime has been essentially mediated by anthropic activity (Abel-Schaad *et al.,* 2014; López-Sáez *et al.,* 2014; Morales-Molino *et al.,* 2016; Vannière *et al.,* 2016). Human impact and fire regime in the Mediterranean region have been analyzed by many research works in the last decades (Colombaroli *et al.,* 2007, 2008; Vannière *et al.,* 2008, 2011, 2016; Connor *et al.,* 2012; Leys *et al.,* 2013, 2014; Doyen *et al.,* 2015), demonstrating that fire was a key factor in mountain ecosystems management since the Neolithic with the aim of creating open spaces in forests for both agricultural and livestock activities (Colombaroli *et al.,* 2008; Lillios *et al.,* 2016). In particular, the comparative analysis of pollen and macrocharcoal records from southwestern Europe has provided substantial evidence of the role played by anthropogenic fires, which have been a major player in establishing interspecific links between plant species and shaping vegetation dynamics from mid-Holocene, causing the expansion of grasslands and scrublands, the progressive disappearance of conifer and mesophilous forests, and finally the establishment of large areas of cultivation and grazing pastures (Colombaroli *et al.,* 2008; Carrión *et al.,* 2010; Bisculm *et al.,* 2012).

Most paleofire reconstructions of the Iberian Peninsula are based on microscopic charcoal (<150 μm) from pollen slides (e.g., Burjachs & Expósito, 2015; Revelles *et al.,* 2015; Burjachs *et al.,* 2016a, 2016b; Expósito *et al.,* 2017), which mainly record a regional signal (Clark, 1988, 1989). Different methodologies, insufficient temporal resolution, and, sometimes, a weak chronological control hamper the implementation of comparative studies among sites (Tinner *et al.,* 1998; Vannière *et al.,* 2016). Anyway, the incidence of human-induced fires on the frequency, fire regime, and biomass burning is still an open issue in Iberia (Carrión *et al.,* 2010; Bal *et al.,* 2011; Bowman *et al.,* 2011; Morales-Molino *et al.,* 2016). Most paleofire studies have reconstructed fire history (e.g., Abel-Schaad *et al.,* 2009, 2014; López-Merino *et al.,* 2009; López-Sáez *et al.,* 2010, 2016a, 2016b; Abel-Schaad & López-Sáez, 2013; Morales-Molino *et al.,* 2013; Burjachs & Expósito, 2015; Silva-Sánchez *et al.,* 2016; Morales-Molino *et al.,* 2017) and in certain cases fire regime (e.g., Bal *et al.,* 2011; Gil-Romera *et al.,* 2014; Morales-Molino *et al.,* 2016), but only a few have taken into account regional variability on a spatial scale discerning discrepancies or agreement among records (Gil-Romera *et al.,* 2010; Vannière *et al.,* 2011; López-Sáez *et al.,* 2014; Morales-Molino *et al.,* 2016).

The aim of this paper is to compare three high-resolution macrocharcoal records from peat bogs located in central Spain (Gredos range, Spanish Central System). Fire variability on mountain areas regarding to anthropogenic disturbances, climate shifts, and changes in vegetation cover at multi-decadal to millennial timescales can be analyzed by means of this study, performed on different sites. The data cover the late Holocene from ca. 3,000 cal. year BP to present. The aim is to examine the timing of fire occurrence at centennial timescales and the spatial variability associated with vegetation and location (valley bottoms vs. slopes). Five questions are addressed: (i) Was fire related to climate seasonality in the high-mountain Mediterranean ecosystems of the Gredos range? (ii) If so, what kind of climate control did the fire regime undergo (i.e., number of fire events within specific chronological frameworks)? (iii) What was the relationship between the increase of human impact and the biomass burning pattern? (iv) Can land use practices be inferred from macroscopic charcoal records? And (v) did late Holocene fire dynamics depend on vegetation type?

MATERIAL AND METHODS

The Gredos range is found in the central part of the Iberian Central System, which divides two wide plateaus: the Northern Iberian (800–1,000 m asl) and the Southern Iberian one (600–800 m asl). Its tectonic structure, a tilted horst along a south-oriented fault, establishes a distinct asymmetry between northern and southern slopes. Wet and cold winters (0–2°C) and dry and warm summers (20–22°C), as well as an average precipitation of 1,400 mm y^{-1}, shape climatic conditions. Regarding vegetation, holm oak (*Quercus ilex* L. subsp. *ballota* (Desf.) Sampa.) and Pyrenean oak (*Quercus pyrenaica* Willd.) spread on the mesomediterranean belt southwards, the former accompanied by xerophilous taxa like *Juniperus oxycedrus* L., *Cistus ladanifer* L., *Lavandula stoechas* Lam., and *Olea europaea* L.; and the latter by mesothermophilous ones like *Arbutus unedo* L., *Corylus avellana* L., *Phillyrea angustifolia* L., *Pistacia terebinthus* L., *Lonicera implexa* Ait., *Paeonia broteroi* Boiss. & Reut., and *Viburnum tinus* L. The supramediterranean belt (>900 m asl) is occupied by other Pyrenean oak forests. Maritime pine (*Pinus pinaster* Ait.) and sweet chestnut (*Castanea sativa* Mill.) woods also extend on the southern slopes (500–1,000 m asl). Finally, the high-supra and oromediterranean belts show the wide range of grasslands and broom communities (*Cytisus oromediterraneus* Rivas-Martínez et al., *Echinospartum barnadesii* (Graells) Rothm., and, to a minor extent, *Erica australis* L.) with isolated pine stands (*Pinus sylvestris* L. var. *iberica* Svoboda and *Pinus nigra* Arnold. subsp. *salzmannii* (Dunal) Franco) reaching the treeline. The Gredos range has historically been one of the "hot" point of forests fires in Spain (Montiel & Galiana, 2016). On the one hand, there is a frequency of storms with large electrical apparatus due to the topographical characteristics of these mountains, their orientation and insolation, and their situation of obstacle between the two aforementioned plateaus; and, on the other hand, it is necessary to consider the great expansion that are having during the last 50 years the second-residence urbanizations, tourism, and mountain's sports, thanks to the forest landscape and the lush nature of the Gredos range (Galiana, 2012).

Three continuous high-resolution macrocharcoal records (16, 29, and 26 years median resolution per samples for Serranillos, Lanzahíta, and Tiemblo, respectively), following standardized methods of quantification, were selected in order to document the last 3,000 cal. year BP of fire regime history in the Gredos range (Figure 1). A Russian corer of 5-cm diameter was used to extract the sediment cores. The diverse sections were then sealed separately and kept on cold storage (4°C) before its handling in the laboratory. The sites were selected with the aim of discerning whether there were differences in fire history according to the type of forest. Pollen records of the three sites have already been published, in which local pollen assemblage zones were established with a constrained cluster analysis made by Coniss by transforming percentage data to its square root (Grimm, 1987). The Lanzahíta (588 m asl; mean annual precipitation 1,007 mm, mean annual temperature 15·1°C; 100-cm depth) and Tiemblo (1,250 m asl; mean annual precipitation 1,400 mm, mean annual temperature 13°C; 120-cm depth) sequences provide the first Iberian pollen records undertaken within monospecific *P. pinaster* and *C. sativa* woodlands, respectively (López-Sáez *et al.,* 2010, 2017), while that of Serranillos (1,700 m asl; mean annual precipitation 937 mm, mean annual temperature 9·3°C; 120-cm depth) comes from a high-mountain area where in the last two millennia there was a *P. sylvestris* forest that disappeared ca. 500 cal. year BP (López-Merino *et al.,* 2009; López-Sáez *et al.,* 2009). The climatic data of each record come from Ninyerola *et al.* (2007).

Twenty-one radiocarbon datings were performed on bulk peat samples (Table I). Most of these radiocarbon dates have already been published in the previously mentioned works of the authors, except one from Serranillos at 120 cm. CALIB 7.1 and the INTCAL13 curve (Reimer *et al.,* 2013) were both used to calibrate the radiocarbon dates, which were then employed by CLAM 2.2 software (Blaauw, 2010) to build an age–depth model (Figure 2), with a confidence interval of 95% (2σ) through a smooth spline solution.

To reconstruct fire history, volumetric samples (1 cm^3) of sediment were collected every centimeter along all cores following the recommendations provided by Whitlock & Larsen (2001). Charcoal samples were then soaked in 15% H_2O_2 for 24 h. The sediment was subsequently sieved, collecting all charcoal particles larger than 150 μm, which are assumed to have local origin (<10 km; Higuera *et al.,* 2007).

The three selected charcoal series were analyzed using the method of charcoal signal decomposition with the aim of reconstructing local fire history in each of the studied records with the CHARANALYSIS 1.1 software (Higuera *et al.,* 2007, 2009). Theses analyses were complemented with an ensemble member procedure in order to assess the sensitivity of fire event reconstruction to varying statistical methods (Blarquez *et al.,* 2013). The charcoal accumulation rate (CHAR, pieces $cm^{-2}\ y^{-1}$) was established by multiplying charcoal concentration (pieces cm^{-3}) of each sample by the corresponding accretion rate ($cm\ y^{-1}$) derived from the

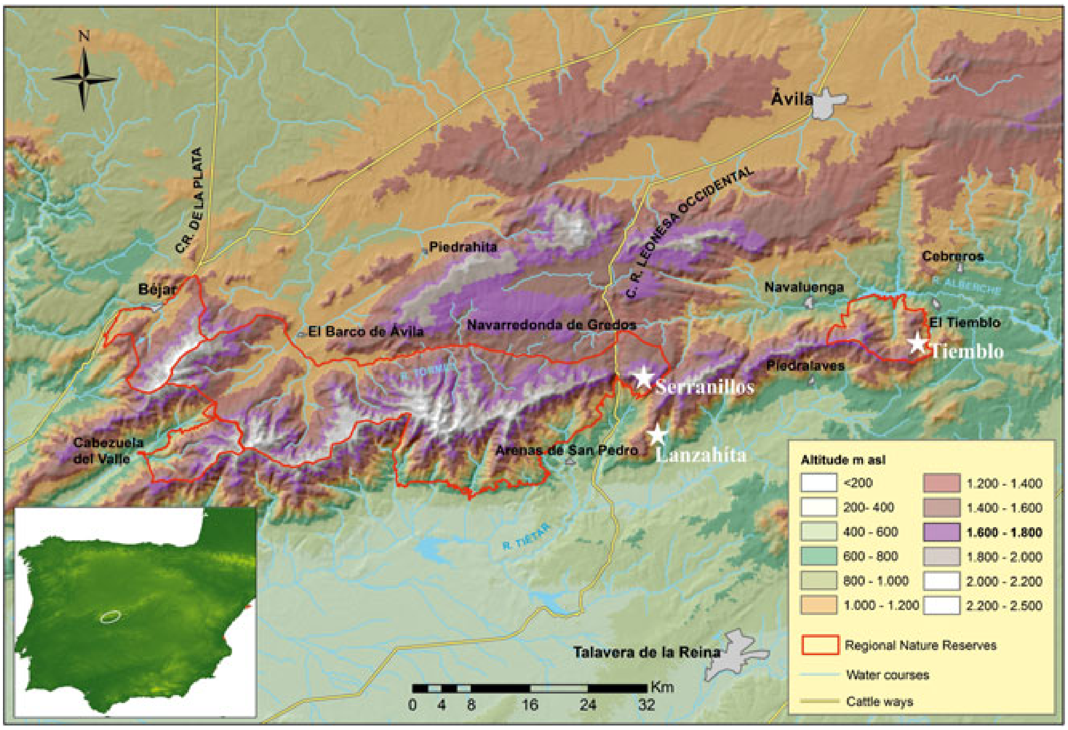

Figure 1. Location of the studied sites in the Gredos range (central Iberia). [Colour figure can be viewed at wileyonlinelibrary.com]

Table I. AMS radiocarbon data with 2σ range of calibration

Laboratory code	Depth (cm)	AMS ^{14}C age BP	Age cal. year BP (2σ)	Mean age cal. year BP
Lanzahíta				
CNA-095	7·5	Modern	—	—
Ua-24879	24·5	780 ± 35	759–667	705
Ua-24878	35	1020 ± 35	1048–800	940
CNA-105	44·5	1315 ± 29	1295–1183	1260
CSIC-1877	64·5	1907 ± 35	1928–1737	1853
Ua-19515	75·5	2280 ± 55	2420–2140	2260
CSIC-1876	100	2387 ± 32	2677–2345	2413
Serranillos				
CSIC-1767	39·5	522 ± 27	624–509	535
CSIC-1768	82·5	1664 ± 35	1693–1420	1569
Ua-21490	91	1895 ± 45	1929–1717	1839
CSIC-1938	102·5	1938 ± 35	1986–1819	1888
Poz-83925	120	2050 ± 30	2113–1932	2013
Tiemblo				
CNA-211	7	210 ± 60	429–0	192
CNA-185	15	375 ± 40	506–316	432
CNA-103	29	815 ± 35	786–680	725
CNA-186	41	1130 ± 35	1173–961	1031
CNA-546	55	1425 ± 35	1380–1289	1327
CNA-551	72	1875 ± 25	1876–1733	1825
CNA-540	88	2290 ± 25	2352–2184	2330
CNA-097	105	2675 ± 25	2844–2750	2775
CNA-096	120	2970 ± 30	3229–3007	3136

AMS = accelerator mass spectrometry.

sediment age–depth models (Figures 2 and 3). The charcoal background component ($CHAR_{back}$) indicates the part of the CHAR series whose temporal variation is slow in response to potential sediment mixing and even to issues arising from sampling, transport, and production of charcoal (Higuera *et al.,* 2010). In order to model the $CHAR_{back}$, raw CHAR series ($CHAR_{raw}$) were filtered using the five smoothing methods available in the CHARANALYSIS software (Higuera *et al.,* 2009). For each method, we ran 19 CHAR background simulations with variable smoothing windows equal to 150, 175, 200, …, 600 years. From the resulting 95 simulations, $CHAR_{back}$ was subtracted from the $CHAR_{raw}$ to obtain the residual high-frequency of charcoal peaks (Figure 3). This component includes the fire-induced signal ($CHAR_{fire}$) and the background noise not related to it but to distant and regional fires ($CHAR_{noise}$), as well as the noise derived from the analysis itself and from the charcoal redeposition.

A Gaussian mixture model, referred to each overlapping 500-year portions of the record, was used in each simulation to discriminate signal from noise, considered as the separation threshold the 99th percentile of the peak distribution. In this sense, $CHAR_{fire}$ surpassing the overall variation of $CHAR_{noise}$ is considered to be related to local fire episodes. A signal to noise index (SNI) was established for each sample, quantifying the discrimination between charcoal peaks related to one or multiple fire events and noise records (Figure 4). From the 95 simulations, we conserved half of reconstructions (i.e., 47 reconstructions) with the higher SNI (Kelly *et al.,* 2011). From that ensemble member, we computed the distribution of the number of reconstructed event by unit of time and determined that reconstructed fires exceeding the 75th percentile of this distribution corresponded to fire events (Figure 5) in the study area (Blarquez *et al.,* 2013).

The amount of time between detectable peaks or fire return intervals (FRIs) was calculated (Figure 6). Fire frequency was also estimated, using a Kernel density estimation technique with a 250-year bandwidth. Bootstrapped 90% confidence intervals around the fire frequency were established by bootstrap resampling of the kernel density estimation using R “paleofire” package (Blarquez *et al.,* 2014). Changes in both FRI and fire frequency allowed us to study the diachronic variation of fire regime (Figure 6). In order to analyze the variation through time of fire disturbances, we examined FRI distributions and medians for different time intervals of the last 3,000 years (Table II).

Using changes in pollen percentages as a guide, we divided the charcoal records from Lanzahíta, Tiemblo, and Serranillos into zones for discussion (Table II, Figures 6 and 7). For Lanzahíta, the zones include two late Holocene *P. pinaster*-dominated intervals between 2,475–1,800 and 1,235–670 cal. year BP (L1 and L3), two intervals with high values of *C. ladanifer* from 1,800–1,235 and 670–195 cal. year BP (L2 and L4), the first one including *O. europaea* and the last one between 195 cal. year BP and present (L5) with alternating values of both pollen taxa and olive tree. For Tiemblo, all zones show high percentage values of *C. sativa* pollen, although between 1,915 and 430 cal. year BP, *O. europaea* and anthropogenic taxa are frequent (T2–T4). Finally, for Serranillos, the zones include a *P. sylvestris*-dominated interval between 2,025 and 800 cal. year BP (S1–S4), an interval with decreasing values of pine pollen from 800–475 cal. year BP (S5), a new *P. sylvestris* interval from 475–90 cal. year BP (S6–S7), and an anthropozoogenic (presence of coprophilous fungi) interval from 90 cal. year BP to present (S8).

RESULTS

Lanzahíta

The CHAR averaged 0·3 pieces cm^{-2} y^{-1} between 2,475 and 1,800 cal. year BP, with values ranging between 0 and 4·7 (Figure 3). High CHAR values generally prevailed between 1,800 and 1,235 cal. year BP with two large peaks at 1,748 and 1,371 cal. year BP (Figures 5 and 7). From 1,200 cal. year BP, three periods of high CHAR are recorded with large peaks at 704, 327, 240, and −21 cal. year BP (Figures 5 and 7). The SNI is typically >3 (Table II, Figure 4), showing that the charcoal peak signal and the inherent noise are separated along the analyzed time series (Kelly *et al.,* 2011).

The ensemble member procedure documents six fire episodes (Table II, Figures 3–5). The mean FRI for the entire record is 354 years, varying among zones, with zone L2 = 377, L3 = 696, L4 = 218, and L5 = 261. Fire frequency shows an increasing trend from 1,000 to 250 cal. year BP

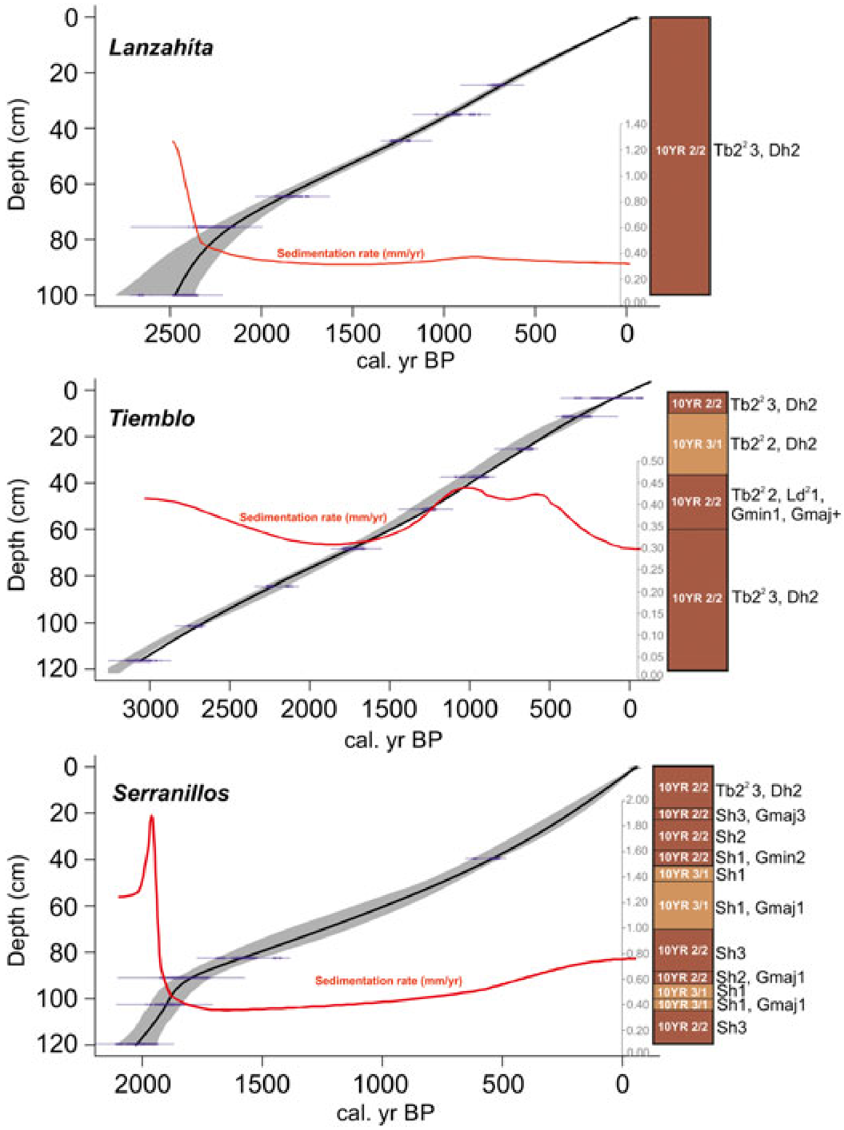

Figure 2. Lithology (following Aaby & Berglund, 1986), sedimentation rate (mm y^{-1}), and age–depth models based on calibrated ^{14}C dates of the Lanzahíta, Tiemblo, and Serranillos cores, which were constructed using the CLAM 2.2 software package. The black line of the plots shows the best-fit age–depth model, and the grey envelope of the plots shows the final 95% confidence. [Colour figure can be viewed at wileyonlinelibrary.com]

where late Holocene maximum fire frequency reaching more than four fires by millennia (Figure 6).

Tiemblo

The CHAR averaged 0·1 pieces cm^{-2} y^{-1} between 1,915 and 1,465 cal. year BP, with values ranging between 0 and 1·4 (Figure 3), while between 3,140–1,915 cal. year BP, macrocharcoals are not documented. High CHAR values (average 0·7 pieces cm^{-2} y^{-1}) are identified between 1,465 and 925 cal. year BP, with two large peaks at 1,401 and 959 cal. year BP (Figures 5 and 7). Lower CHAR reappears between 140 and 0 cal. year BP, including a low peak at 127 cal. year BP (Figures 5 and 7). SNI values are consistently ≥3 between 1,915 and the present (Table II, Figure 4). However, SNI values of 0 occur between 3,140 and 1,915 cal. year BP.

The ensemble member procedure indicates that a total of three fire episodes (peaks) were identified (Table II, Figures 3–5). The mean FRI interval is 637 years (Figure 6). FRIs were not determined for T1, T2, T4, and T5 zones because no fire events were recorded in those zones. Fire frequency shows maximum values between 1,300 and 1,100 cal. year BP, and later a decreasing tendency until 500 cal. year BP followed by a progressively increasing trend until the present (Figure 6).

Serranillos

The CHAR averaged 0·1 pieces cm^{-2} y^{-1} between 1,925 and 1,775 cal. year BP, with values ranging between 0 and 0·6 (Figure 3), including a low peak at 1,852 cal. year BP, while between 2,025 and 1,925 cal. year BP, macrocharcoals are not documented (Figures 5 and 7).

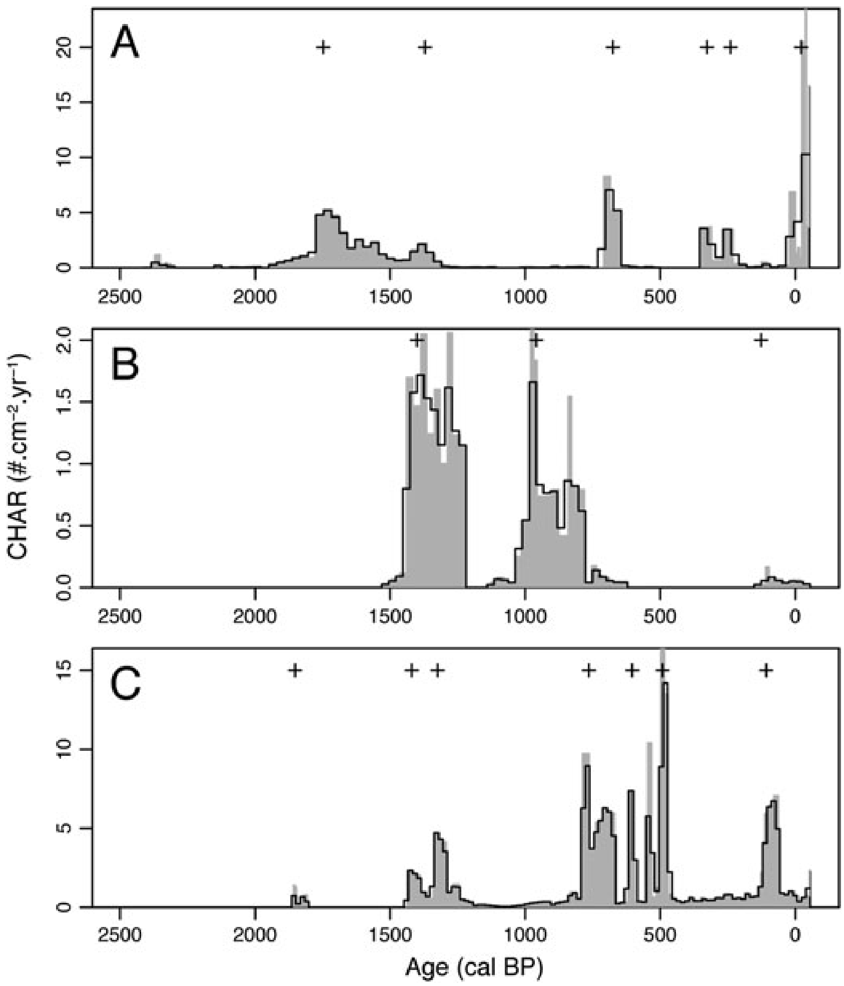

Figure 3. Raw charcoal accumulation rate series ($CHAR_{raw}$; grey bars), interpolated CHAR (stair-step, black line), and identified fire events (+ symbol) for (A) Lanzahíta, (C), Tiemblo, and (C) Serranillos.

Three main periods of high CHAR values are then recorded from 1,450–1,220, 800–475, and 100–50 cal. year BP with large charcoal peaks at 1,420, 1,324, 764, 604, 492, and 108 cal. year BP (Figures 5 and 7). The SNI is >3 (Table II, Figure 4), showing that the charcoal peak signal and the inherent noise are separated along the analyzed time series (Kelly *et al.,* 2011).

The decomposition of the charcoal time series and associated ensemble member procedure reveals seven fire episodes (Table II, Figures 3–5). The mean FRI for the entire record is 291 years, varying among zones, with zone S2 = 432, S3 = 264, S5 = 277, and S7 = 384. FRI intervals were not determined for zones S1, S4, S6, and S8 because there were too few fire events. Period with longer FRIs are documented ca. 1,420–780 and since 500 cal. year BP where a single event is detected at 108 cal. year BP, whereas shorter FRIs occur from 780–490 cal. year BP. Fire frequency progressively increase from 1,800–1,400 and 1000–450 cal. year BP and then shows a slight downward trend to the present (Figure 6).

DISCUSSION

Numerous local and regional studies have clearly demonstrated that the activity of long-term fires in the Mediterranean basin follows specific activity patterns (Colombaroli *et al.,* 2008; Turner *et al.,* 2008; Vannière *et al.,* 2008, 2011; Gil-Romera *et al.,* 2010; Leys *et al.,* 2013; Burjachs & Expósito, 2015). Such research provides solid evidence on synchronous trends usually interpreted as climatically driven but also documents unforeseen ecosystem behaviors in response to particular physical configurations, vegetation, and anthropic pressure. The dynamics followed by forests in the Gredos range is embedded within this sub-continental framework, demonstrating that fire activity has varied diachronically and spatially during the last two millennia (Morales-Molino *et al.,* 2013; López-Sáez *et al.,* 2014). These facts fit current fire activity in Mediterranean ecosystems, characterized by its erratic dynamics at spatial and temporal scales depending on biomass burning, fuel availability, settlement patterns, and land use strategies (Pausas *et al.,* 2008; Vannière *et al.,* 2010, 2016; Marlon *et al.,*

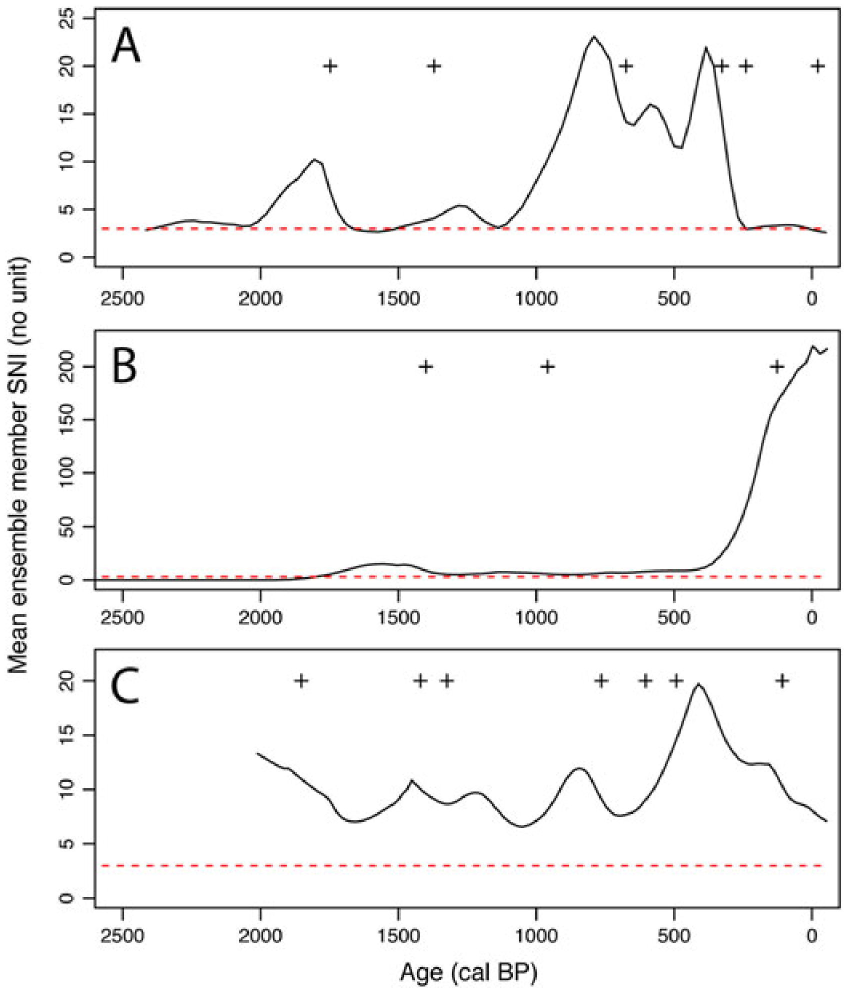

Figure 4. Mean signal-to-noise index (SNI) for the ensemble members (47 reconstructions) and identified fire events (+ symbol) for (A) Lanzahíta, (C) Tiemblo, and (C) Serranillos. [Colour figure can be viewed at wileyonlinelibrary.com]

2013). Although fire history of the Mediterranean basin seems to be mediated mainly by the variability of the Holocene climate (Turner *et al.,* 2008; Pyne, 2009; Vannière *et al.,* 2011; Marlon *et al.,* 2013), several paleofire reconstructions from the Iberian Peninsula have shown that sometimes the inherent dynamics of vegetation and human activities may eclipse the climate regulating role on the fire regime, especially during the late Holocene (Gil-Romera *et al.,* 2010; Connor *et al.,* 2012; Morales-Molino *et al.,*

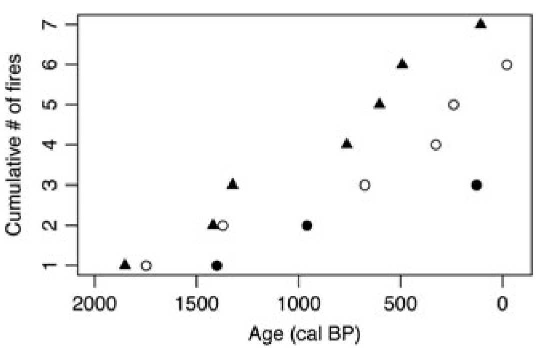

Figure 5. Cumulative fires through time. Black triangles = Serranillos, black circles = Tiemblo, and white circles = Lanzahíta.

2013, 2016; Abel-Schaad *et al.,* 2014; Morales-Molino *et al.,* 2017). For instance, in southeastern Iberian Peninsula, it has been shown that the expansion of *P. pinaster* forests during the mid-Holocene likewise produced significant changes in the fire regime independently of regional climate variability (Carrión & van Geel, 1999).

Considering pollen zones in the study of fire regimes in the three studied records allows us to correlate fuel types (tree species) and vegetation history with fire frequency over time. Thus, these pollen zones differ among them (Table II), so they can be interpreted as a temporal summary of average vegetation data for periods that can be considered stable within a watershed or pollen source area. This type of summary provides a large-scale examination of the control exerted by climate or by diverse disturbances of the watershed on the vegetation.

The data from Lanzahíta, Tiemblo, and Serranillos peat bogs indicate that fires were infrequent prior 1,800 cal. year BP (Figures 3 and 6). Between the Iron Age and the Early Roman period, the forest consisted of dense Scots pine (*P. sylvestris*) woodlands in the oromediterranean bioclimatic belt, as well as Maritime pine (*P. pinaster*) and chestnut (*C. sativa*) woodlands in the supramediterranean one

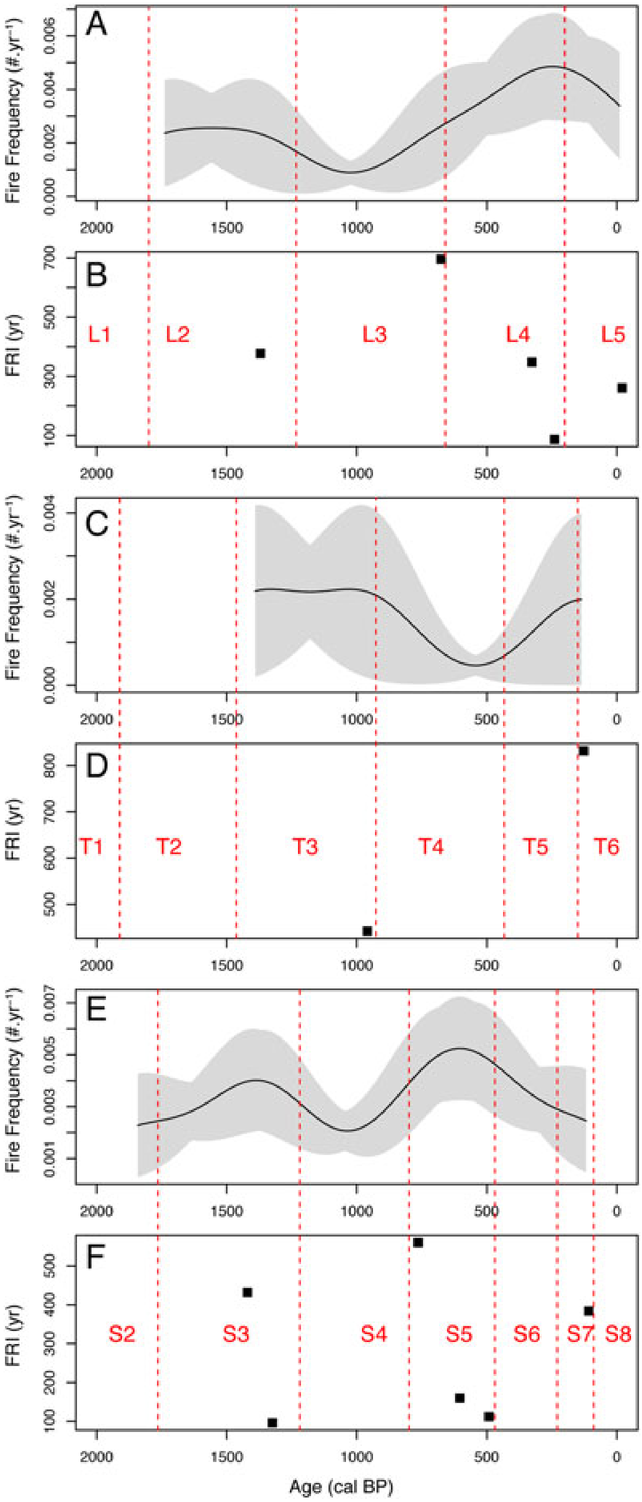

Figure 6. Late Holocene fire disturbance history for Lanzahíta (A and B), Tiemblo (C and D), and Serranillos (E and F). Fire frequency from the kernel density estimation procedure is represented using a black line along with its bootstrapped 90% confidence interval (grey area, A, C, E). Fire return intervals (FRIs) are represented using black squares (B, D, F). Also shown are zone boundaries for Lanzahíta (L2–L5), Tiemblo (T2–T6), and Serranillos (S2–S8). [Colour figure can be viewed at wileyonlinelibrary.com]

(Figure 7). However, a low CHAR peak is observed in Serranillos at 1,852 cal. year BP (Figures 3–5), probably related to local woodland clearings by means of fire during the Early Roman period, which scarcely affected Scots pine forests. At Lanzahíta, the FRI varies during the late Holocene (Figure 6), with recorded FRIs of 261, 218, 696, and 377 years. At a regional scale, Tiemblo and Serranillos records exhibit somewhat comparable return intervals. The aforementioned values suggest that the regional FRI was high (>300 years) between the Iron Age and the Roman period, and progressively shorter from the Visigothic period onwards, although with remarkable differences between sites. For instance, a mean FRI of 442 years was documented from Tiemblo during the Visigothic and Muslim periods, while at Lanzahíta, the FRI at this time averages 377 years (Table II). During the Christian and Early Modern periods, the mean FRI is even shorter at Serranillos (277 years) and Lanzahíta (218 years), while during the Late Modern period, the FRI tends to be longer at both sites. Undoubtedly, these data indicate that medieval human societies played a crucial role on the fire regime throughout the late Holocene.

Resilience of Forests, Human-Driven and Climate-Influenced Fires ca. 1,800–1,240 Cal. Year BP

Increasing fire disturbance is likewise documented at Lanzahíta, Serranillos, and Tiemblo ca. 1,800–1,240 cal. year BP (Late Roman and Visigothic periods), with the rising fire frequency (Figure 6). High CHAR peaks are observed at this time in these records at 1,748 and 1,371 (Lanzahíta), 1,401 (Tiemblo), and 1,420 cal. year BP (Serranillos). Pine decreased in Lanzahíta, while olive tree (*O. europaea*) and gum rockrose (*C. ladanifer*) increased from 1,800 to 1,235 cal. year BP. The increase in gum rockrose may be related to more frequent fires. In fact, a sharp CHAR peak is detected at 1,748 cal. year BP (Figures 3 and 5), which coincides with maximum values of *C. ladanifer* and the beginning of olive cultivation in the area (Figure 7). A new high CHAR peak is documented at 1,371 cal. year BP and also corroborates a maximum percentage of gum rockrose at the end of the Visigothic period. The observed increase in fire probably benefitted *C. ladanifer* at Lanzahíta, given that it is sensitive to fire and is a key species helping in recolonization of *P. pinaster* woods after wildfires (Calvo *et al.*, 2003; Gil *et al.*, 2009). For Tiemblo, fire frequency was high up to 1,000 cal. year BP, and while *C. sativa* values softly decrease, olive pollen appears for the first time and anthropogenic pollen taxa increases, particularly during the Visigothic period when a very sharp CHAR peak is observed at 1,401 cal. year BP (Figures 3 and 7). This generalized increase in fire disturbance can be correlated with the cultivation of olive trees at regional scale in the valleys of the Gredos range (López-Sáez *et al.*, 2014). Both olive tree growing and intensive fires could have triggered the shifts recorded on vegetation throughout zone L2, as shown by CHAR analysis of Lanzahíta sequence. The initial sharp peak of CHAR at 1,748 cal. year BP, when the first Roman settlements are reported (Martino, 2004), suggests an anthropic origin for such increase of fire regime bringing about these landscape changes in a humid phase, while the second

Table II. Zone, mean values for selected pollen and non-pollen palynomorph percentages, and CHAR and measures of fire disturbance for Lanzahíta (L1–L5), Tiemblo (T1–T6), and Serranillos (S1–S8)

Zone	Age (cal. year BP)	CHAR ($\times 10^{-1}$)	SNI	Fires (no.)	FRI (years)	Pollen and non-pollen palynomorph percentages							
						Pinus pinaster	*Pinus sylvestris*	Genisteae	Poaceae	*Castanea*	Coprophilous fungi	*Olea*	*Cistus ladanifer*
L5	0–195	13.51	~3	1	261	32–50	<3	—	7–18	<3	2–25	1–6	3–10
L4	195–670	10.67	≥3	2	218	29–65	<3	—	4–13	<3	2–23	—	4–16
L3	670–1235	7.79	≥3	1	696	53–69	<3	—	4–7	<3	<3	—	2–8
L2	1235–1800	16.03	≥3	2	377	29–45	<3	—	9–16	<3	2–15	4–11	2–10
L1	1800–2475	2.95	≥3	0	N/A	52–62	<3	—	5–10	<3	<3	—	<3
T6	0–140	0.52	≥3	1	832	3–7	3–6.5	<3	<3	46–48.6	—	<3	<3
T5	140–430	0.00	≥3	0	N/A	<3	<3	<3	<3	37–46	5–13	<3	<3
T4	430–925	1.64	≥3	0	N/A	<3	<5	<3	<3	34–44.5	6–10	<3	<3
T3	925–1465	7.33	≥3	2	442	2–4	3–6	<3	<3	30.5–38	3–7	2–4	<3
T2	1465–1915	1.08	≥3	0	N/A	<2	8–10	<3	<3	34–41	5	0–1	<3
T1	1915–3140	0.00	0	0	N/A	<5	4–11	<3	<3	31–42	<1	—	<3
S8	0–90	28.22	≥3	0	N/A	<1	10–20	<3	25–50	—	5–13	5–12	<1
S7	90–230	8.75	≥3	1	384	<3	35–58	<5	20	—	4–22	2–4	<1
S6	230–475	11.25	≥3	0	N/A	1–11	20–50	—	19–49	—	<3	1–6	<1
S5	475–800	42.26	≥3	3	277	—	25–42	—	25–50	—	<1	—	1
S4	800–1220	2.18	≥3	0	N/A	<3	56–70	<1	4–15	—	<1	—	<1
S3	1220–1775	7.31	≥3	2	264	<3	45–67	—	5–17	—	<1	<1	<1
S2	1775–1925	1.32	≥3	1	432	5–7	57–69	—	8–19	—	<1	<1	—
S1	1925–2025	0.00	≥3	0	N/A	5–7	60–70	<3	<5	—	<1	—	—

cal. yr BP = calendar years before present; CHAR = charcoal accumulation rate; SNI = signal to noise index; FRI = fire return interval; N/A = not available.

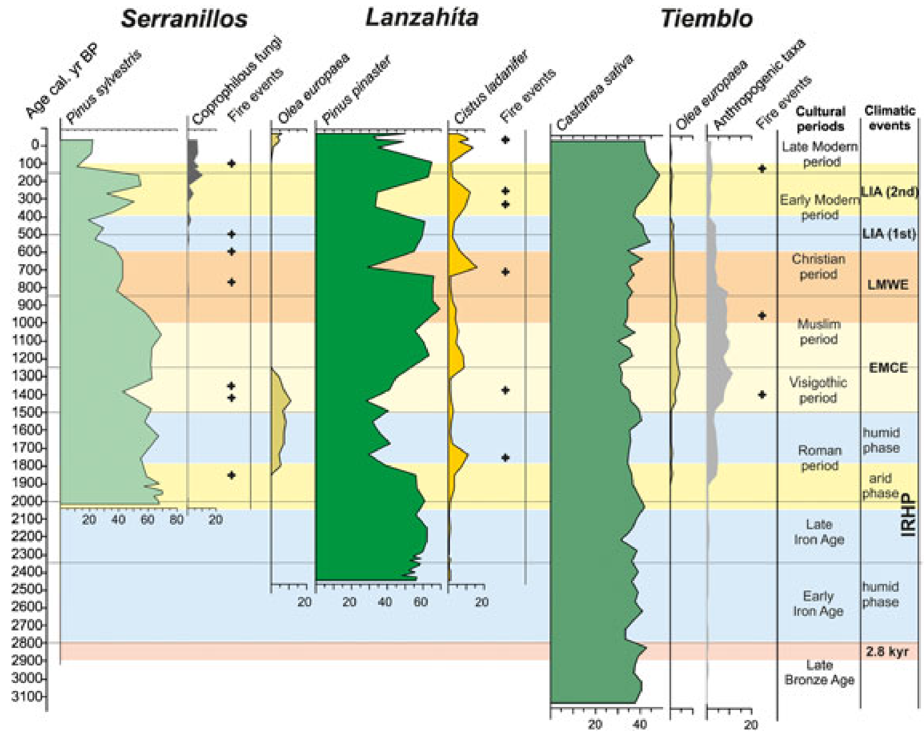

Figure 7. Fire events and pollen abundances from Serranillos, Lanzahíta, and Tiemblo records plotted against age (cal. yr BP) and cultural periods. Color shading corresponds to climatic events discussed in the text (LIA = Little Ice Age; LMWE = Late Medieval Warm Episode; EMCE = Early Medieval Cold Episode; IRHP = Ibero-Roman Humid Period; 2·8 kyr = 2·8 cal. kyr BP event). Coprophilous fungi include *Sordaria* and *Sporormiella*. Anthropogenic taxa types include *Aster*, Cardueae, and Cichorioideae. Pollen and non-pollen palynomorph values are relative to total terrestrial pollen abundance. [Colour figure can be viewed at wileyonlinelibrary.com]

at 1,371 cal. year BP occurs during the Visigothic period, usually considered as a point of no return for the vegetation of mountain areas of the Gredos range (López-Sáez *et al.,* 2014, 2016a).

Taking into account the aforementioned data, there is a curious fire paradox at Lanzahíta because the increase on fire frequency occurs in a humid phase during the Late Roman period (Ibero-Roman Humid Period; Figure 7; Martín-Puertas *et al.,* 2008). Additionally, fire detection from peat bogs is challenging because charcoal taphonomy in peatlands is more variable than that in lakes. Overall, only severe fire years associated with extreme droughts conditions are recorded because they can result in fires that are able to reach the coring location and burn drier peat (Conedera *et al.,* 2009; van Bellen *et al.,* 2012). If fire were related to climate factors only, such as extreme droughts, we should expect fire synchronicity at the regional scale. Here, the lack of synchronicity between the three sites rather argues that climate and extreme droughts are not the only process triggering fires and that human-induced vegetation changes and fire regime can offset the direct influence of climate. In fact, fires appear to be synchronous only ca. 1,800–1,700 cal. year BP for Lanzahíta and Serranillos (Late Roman period) and around 1,400–1,300 cal. year BP (Visigothic period) for the three sites, suggesting anthropogenic fire control in relation to the cultivation of olive trees in the nearby valleys and a greater human impact in high-mountain areas. It is possible, however, that the aforementioned synchrony ca. 1,400–1,300 cal. year BP would also be related to drier and colder climatic conditions at the beginning of the Early Medieval Cold Episode (Martín-Puertas *et al.,* 2008).

From Site Variability to Regional Fire History: Asynchronous Fires ca. 1,240–850 Cal. Year BP

In response to cooling and dryness during the Early Medieval Cold Episode (Martín-Puertas *et al.,* 2008), pine (*P. sylvestris* at Serranillos and *P. pinaster* at Lanzahíta) and chestnut (Tiemblo) forests persisted between 1,500 and 1,000 cal. year BP (Figure 7). Subsequently, the pine forest recovers between 1,235 and 750 cal. year BP in Lanzahíta when olive tree is no longer cultivated between the Muslim period and the beginning of the Christian period. However, gum rockrose pollen percentages remained high after fire frequency declined (Figure 7). In this sense, the increase in *C. ladanifer* values can also respond to the arrival of drier climatic conditions and lower temperatures related to the Early Medieval Cold Episode (1,500–1,000 cal. year BP; Martín-Puertas *et al.,* 2008) that could have been beneficial to *C. ladanifer* at this site (Pérez & Moreno, 1998).

Dry climatic conditions in this chronological interval have also been documented at other sites in the Gredos range (Abel-Schaad & López-Sáez, 2013; López-Sáez *et al.,* 2014, 2016a). Meanwhile, FRIs are shorter in Lanzahíta and Tiemblo between the Visigothic and Muslim periods (Figure 6). While in Lanzahíta and Serranillos it can be assumed that climate affected fire dynamics (fire frequency notably increases from 1,000 cal. year BP; Figure 6), although no sharp CHAR peaks are observed (Figures 3 and 5), in Tiemblo, fire regime is clearly mediated by human activities because in these periods olive cultivation reaches its peak and anthropogenic pollen taxa increase their percentages (Figure 7; Morales-Molino *et al.,* 2015). In fact, a high CHAR peak is documented in Tiemblo at the end of the Muslim period (959 cal. year BP; Figure 3). In summary, during the Muslim period (1,240–850 cal. year BP), fire frequency initially decreases and then increases (Lanzahíta and Serranillos) or remains relatively constant and then decreases (Tiemblo) (Figure 6), demonstrating that fires were asynchronous in the whole of these mountains and essentially related to human activities at Tiemblo, while in the other two records, the increase on fire frequency ca. 1,000 cal. year BP could be correlated with the onset of the Late Medieval Warm Episode.

Grazing versus Climate: Synchronous Fires ca. 850–500 Cal. Year BP

Fire frequency increased apparently in the Gredos range between 850 and 500 cal. year BP as warm conditions related to the Late Medieval Warm Episode prevailed (Desprat *et al.,* 2003; Martín-Puertas *et al.,* 2008). These facts become evident in Serranillos and Lanzahíta, including several high CHAR peaks at 764, 704, 604, and 492 cal. year BP (Figures 3 and 5) and shorter FRIs, but they do not in Tiemblo where fire frequency decreases. During the Christian period (850–500 cal. year BP), a different landscape setting can be observed in Serranillos record with a moderate decrease of *P. sylvestris* forests, which coincides with increasing fire frequency and fire events (Figure 7). This is indicative of anthropogenic forest clearances by means of fire in relation to summer grazing of high-mountain areas (López-Merino *et al.,* 2009) and the Christian repopulation of the highlands of the Tiétar valley (Mariné, 1995). In contrast, the reduction of *P. pinaster* forests and the increase of *C. ladanifer* in Lanzahíta at 675 cal. year BP do not seem to be the result of anthropic activity but rather of a dry and warmer climate. In fact, the new fire episode in Lanzahíta at 704 cal. year BP (Figures 3 and 5) agrees with the transition between two pollen zones (L3–L4), evidencing that this episode was the driver of vegetation change. At this time, *P. pinaster* values drastically decrease (<40%), while those of *C. ladanifer* increase at the end of the Christian period (Figure 7). The increase of gum rockrose seems to be mainly related to a warmer regional climate during the Late Medieval Warm Episode (1,000–600 cal. year BP; Desprat *et al.,* 2003; Martín-Puertas *et al.,* 2008) than with a change in the fire regime. In this sense, the observed changes in the relationship between the canopy and the understory seem to indicate some variation in the physiognomy and floristic composition of pine forests at Lanzahíta peat bog towards open woodlands owing to a mixed-severity fire regime and shorter FRIs (696 years in L3 to 218 years in L4; Table II). In any case, burned Maritime pine forests regenerate quickly after fire (Pérez & Moreno, 1998; Calvo *et al.,* 2003), recovering high pollen values between 670 and 400 cal. year BP (bottom of L4; Figure 7).

Human-mediated and/or Climate-mediated Fires? Complexity of Fire Regime over the Last 500 Years

Fire episodes became more frequent in Lanzahíta from 400 to 195 cal. year BP (top of L4), with two sharp CHAR peaks at 327 and 240 cal. year BP (Figures 3 and 5) coincident with increasing *C. ladanifer* pollen abundance and decreasing *P. pinaster* values (Figure 7). Early Modern period (400–150 cal. year BP) climatic conditions, included in the second phase of the Little Ice Age (400–100 cal. year BP), might have heightened these effects in a period of great climatic complexity characterized by a progressive increase in temperature and extreme events of aridity and rainfall (Desprat *et al.,* 2003). These climate conditions probably caused a shortening of FRIs (218 years in zone L4; Table II). In contrast, no apparent high CHAR peaks are observed at this time in Serranillos and Tiemblo (Figure 3), although in the latter fire, frequency shows an increasing trend from 400 cal. year BP (Figure 6). Therefore, it is difficult to decide whether the fire regime in Lanzahíta in this period was mediated by climate or human activities, because there is no parallelism between the three macrocharcoal records.

After the fire episode at 240 cal. year BP from Lanzahíta, a 260-year fire-free period is documented until −21 cal. year BP coinciding with an increase in *P. pinaster* values (Figure 7). In fact, during this period of decreased fire frequency from 195 cal. year BP to the present (FRI = 261 years), this pollen type remains dominant until 100 cal. year BP while *C. ladanifer* and *O. europaea* increased from this date onwards, and a new sharp CHAR peak is observed at −21 cal. year BP (Figure 3). The inconsistent signal displayed by *P. pinaster* pollen abundance during the last 200 years could be indicating that at Lanzahíta, the fire did not play a significant role in vegetation structuring during the Late Modern period, but vegetation dynamics was essentially determined by human activities.

While in Tiemblo fire frequency continues showing an increasing trend because 200 cal. year BP, in Serranillos, the opposite happens (Figure 6). These facts can be correlated with several fires occurring near Tiemblo record during the 18th and 19th centuries (Palacios, 2013). At Serranillos, a last high CHAR peak is observed at 108 cal. year BP, more or less contemporary of another documented in Tiemblo at 127 cal. year BP. While in Tiemblo this new fire episode hardly influenced the chestnut forest (FRI = 832 years), in Serranillos, the incidence of fires and a high pastoral pressure (maximum values of coprophilous fungi; Figure 7) led to the disappearance of Scots pine forests at 500 cal. year BP, whose percentages below 30% indicate a regional rather than a local origin (López-Sáez *et al.,* 2013). These data seem to suggest that the increase of human-mediated fires and livestock grazing in Serranillos was connected to the decline of Scots pine in the oromediterranean bioclimatic belt (López-Sáez *et al.,* 2016c). Vázquez & Moreno (2001) showed that in the Gredos range, the fire cycle has been accelerated in the 20th century as a result of the dynamics introduced by fire, documenting an average FRI of 6·4 years in burned areas. Scots pine is considered an opportunistic species with high resilience to disturbance thanks to their light-demanding seedlings (Keeley *et al.,* 2012). However, experimental studies of the fire ecology in Iberian *P. sylvestris* populations have shown that this species shows significant problems to regenerate after intense fires (Escudero *et al.,* 1997, 1999; Retana *et al.,* 2002; Rodrigo *et al.,* 2004) as it does not have serotine pine cones (Tapias *et al.,* 2004), dispersing their seeds between late winter and early spring; thus, a greater frequency of forest fires in summer entails the disappearance of most seedlings, limiting the regeneration of this species and affecting its distribution area (Núñez *et al.,* 2008). These experiments also demonstrate that Scots pine finds many difficulties of regeneration in high-mountain pasturelands when competing with diverse herbaceous species (Castro *et al.,* 2002).

CONCLUSIONS

The landscape of the Gredos range has behaved during the last millennia as a dynamic system thanks to its topographical heterogeneity, varied vegetation, human settlement patterns, and fire history, containing different types of forests with distinct susceptibilities to fire. The sediment-charcoal analysis of three peat bog records has allowed unraveling the fire history of the Gredos range (Iberian Central System, central Spain) during the late Holocene. Understanding the complex interactions between fire, climate, and anthropic activity is of paramount importance, in order to establish measures of protection against landscape degradation. Paleofire histories for the three sites demonstrate coeval changes on fire frequency, similar FRI distributions, and millennial-scale synchrony. However, the fire signal also shows substantial differences among the three sites, which suggests that the fire regime also depends on the environmental gradient and local type factors separating warmer southern (Lanzahíta) from cooler sites to the north (Tiemblo), and both from the one located at higher altitude (Serranillos).

The regional susceptibility to fire of each of the studied vegetation types in the Gredos range appears to be the result of several factors, sometimes complementary, such as ignition trends, climatic variability, forest management practices, and floristic composition, as well as fire-fighting strategies and effectiveness (Viedma, 2008; Moreno *et al.,* 2011). CHAR background and pollen data indicate that forests were relatively dense and capable to withstanding fires between 3,140 and 1,800 cal. year BP in both the oromediterranean and supramediterranean bioclimatic belts. Synchrony between 1,800 and 1,240 cal. year BP suggests that fire regime was controlled by regional anthropic activities during the Late Roman and Visigothic periods, particularly by olive growing in the valleys and a greater human impact in high-mountain areas. Asynchronous fire episodes between 1,240 and 850 cal. year BP suggest, instead, that local controls on fire activity, such as fuel availability and orography, were important during the Muslim period. These facts seem to rather respond to existing differences in vegetation composition, climatic conditioning, and the heterogeneity of the settlement pattern and land use in each of the studied records.

One of the most noteworthy results of our paleofire analysis has been the documentation of a period in which fire episodes are synchronous between 850 and 500 cal. year BP (Christian period), with increases in CHAR background, fire frequency, and fire events, especially at Lanzahíta and Serranillos, during the warmth of the Late Medieval Warm Episode. However, such synchrony not only does respond to climatic variability but is rather due to high human impact in the case of Serranillos. Very low CHAR at Tiemblo could be related to a certain type of limitation on the spread of fire at mid-elevations or reduced forest fuel availability, for example, under cooler summer temperatures. It could be also linked to the fact that chestnut forest is constantly under anthropic management for the exploitation of its fruits (chestnuts) and timber, making it more difficult to burn (Seijo *et al.,* 2016). Fire has been also a major disturbance affecting Gredos range landscapes during the last 300 years (Modern period), when both fire frequency and fire episodes have increased in these mountains. The reason could lie on the progressive land abandonment and degradation, with the consequent proliferation of shrubs, and the development of afforestation policies of former pasturelands, leading to the increase of accumulated fuel biomass.

Resilience to fire in the Gredos range appears to be mediated by the interaction between the severity and duration of each fire episode and the adaptive traits of forest species involved in the postfire response, but also by the particular human history of each area and land use patterns. Our paleofire record suggests that the most fire-resilient forests were those that showed a rapid recovery against high fire frequency and fire events, that is, *P. pinaster* in Lanzahíta, while those associated with low combustibility areas (i.e., *C. sativa* in Tiemblo) show a less obvious fire behavior further than the effects of fire on their forests are lower than in conifer ones. In contrast, human-driven land use changes in high-mountain environments (i.e., Serranillos) interacted with physical environment and fire in the last 300 years, supporting the spatio-temporal dynamics of *P. sylvestris* forests extinction when a susceptible threshold was reached.

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