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The Iberian Peninsula's Burning Heart—Long-Term Fire History in the Toledo Mountains (Central Spain)

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Abstract: Long-term fire ecology can help to better understand the major role played by fire in driving vegetation composition and structure over decadal to millennial timescales, along with climate change and human agency, especially in fire-prone areas such as the Mediterranean basin. Investigating past ecosystem dynamics in response to changing fire activity, climate, and land use, and how these landscape drivers interact in the long-term is needed for efficient nature management, protection, and restoration. The Toledo Mountains of central Spain are a mid-elevation mountain complex with scarce current anthropic intervention located on the westernmost edge of the Mediterranean basin. These features provide a perfect setting to study patterns of late Holocene fire activity and landscape transformation. Here, we have combined macroscopic charcoal analysis with palynological data in three peat sequences (El Perro, Brezoso, and Viñuelas mires) to reconstruct fire regimes during recent millennia and their linkages to changes in vegetation, land use, and climatic conditions. During a first phase (5000–3000 cal. BP) characterized by mixed oak woodlands and low anthropogenic impact, climate exerted an evident influence over fire regimes. Later, the data show two phases of increasing human influence dated at 3000–500 cal. BP and 500 cal. BP–present, which translated into significant changes in fire regimes increasingly driven by human activity. These results contribute to prove how fire regimes have changed along with human societies, being more related to land use and less dependent on climatic cycles.

Keywords: fire regimes; paleoecology; fire ecology; Toledo Mountains; paleofire R-package; global charcoal database

1. Introduction

Fire has been perceived as a dramatic hazard despite its early and deep presence in the Mediterranean basin. In fact, it has played an essential role in defining the landscapes and biota present there, so much so that fire became an intrinsic component of the Mediterranean cultures [1–4]. On top of that, fire has long been used in the Mediterranean region as a major tool for landscape transformation and management by human communities [5–8]. Indeed, a great number of human activities are linked to the use of fire in the Mediterranean basin, which has led to extremely short fire

return intervals, usually below 100 years and sometimes even shorter [9,10]. Therefore, it is clear that fire is part of Mediterranean ecosystems. This makes it impossible to understand their evolution and current dynamics without looking at the role played by fire through time [3,11–16].

Fire has driven the distribution, structure, and composition of Mediterranean ecosystems, building time-since-fire mosaic patterns and increasing the biodiversity in some areas [6,10,17,18]. It also plays an important role in determining communities' susceptibility to many other hazards, such as floods or resprouting ability [19,20].

However, fire regimes do not show a strict and uniform pattern in time and space [21–23]. Fire occurrence is determined by many interlinked factors, such as vegetation dynamics, climatic conditions, and land use, among others. Vegetation composition and structure regulate the availability, flammability, and amount of fuel present in every landscape [10,13,24]. At the same time, it is necessary to point out those climatic drivers such as temperature and precipitation, regulating the amount of biomass and fuel available in the ecosystem and humidity or dryness controlling fuel ignition [13,21]. Furthermore, fire can start by natural causes or mediated by humans, which also plays an important role in the fire regime. Despite the importance of this element in human management, some activities such as grazing or different land use (e.g., agricultural and urban patterns) modify the occurrence of fires [10,13,24,25]. Therefore, there is a need to understand fire history in the Mediterranean area and the relationship between all the actors involved in the fire regime. The current fire dynamic is a consequence of the past fire regimes but despite the adaptations, fire has become a threat for ecosystems and human communities because of the changes in the fire regime drivers [3,12,26]. This circumstance brings uncertainty to the future because some new changes are expected and this makes it difficult to choose the best management goals which could take into account the many involved factors and helped to preserve ecological richness and land use interests, for example [3,7,26–28].

Different methods to reconstruct past fire regimes have been developed, such as fire scars and historical data, but these rarely allow researchers to go back longer than several centuries [15,29]. Here is where sedimentary charcoal records emerge as the best tool for reconstructing fire history, given that multi-millennial records are relatively frequent [30,31]. Fire occurrence can be inferred from the charcoal deposited in lake sediments and peatlands, among other natural deposits. Charcoal accumulation rates are actually a proxy for the biomass burnt in an area during one fire episode, which may in turn embrace one or several fire events depending on the time resolution of sediment record and the subsequent sampling [28,32]. Both theoretical and empirical research on charcoal dispersal has shown that peaks in the deposition of macroscopic charcoal particles are commonly associated with local fire events mostly occurring in the study catchment and adjacent areas; meanwhile sieved charcoal is more accurate at showing local fires [33–38]. Therefore, the so-called "peak detection analysis" is often used to reconstruct local fire regimes [10,14,26,33].

In this paper, we use macroscopic charcoal series from three mires located in different areas of the Toledo Mountains, in the heart of the Iberian Peninsula, to reconstruct historical fire regimes in the region. The diverse locations and historical development could highlight unequal fire patterns related to the physical and socio-economical features of these lands. We have focused on the possible occurrence of common trends and their causes as well as the divergences between the reconstructions. By comparing the fire history reconstructions with vegetation and land use records from the study sites, we have assessed whether climate change or human activities took the lead in driving fire activity in these mid-elevation mountains of central Spain and the impact of fire on long-term vegetation dynamics. Furthermore, we have compared the regional fire activity of the Toledo Mountains with the general trends in Spain. Finally, we provide some management guidelines inspired by the inferences taken from the fossil charcoal records.

2. Materials and Methods

2.1. Study Area

The Toledo Mountains is a west-to-east-aligned mid-mountain range complex located in central Spain, between Toledo and Ciudad Real provinces (Figure 1). This mountain chain extends over more than 3800 km^2 at the western side of the southern Iberian plateau, where it separates the River Tagus and River Guadiana's basins. Eastwards, the Toledo Mountains border La Mancha plain [39,40]. The average height of this mid-mountain complex is 800–1100 m.a.s.l. [39,41]. One of the most typical geomorphological features of this mid-mountain area is the locally named *rañas*, ramp alluvial/colluvial deposits located at the foothills of the main massifs [39].

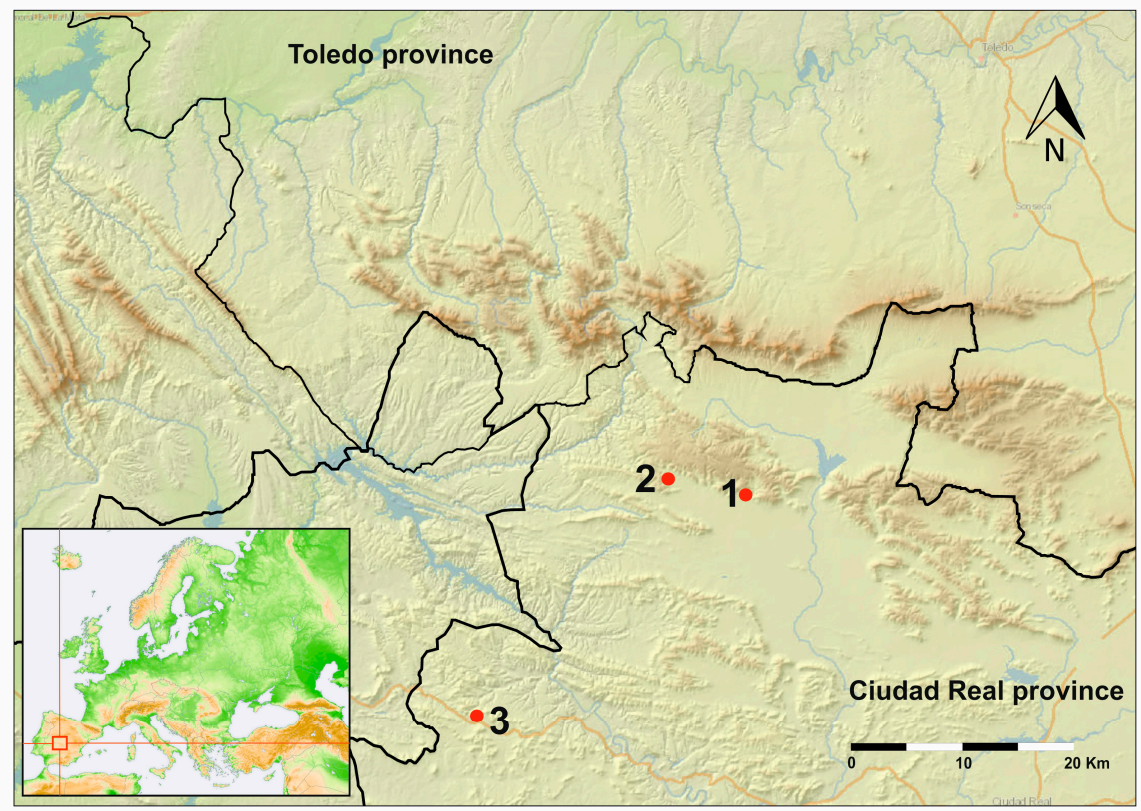

Figure 1. Map of the Toledo Mountains in central Spain with location of the selected peatlands (red dots): **1**. Brezoso [42,43]; **2**. Viñuelas [43]; **3**. El Perro [this paper].

The climate of the Toledo Mountains is predominantly Mediterranean, with dry and warm summers, cold and wet winters, and the usual occurrence of extreme events such as severe droughts and floods. The western side of the range receives certain oceanic influence related to the westerlies (lower seasonality, higher rainfall). The average annual temperature is 17 °C and the mean annual rainfall oscillates between 600 and 800 mm [40,41,44]. The vegetation in the Toledo Mountains meso-Mediterranean foothills is mainly composed of holm oak (*Quercus ilex* subsp. *ballota*) and cork oak (*Q. suber*) woodlands. Holm oak-dominated communities usually include meso-thermophilous taxa such as *Arbutus unedo*, *Phillyrea angustifolia*, *Pistacia terebinthus*, or *Pyrus bourgaeana*. The *Quercus suber* woodlands are also often associated with deciduous trees such as *Quercus faginea* subsp. *broteroi*, *Q. pyrenaica* and *Acer monspessulanum*, on moister settings. Deciduous *Quercus pyrenaica* forests are dominant in the supra-Mediterranean belt (roughly above 1000 m a.s.l.). There also are some pine reforestations in the Toledo Mountains, carried out during the second half of the 20th century. The Toledo Mountains host some of the southernmost populations of several temperate and Atlantic species such as *Myrica gale*, *Corylus avellana*, *Betula pendula*, *or B. pubescens* [42,43,45–47].

Previous research has identified more than 130 peatlands in the Toledo Mountains, most of them located in the Ciudad Real province. Despite this optimistic number, these peatlands present a limited extension (the smallest mire presents a surface of 0.02 ha and the largest 113.6 ha, but the average extension is around 4.5 ha) [40]. The Toledo Mountains peatlands are mainly minerotrophic mires formed by terrestrialization and connected to groundwater discharge in springs or to impeded stream flow in the *rañas* [40].

For this study, three mires have been selected (Table 1, Figure 1) based on their different situations into the mountainous complex. They are in the Ciudad Real province, on the northern and southern sectors of the Toledo Mountains, helping us to discern whether fire history significantly differed in these two areas during recent millennia. In addition, Viñuelas and Brezoso are in higher and more difficult-to-access locations, meanwhile El Perro mire is close to the valley, nearer to the populated area. Some of the mires present in these provinces are protected under the Natura 2000 Network and by specific strategies created inside the Spanish and Provincial laws, such as micro-reserves, river reserves, or the most important figure: national parks. Brezoso and Viñuelas mires are under this particular protection plan [40]. Despite efforts the different authorities have made to guarantee the protection of these special ecosystems, they have to face several threats such as drainage (Brezoso and El Perro), erosion (Viñuelas, Brezoso, and El Perro), and trampling/overgrazing by wild ungulates (Viñuelas, Brezoso), among others. Just to illustrate the relevance of these degradation processes, intensive drainage to reclaim land for agricultural purposes has led peat accumulation to stop at El Perro mire [40,42,43].

Table 1. Main features of the studied peatlands. Nutrients source: M = minerotrophic. Protection: RNP = reserve national park; NP = Non-protected.

Name	Municipality	Latitude	Longitude	Altitude (m.a.s.l.)	Area (ha)	Nutrients	Protection
Brezoso	Alcoba de los Montes	39°20′56.69′′ N	4°21′39.80′′ W	733	10.62	M	RNP
Viñuelas	Alcoba de los Montes	39°22′28.00′′ N	4°29′18.08′′ W	761	0.02	M	RNP
El Perro	Puebla de don Rodrigo	39°3′51.49′′ N	4°45′20.25′′ W	690	3.74	M	NP

2.2. Sampling and Chronology

A Russian peat sampler (5 cm diameter) was used to core El Perro mire. In the field, peat sections were placed in PVC tubes, and later, in the laboratory, they were stored under dark and cold conditions (4 °C). The core was then subsampled into contiguous 1 cm thick slices. The chronology of the El Perro peat sequence was established by means of 11 AMS (accelerator mass spectrometry) ^{14}C dates on peat samples. AMS dating was conducted at the Poznán (Poznán, Poland) and Belfast (United Kingdom) radiocarbon laboratories. The radiocarbon dates were converted to calendar years using the software CALIB 7.1 with the IntCal13 calibration curve [48]. Post-bomb samples (i.e., younger than 1950 CE = 0 cal. BP) were treated according to Hua and Barbetti [49]. Finally, an age–depth model was produced fitting a smoothing spline (smoothing parameter=0.2) to the accepted radiocarbon dates using the R-Package "clam" [50,51] running in R 3.2.2. (Table 2, Figure 2). Confidence intervals of the calibrations and the age–depth model were calculated at 95% (2σ) with 1000 iterations (Table 2). The chronology of the Brezoso and Viñuelas paleo-ecological records is also based on AMS radiocarbon dating of terrestrial plant macrofossils and peat (the reader is referred to [42,43] for details), and the age–depth relationships were also modelled using smoothing splines fitted with clam (details in [42,43] for Brezoso and in [43] for Viñuelas).

Table 2. AMS radiocarbon data with 2σ range of calibrated ages from El Perro mire.

Laboratory Code	Depth (cm)	^{14}C Age (BP)	Calibrated Age (cal. BP, 2σ)	Calibrated age (cal. BP, Average Probability)
Ua-55290	20	122.3 ± 0.3	−6.04–(−5.56)	−5.8
Ua-55291	40	185 ± 25	0–294	181
Poz-84254	52	955 ± 30	796–927	855
Ua-55292	60	2345 ± 27	2324–2439	2352
Poz-84255	68	2485 ± 30	2438–2724	2585
Ua-55293	75	2594 ± 27	2719–2762	2743
Ua-55294	84	3445 ± 31	3632–3828	3704
Poz-84256	90	3830 ± 35	4099–4406	4232
Ua-55295	95	4148 ± 31	4575–4824	4693
Poz-84257	99	6470 ± 40	7293–7457	7376

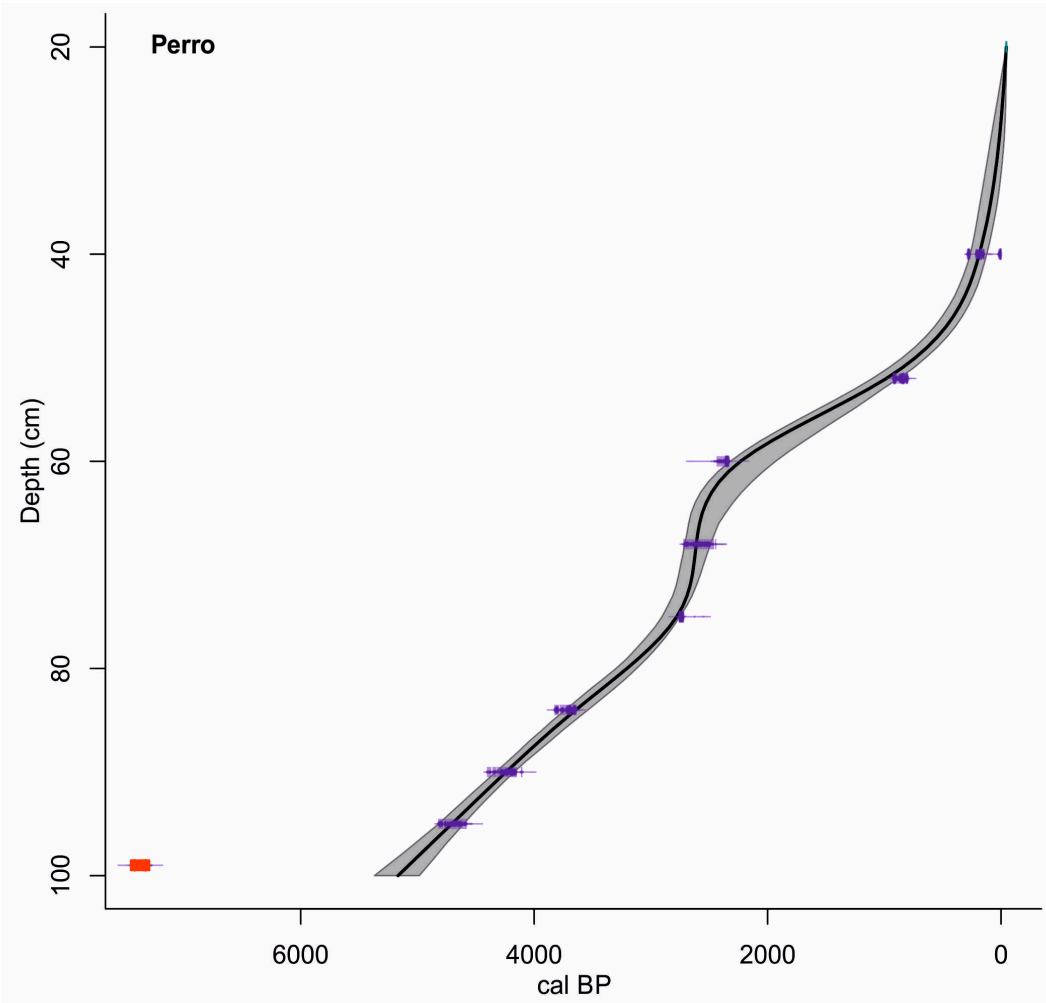

Figure 2. Age–depth model of El Perro mire. The red mark represents an outlier.

2.3. Pollen Analysis

Pollen analysis was carried out along El Perro, Brezoso, and Viñuelas following the methods described by Moore [52] treated with hydrochloric acid (HCl), potassium hydroxide (KOH), and hydrofluoric acid (HF) for removing carbonates, silicates, and organic matter, respectively. The El Perro pollen samples were recovered using Thoulet solution [53]; meanwhile Brezoso and Viñuelas were sieved using a 250 µm mesh and decanted. Lycopodium tablets were added to the samples to estimate the pollen concentration [42,43,54].

Palynomorphs were identified using different pollen atlases and keys [52,55–57]. Betula, Myrica and Corylus pollen types were identified following [46,58], and Erica pollen types according to [59]. Pollen diagrams have been plotted against depth and age using TGview [60].

2.4. Charcoal Analysis

For macroscopic charcoal analysis, we treated contiguous 1 cm thick subsamples of 1 cm^3 volume throughout the El Perro sequence [33,61], soaking them in a 10% KOH solution for 24 h and then adding 15% H_2O_2 for 24 h to bleach the uncharred organic matter. The sediment was then sieved through a 125 µm mesh, and we finally counted the number of charcoal particles in each sample under the stereomicroscope. We also included in this study the previously published macroscopic charcoal series from Brezoso and Viñuelas [43], which also consist of contiguous 1 cm thick 1 cm^3 samples, treated in a different laboratory following a slightly different but comparable protocol (100 µm instead of 125 µm mesh size and sodium hexametaphosphate as deflocculant agent instead of KOH; see details in [43]). In any case, those differences do not affect either the statistical treatment of the data nor the obtained results, so they are completely comparable.

Charcoal analysis has been run with MATLAB and R, using CharAnalysis software [26,30,62] and Paleofire R-Package [63]. These analyses are based on the charcoal accumulation rates (CHAR) curve decomposition by two main elements: CHARbackground (Cback) and CHARpeak (Cpeak) [27]. The first one is the slow trend variation charcoal income, related with the regional fire event charcoal production and adds some noise to the charcoal records; meanwhile, Cpeak, superimposed data over the Cback, is related to the local fire events [22,64,65].

The analysis requires a pre-treatment step which interpolates to the median resolution CHAR data to correct the temporal variability and the bias produced by the different sedimentation rates which could shadow many of the smallest charcoal accumulation data. Once the CHAR has been interpolated, it is necessary to apply some smooth trends for detrending CHAR, obtaining Cback and Cpeak. In this case, all the 5 possible smoothing methods available within CharAnalysis have been applied for finding the Cback [31] using a smoothing window width ranging from 100 to 1500 years such as t=100, 175, 200, . . . , 1500. In total, for each site we obtained a $5 \times 55 = 275$ reconstructions ensemble member. Cpeak has been obtained by subtracting Cback to interpolated CHAR (Ci-Cback) [26].

Cpeak curve is still composed by the Cnoise, which is the statistical noise derived from charcoal accumulation, mixing, and redeposition, and Cfire, related to the occurrence of one or more fires in the site's catchment area, hereafter referred as fire events. They have been obtained and separated by using a Gaussian mixture model, following the recommendations made by Gavin et al. [27], using a 99th-percentile threshold in each reconstruction for separate both components. The local threshold has been applied using a 500-year time window [26]. We identified fire events corresponding to one or more fires in the mire catchment area. Given the short fire return intervals in the Mediterranean area, the time resolution of paleo-ecological analysis is too coarse to identify, without uncertainty, single fire events. Then fire peak may correspond to one or multiple fire events. A signal-to-noise index (SNI) has been used to select all members (i.e., analysis reiterations) with a median SNI > 3 [66]. We used 75% agreement between the members for a fire episode that is considered to be a statistically robust fire event [10].

Fire frequency was estimated using kernel density estimation with a width of 250 years. Bootstrapped 95% confidence intervals around the fire frequency were established by a bootstrap resampling of the kernel density estimation using the Paleofire R-Package [50,67]. Those data help to better understand the changes in the fire regime trends [10,63]. Fire return interval was calculated using the lagged differences function in R using the robust fire events found in previous steps in the analysis.

2.5. Fire Synchrony

We used the Ripley K-function simplified for one dimension to test whether fire events in the three sites co-occur more than would be expected by chance. To do this, we calculated the bivariate K-function and its transform (L) using an edge correction; the function was computed for T/2 years where T is the length in years of the longest record (here T/2 was 2000 years). Then, we assessed 95% confidence envelope around the L-function by randomizing the fire events of the three sites 200 times. The analysis was run using the K1D software v1.2 [64]. The L-function lying above or below the confidence envelope indicated significant synchrony or asynchrony. When the L-function was between the envelope it indicated an independence of fire occurrence for the three sites. For details on the Ripley K-function the reader may refer to [64,68,69].

2.6. Sites Comparison

Compositing of multiple charcoal records from different settings, with different methods and trends, has been recognized for almost two decades as a way to understand trends in biomass burning and global past fire emissions [33,70]. Site comparison has been made using R and the pf.CompositeLF function included in the Paleofire R-Package [63,70]. As for the CHAR analysis it is necessary to interpolate the data before any comparison to reduce the bias due to the different sedimentation rates and the temporal resolution anomalies present in the studied cores due to their different natures. The data produced in the Toledo Mountains have been compared to those 33 available sites for the Iberian Peninsula in the Global Charcoal Database. We used the same procedure as for comparing the three selected Toledo Mountains sites (see above). At the same time, we conducted a Kruskal–Wallis test to understand the statistical differences between the compared composites (Table S1) [13,63].

3. Results and Discussion

The results show different charcoal accumulation trends for the three studied mires. Mean CHAR are variable in the studied sequences (Figure 3), with the highest mean values at Viñuelas (26.22 # cm^{-2} $year^{-1}$), followed by Brezoso (8.64 # cm^{-2} $year^{-1}$), and finally the lowest accumulation rate at El Perro (4.1 # cm^{-2} $year^{-1}$). In all the records, it is possible to see a major fire activity in the oldest samples, a second period between 3000 and 500 cal. BP with variable results, and one last significant change in the last five hundred years in the three records. (Figures 3, A1 and A3 in Appendix A).

3.1. Fire along the Time: First Sights

The Brezoso mire charcoal record shows an overall high fire activity, with very high CHAR values at the bottom of the sequence and comparatively moderate to low values in the rest of the samples (Figures 3 and A2 in Appendix A). Altogether, 17 robust fire episodes have been identified along the sequence. On the other hand, CHAR values are highest in the middle section of the Viñuelas sequence (Figure 3). Apart from a minor peak around 3900 cal. BP, CHAR are mostly low (3–4 # cm^{-2} $year^{-1}$) until ca. 3200 cal. BP, when an increasing trend begins. The Kruskal–Wallis test corroborates this perception, separating three major phases regarding the values of CHAR (Figure A3 in Appendix A). In this case, 7 fire episodes have been detected along the record (Figures 3–5). Finally, El Perro CHAR and fire frequency curves follow an overall gently ascending trend, especially evident from 1000–500 cal. BP. It is particularly remarkable the low amount of biomass burning registered at the bottom of the record, with CHAR values ranging from 0.7 to 2.12 # cm^{-2} $year^{-1}$ between ca. 5000 to 3750 cal. BP, from when CHAR begins to increase. The second part of the record, until ca. 400 cal. BP, shows rather continuous moderate CHAR values indicative of enhanced biomass burning. Subsequently, a sharp increase in CHAR starts at ca. 400 cal. BP, which leads to the highest CHAR values of the whole sequence (28.28 # cm^{-2} $year^{-1}$ in the peak at ca. 90 cal. BP, Figure 3).

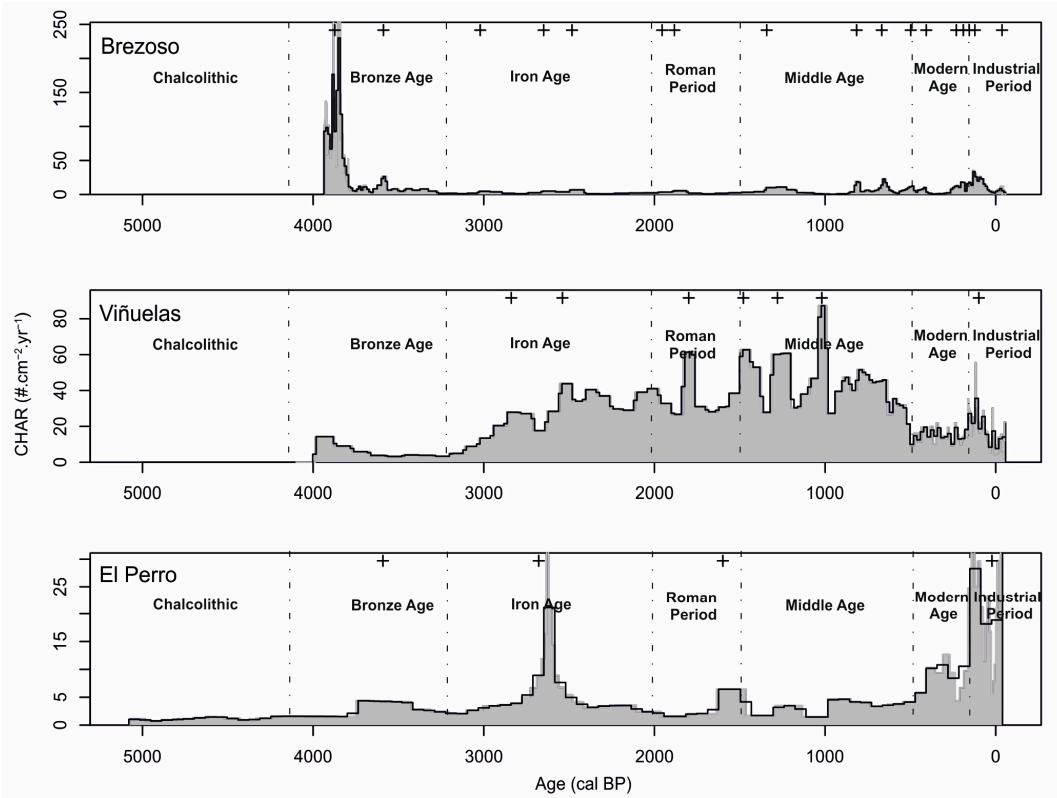

Figure 3. Charcoal accumulation rates (CHAR) and robust fire events for (**top**) Brezoso, (**middle**) Viñuelas, and (**bottom**) El Perro mires. "+" denotes statistically robust fire events. The grey areas correspond to raw charcoal data while the black lines correspond to CHAR interpolated to the median resolution of the records. Note the different scale of the Y axes.

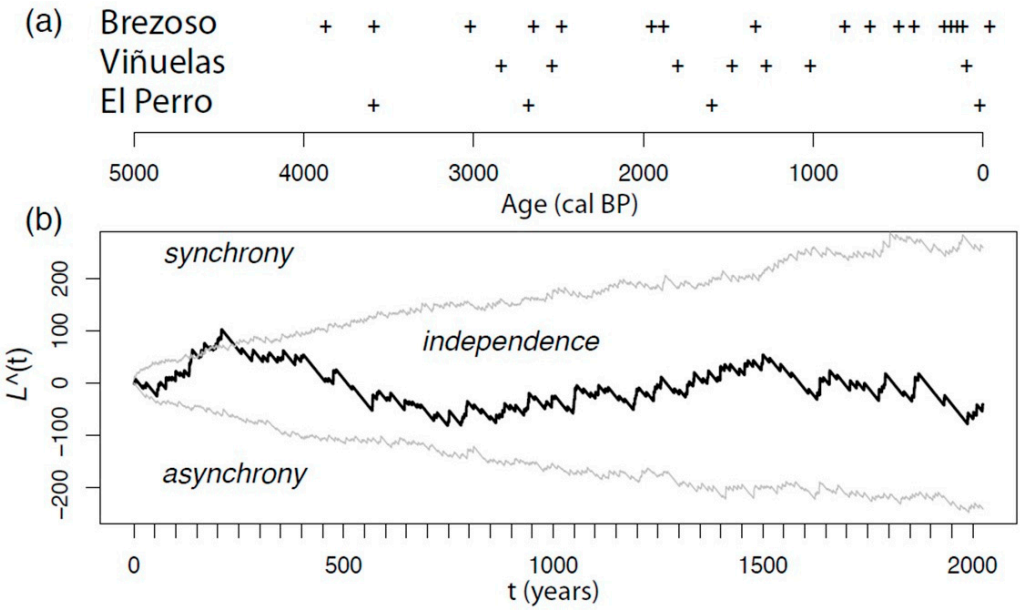

Figure 4. Fire synchronicity. (**a**) Timing of fire events in the three records. "+" denotes statistically robust fire events. (**b**) The L-function (transform of the K-function) for the events in (a) with 95% confidence envelope (thin grey lines) based on 1000 randomizations. The function exceeds the upper confidence envelop from 150 to 250 years, indicating strong correlation of event times within windows of that scale, but lack of long-term patterns in the three records for longer windows, i.e., independence in fire occurrence.

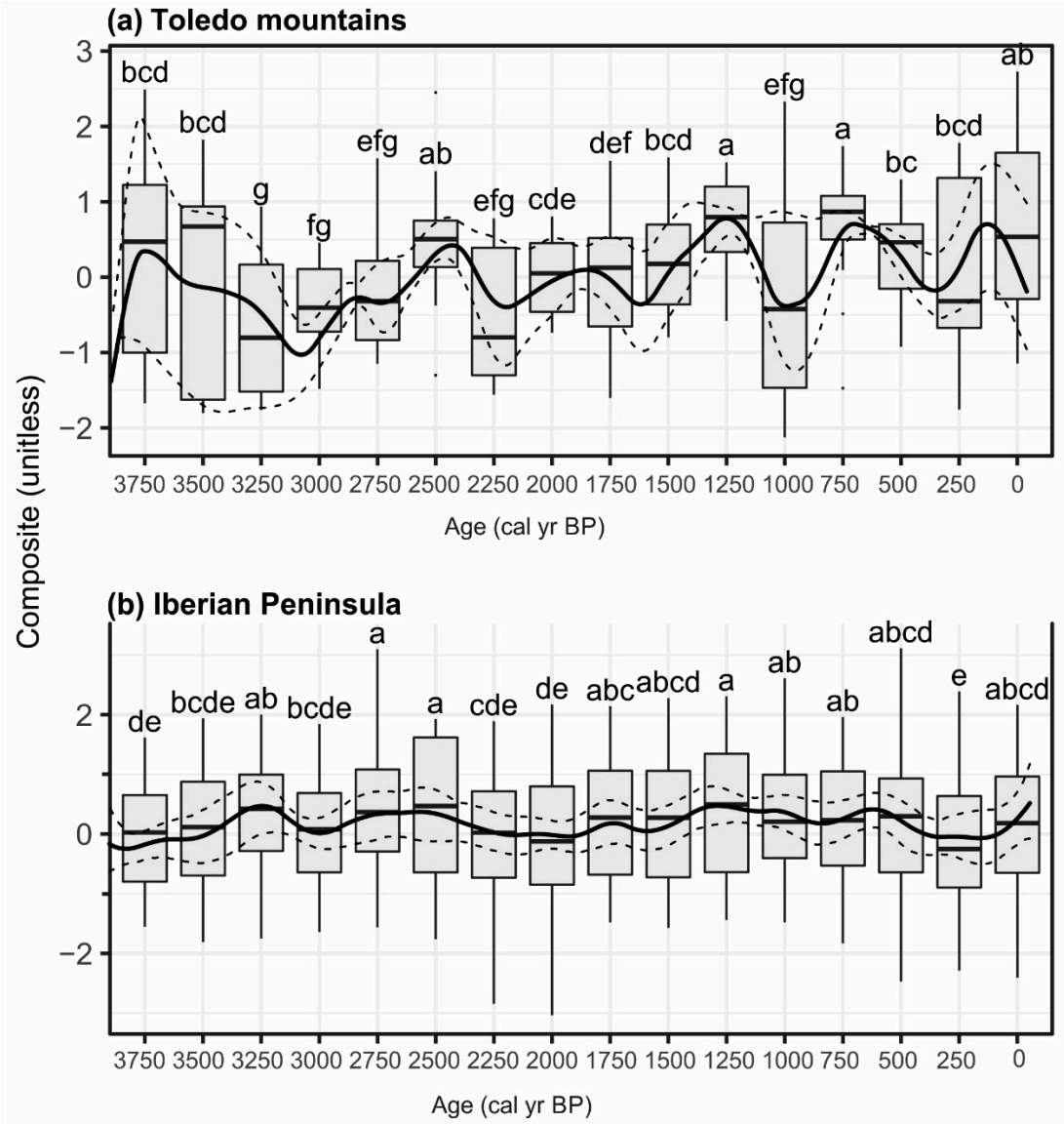

Figure 5. Composite curve of fire history in the three studied sites (**a**) and the entire Iberian Peninsula (**b**). Data obtained from the Global Charcoal Database [63], the complete list of sites used to construct the Iberian Peninsula composite curve are in supplementary Table S1. This study was combined with a Kruskal–Wallis tests to better perceive the similarities and differences between trends in both composites.

There are noticeable differences in the mean fire return intervals shown by the mires: 244 years in Brezoso, 296 years in Viñuelas, and 548 years in El Perro (Figure A1 in Appendix A). However, despite the large differences in fire return intervals and fire frequencies (Figure A1 in Appendix A), it is possible to discern some patterns, as shown in the L-function (transform of the K-function) [64]. It has been run for the fire events represented in (a) with 95% confidence envelope based on 1000 randomizations and it shows a fire recurrence within 150–250 years, which points through a growing human influence in the fire regime in the Toledo Mountains since shorter fire intervals are related with human land management more than climatic trends, something visible in the pollen data [13] (Figure 4).

Previous studies have widely proved the importance of fire in defining the structure, composition, and distribution of Mediterranean ecosystems [24,71], and this holds particularly true for the Iberian Peninsula. During the early and middle Holocene, a drier climate favored the occurrence of particularly frequent and severe fire events modifying the entire landscape [4,9,12], whereas late Holocene fire history is mainly human-mediated. Fire has been used as a tool to manage the environment, increasing

or improving the available resources, creating new spaces for crops or livestock [10,72]. This use of fire as a management tool is especially relevant in mountainous lands, although some authors have questioned the importance of human influence in shaping mountain landscapes during the middle Holocene [73]. In fact, many studies have demonstrated the essential role that human societies have had in these spaces, by using the resources, clearing the vegetation for crop cultivation and livestock, raising even to the point of developing an unquestionable co-evolution [10,74,75].

Despite the above-mentioned importance of this element in the Iberian Peninsula, fire history in the Toledo Mountains does not match the general trends reconstructed from the Iberian Peninsula fire records, as is evident in Figure 5, nor shows a regular pattern in the whole territory. As Figure 5 reflects, there is a lack of resemblance between general trends of the Iberian charcoal records and the selected sequences from the Toledo Mountains. Although through the core it is possible to find some minimum correlations as it highlights the Kruskal–Wallis tests, it is easy to see how different the trends are. Nevertheless, it is possible to find agreement between the periods centered in 1250 cal. BP, where the Kruskal–Wallis tests shows statistical significance between the Iberian Peninsula and the Toledo Mountains records. Apart from that, it is possible to find partial matches between the trends in the Toledo Mountains and the Iberian Peninsula, i.e., in the period centered at 3500 cal. BP and 2500 cal. BP.

In the Toledo Mountains records, there is certain resemblance in the timing of the reconstructed changes in fire regimes. For instance, between ca. 4000–3000 cal. BP, fire occurrence tends to increase in the Iberian Peninsula as a whole while it seems to diminish in the Toledo Mountains. This disagreement is easily visible in Figure 5 and statistically different, as the Kruskal–Wallis tests highlighted, finding only partial agreement in the period centered in 3500 cal. BP. There is more disagreement in the oldest moments of the record, as is possible to see in Figure 5. Until around 2500 cal. BP the fire activity recorded from the Iberian Peninsula and the Toledo Mountains is statistically different one from the other, except for the beginning of the core, when some significance is registered. From around 2000 cal. BP onwards, it is possible to find more agreement between the composites, although only there is a perfect match between the fire records in the above-mentioned events around 1500–1250 cal. BP. In the last part of the record, the agreement is once again scarce, although some similarities can be recognized in the fire activity in the comparison, as the Kruskal–Wallis tests show (Figure 5).

3.2. Climatic Influence: from 5000–3000 cal. BP

The first part of the El Perro charcoal record, from 5000 to 3000 cal. BP, shows an overall, although soft, rise in fire activity with increasing CHAR values (Figure 3). Additionally, the fire regime reconstructions depict increasing fire frequencies in all the sites for this period (Figure A1 in Appendix A). Dry pulses during the 4.2 ka event (*ca.* 4300–3800 cal. BP) [76–80] provide a favorable setting for fire spread as suggested by the Brezoso and, to a lesser extent, the Viñuelas charcoal records [76–78]. Indeed, the largest CHAR values of the last 4000 years are recorded at Brezoso from 3900 to 3800 cal. BP (53.29–230.06 # cm^{-2} $year^{-1}$), which is corroborated by the Kruskal–Wallis test (Figure A3 in Appendix A). Peak detection suggests the occurrence of two fire episodes with a severe impact on the surrounding vegetation [42,43]. Thus, *Quercus* woodlands retreated while disturbance-tolerant communities such as *Betula* woods and Mediterranean shrublands dominated by *Erica* expanded [42,43,81]. Minor increases in Asteraceae, Poaceae, and anthropic herbs (see Figure 6 and [42]) point to a discrete but constant presence of human activity in the area. Similarly, discontinuous occurrences of cereal pollen grains suggest that cereal cultivation occurred not far from the mire but was not widespread (Figure 6).

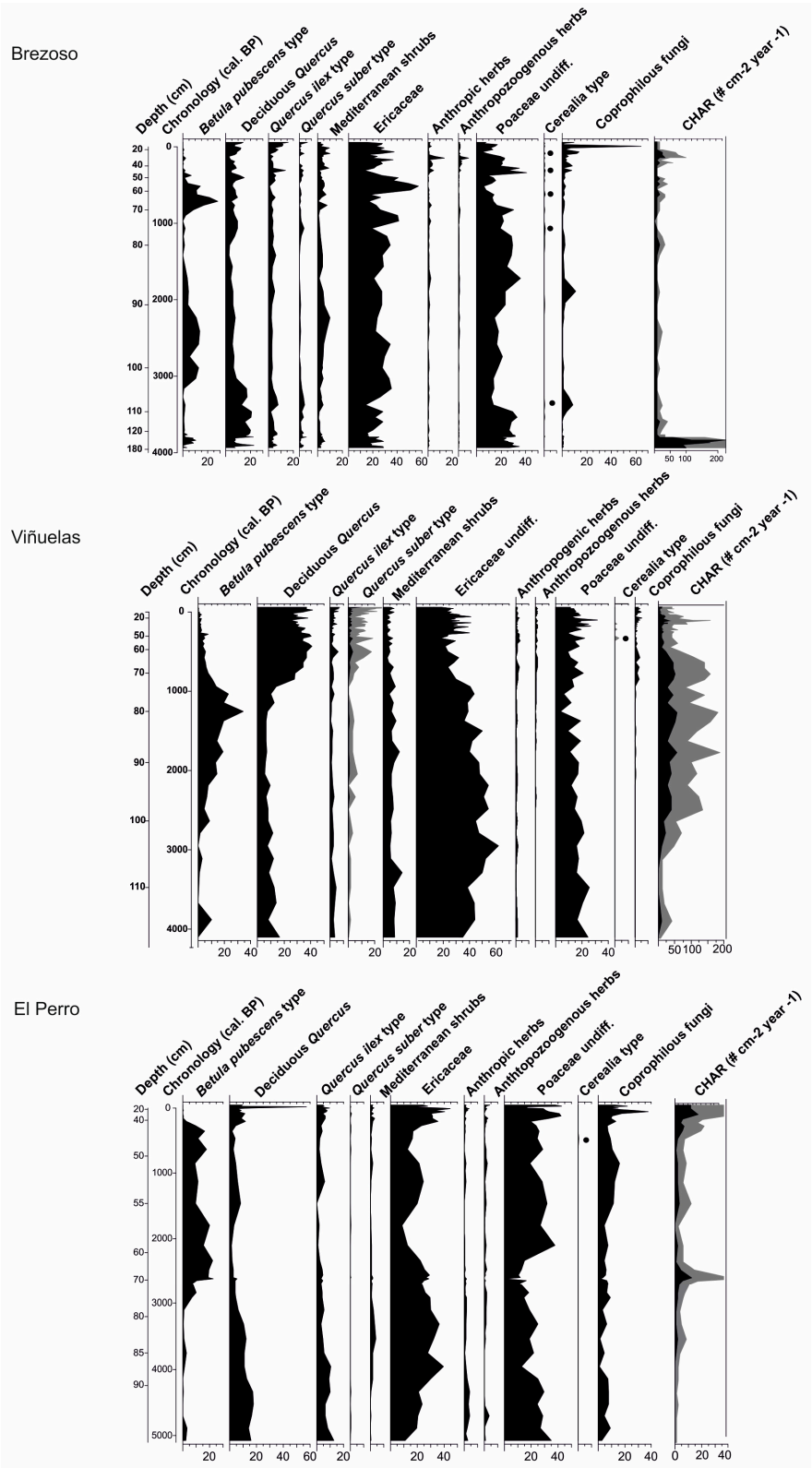

Figure 6. Summary percentage pollen diagrams of the (**top**) Brezoso, (**middle**) Viñuelas, and (**bottom**) El Perro mires. Dots represent percentages below 0.5%. Mediterranean shrubs: *Cystus*; *Phillyrea*. Anthropic herbs: Apiaceae; *Asphodelus; Aster* type; Boraginaceae; Cardueae; *Centaurea*; Cichorioideae; *Convolvulus* type; *Dipsacus* type; *Echium*. Anthropozoogenous herbs: Chenopodiaceae; Plantaginaceae; *Urtica*. Coprophilous fungi: *Sordaria* type (HdV-55); *Sporomiella* type (HdV-113). Taxonomical groups following Behre [82]. Grey lines are x3 exaggeration curves.

El Perro mire registers the lowest CHAR values in the initial part of the sequence in comparison to Brezoso and Viñuelas mires, averaging values 1.86 # cm^{-2} $year^{-1}$ (Figure 3). Fire frequency does not experience major changes during this phase but a final increase starting at ca. 3500 cal. BP (Figure A1 in Appendix A), given that only one fire episode has been identified during this period (at ca. 3661 cal. BP) (Figures 3 and A1 in Appendix A). Following this fire episode, deciduous and evergreen *Quercus* communities were partly replaced with Mediterranean shrublands and grasslands (Figure 6). Minor increases in grazing pollen indicators and coprophilous fungi suggest that probably fire events in this period were human-induced, in particular by Bronze Age communities (*ca.* 4300–3800 cal. BP) [78,81,83].

CHAR values at Viñuelas mire (Figure 3) are considerably low at the beginning of the record except for the small peak at the very bottom of the sequence. Low fire activity at Viñuelas during this period is somehow unexpected, considering the dominant dry conditions [83,84]. This behavior is marked in the Kruskal–Wallis test as different, and it is coherent with the other results (Figure A3 in Appendix A). This likely fire episode, although not identified as robust by peak detection analysis, probably influenced the local spread of *Betula* at the expense of *Quercus* [43]. The palynological record indicates that human activities around this mire were rather limited during this period [43] (Figure 6).

This period roughly corresponds to the Bronze Age (*ca.* 4150–3350/3300 cal. BP), when human communities developed livestock husbandry and agriculture as their main economic activities and land use becomes more intense, producing real impact in the environment [15,42,85], despite the many changes in human communities' behavior due to climatic variability [40,83].

3.3. Climatic and Human Influence: 3000–500 cal. BP

In this period, the tendency presented by the three studied sites is mainly different. Nevertheless, there is an evident reflection in the statistical tests which separates this part of the record from the extremes (Figures 3 and A3 in Appendix A). This long time includes several climatic and cultural periods, with potential influence on fire history such as the warm and humid Iberian–Roman Humid Period (2660–1450 cal. BP) [86], the colder and drier Early Medieval Cold Episode (1450–1050 cal. BP) or the warm Medieval Climate Anomaly (1050–650 cal. BP). Finally, it also includes the Little Ice Age (650–150 cal. BP), a long time when the cold and dry conditions characterized the climate in the northern hemisphere [87,88].

The Brezoso mire shows the lowest CHAR values during this phase, especially at 2500–1500 cal. BP (Figure 3). Nevertheless, fire frequency is still higher than in Viñuelas and El Perro despite it following a decreasing trend throughout this period (Figure A1, supplementary material). In contrast to Brezoso and El Perro mires, the Viñuelas charcoal record depicts significant biomass burning throughout this period, following a rising trend starting at ca. 3200 cal. BP (Figure 3) [43]. It is interesting to highlight the deceleration in fire activity between ca. 1150 cal. BP and ca. 850 cal. BP, a noteworthy reduction which is also recorded in El Perro mire (Figure 3, and Figures A1 and A2 in Appendix A). In both mires between 3000–2000 cal. BP there is still a remarkable amount of charcoal accumulation, although in El Perro mire it begins to increase a bit earlier (Figure 3). Interestingly, the ensemble member procedure for peak detection analysis detects a nearly synchronous fire episode dated at ca. 2651 cal. BP at the three study sites (Figures 3 and 4), at the beginning of the Iron Age, when an intensification of human activities is usually recorded [9,42,89].

This fire episode or episodes occurred after the climatic event 2.8 ka. cal. BP. [90–92] and within the Iberian–Roman Humid Period, when climatic conditions were mostly warm and humid [86,87]. At Brezoso and El Perro, *Betula* slightly spread following this fire episode alongside *Erica* under low anthropogenic impact, just indicated by minor increases in Cardueae, Asteraceae, and Poaceae. Lack of Cerealia-type pollen grains and grazing indicators indicated that farming was limited around the mires [42,43] (Figure 6). In marked contrast, at Viñuelas CHAR values are rather high from 2542–662 cal. BP, with a couple of fire episodes recorded (2839, 2539 cal. BP). Enhanced biomass burning (Figure 3) and increased fire frequency (Figure A1 in Appendix A) seem to have favored

certain local spread of *Betula* around the mire. The paucity of anthropogenic indicators during this period suggests climate–vegetation feedbacks promoting the increase in fire activity.

From 2000 to 500 cal. BP the three mire records show different trends (Figure A1 in Appendix A). Viñuelas mire shows an evident increase in the CHAR values, (mean values for this period 42.28 particles cm^{-2} $year^{-1}$ (Figure 3)). The Kruskal–Wallis test individualizes these charcoal trends in the whole record as statistically different (Figure A3 in Appendix A). On the contrary, El Perro and Brezoso do not accumulate a great amount of CHAR (Figure 3). During this sequence, the Roman Period (2000–1500 cal. BP) promoted the intensification of cereal cultivation and the livestock. This has its reflection in the pollen diagrams (Figure 6) with the spread of Poaceae, *Rumex*, and *Plantago* among others, indicating the success of these activities, which are kept in the first part of the Early Middle Age [42,43]. The Visigothic Kingdom, which maintained strong persistence in the rural areas [77], successfully developed a slash-and-burn system, preparing the land for crops and grazing by using fire as the main tool for managing the environment [42,93–96].

Between all these fire events, the moments where there is a lack of fire activity are also relevant (Figure A1, supplementary material) although it is precisely in these kinds of situations where the differences between the three records are more visible. Viñuelas is the mire which most of these periods without fire or little fire activity registers (Figures 3 and A1 in Appendix A). Nevertheless, Viñuelas' record gathers in this period three great peaks in 1019, 1296, and 1479 cal. BP, with CHAR values between 60 and 80 particles cm^{-2} $year^{-1}$. The fire frequency increases in this interval and tends to descend from ca. 1000 cal. BP. El Perro and Brezoso mires, by their part, share a moment of fire absence from *ca.*1200–900 cal. BP. This period with less fire activity shows how the lack of fire can help the forest to develop and be useful for the human communities living around the study area. Thus, it is possible to appreciate an increase in the woodlands with the spread of *Quercus ilex*, *Quercus pyrenaica*, and *Quercus suber*, which are species with an evident economic interest for the human communities. At the same time, the reduction trends of *Corylus* and *Betula*, opportunistic species, are visible in the diagram. In this moment, Brezoso mire gathers the highest percentages of cereal pollen, also present in El Perro mire, and there is an evident increase in livestock and human pressure [42,43] (Figure 6).

The population is scarce in these lands during the Middle Ages (1500–500 cal. BP) although some development is visible along the time. The Islamic Period (1239–850 cal. BP) brings a small demographic growth and the Muslim communities living in this mid-mountain system maintain spread cereal cultivation and livestock, since grazing is the most important economic resource for these communities. These activities are linked to the development of some roads connecting different Islamic territories crossing these mountains, used by flock movements and commercial routes [42,43,94,97–99]. However, the war is also present in the fire regime because fire is an element used for clearing the landscape and avoiding ambushes or forcing the enemy to move, as well as for destroying enemy resources. It is not until the ca. 650 cal. BP, when the peace is established in the territory, that the Castilian Kingdom can repopulate the taken lands and develop their economic activities. Among them, livestock is the most important practice for the economy. Especially relevant are the transhumance movements through the pacified territory, because the movement of those great flocks helped the landscape shaping [42,43,99,100].

3.4. The Fire That Creates: from 500 cal. BP to Present

In the Iberian Peninsula, the general trend shows an evident growth in fire activity in the three studied sites. This final period includes the Modern and Contemporary age (500–150 cal. BP; 150 cal. BP–present) and the climate is determined by the final stages of the Little Ice Age (600–150 cal. BP) [101]. However, human activities will become the most important driver in the fire regime during this period. This fact will be of such importance that these fires recorded in the first part of the Modern Age will be also present in the legal contemporary literature, since many of those documents try to regulate and control the use of fire [42,43,99,102].

El Perro mire shows a sharp increase in CHAR values (Figure 3) despite there being only one although large robust fire episode according to peak detection analysis. This is a consequence of the registration of the biggest fire events in this mire. In fact, this part of El Perro record is statistically different from the rest of the core, showing just a few similarities with the above-mentioned fire event in 2651 cal. BP. The Viñuelas and Brezoso also records moderate to high CHAR values (Figure 3), although fire frequencies seem to have descended (Figure A1, Supplementary material). In El Perro mire, the two registered episodes trigger different vegetation responses. There is a fire event in 333 cal. BP, which opens the woodlands meanwhile the shrubs show a descending trend. The human activity increases around this space from the Modern Age and the 19th century, with an evident growth in the anthropic herbs but especially in the grazing for livestock. This population growth forces the neighbors to include in the cultivation circuits some lands never exploited before due to their location, insufficient quality, or low fertility, putting pressure on the mountains and other spaces not exploited in the past [74]. On the other hand, the fire event in 92 cal. BP does not disentangle such a landscape change, but the woodlands closed and got denser, meanwhile the anthropic herbs show an evident descent.

Brezoso mire shows an increase in the fire activity, slight at the beginning of the period and sharper in the end. The final stage shows a further gentle increase, from ca. 300 cal. BP until the present, especially evident in the fire events recorded (Figure 3). However, despite the opening landscape it implies, the drop of fire events at the very end helped the arboreal layer take back the space. Thus, at the end of the period, the landscape is dominated by *Quercus* with a herb layer dominated by Poaceae and anthropic species. Cereal cultivation is also present around the mire surroundings, although not in a representative way [42,43] (Figure 6).

Finally, Viñuelas mire shows a very irregular CHAR trend (Figure 3) and the fire activity in this moment is also statistically different from the other events recorded, although the fire frequency descends (Figure A1 in Appendix A). The landscape is dominated by deciduous *Quercus*, but the evergreen *Quercus* is scarce. The shrublands have a representative presence and the herbs dominate the ensemble, although the livestock does not show a representative impact in the landscape [42,43] (Figure 6). The demographic growth and the political circumstances, and the owning changes coming from the Confiscation Laws promulgated against some ecclesiastic and public properties in the 19th century, promoted some intense changes in land use and forest exploitation. The 20th century, on the other hand, implies some population shift and rural abandonment, which has the above-mentioned consequences in the landscape. After some time with a descending fire regime and woodland spreading, the trend is increasing, favored by warm and dry climatic conditions and human hand or, in this case, desertion [21,42,43,74,103–105].

4. Conclusions

The reconstructed fire history for the Toledo Mountains highlights how human activities take on progressively more importance over time. Socio-economic changes were essential for defining fire regimes in this mid-elevation range, especially during recent times. Land use has determined vegetation composition, structure, and recent fires. Thus, fire history runs along the different cultural stages and human interests and actions [7,21,105,106].

This study dives into the fire regimes of the Toledo Mountains, following the trends present by El Perro, Brezoso, and Viñuelas mires' records. This study shows the evident disagreement between the Iberian Peninsula general trend and the fire history recorded in the Toledo Mountains, where it is possible to distinguish three moments with different fire trends. In the first one (*ca.* 5000–3000 cal. BP), the climate has an indisputable effect on fire regimes, while in the second one (*ca.* 3000–500 cal. BP), human activities also regulate the fire trends, becoming the most important fire driver in the last five hundred years. In the very last one, from 500 cal. BP onwards, human activities—or the lack of them—determined the fire activity.

It is necessary to understand the fire regime of the past and the way it affected ecosystem dynamics to better understand the current fire events and their impact in the landscape [107,108]. More long-term

fire ecology studies are needed to complete this essential task for environment management, especially in the Toledo Mountains, where there is still a lot of work to do.

Supplementary Materials: The following are available online at http://www.mdpi.com/2571-6255/2/4/54/s1.

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Appendix A

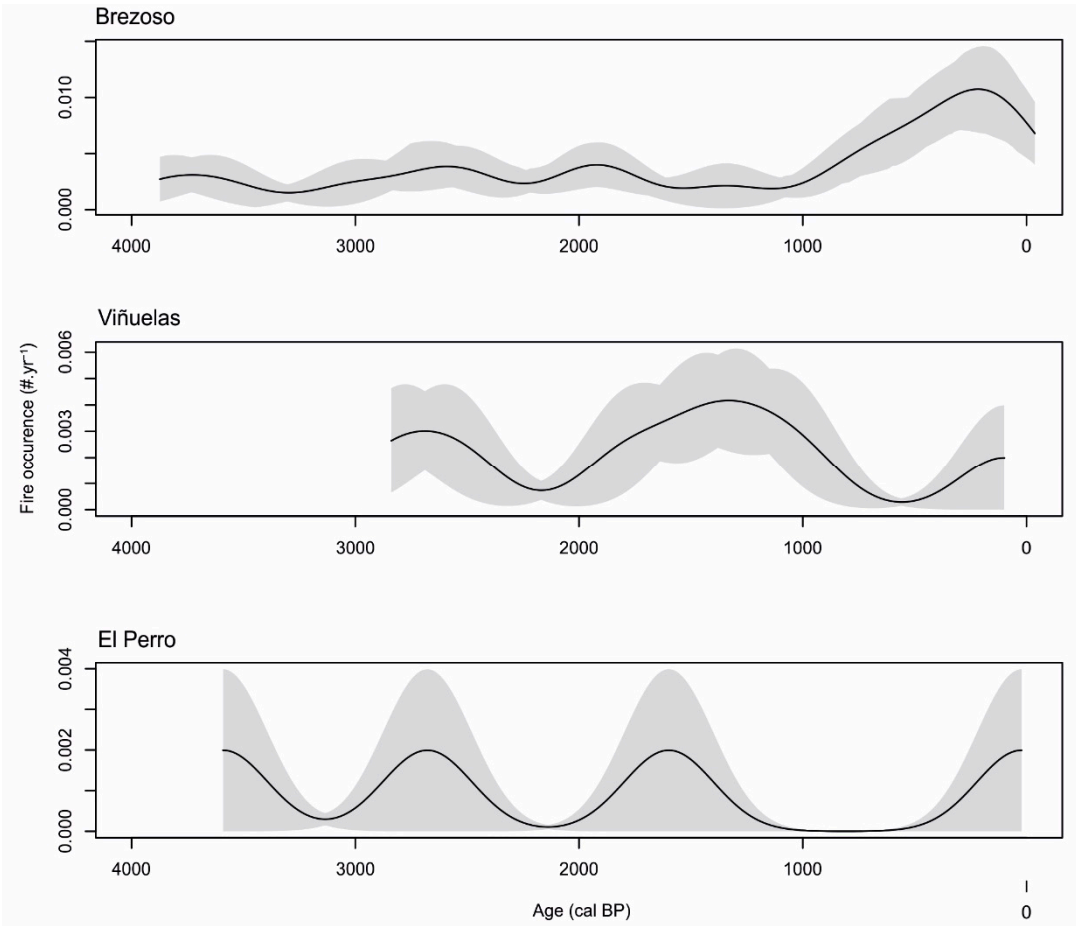

Figure A1. Fire Frequency in the selected mires.

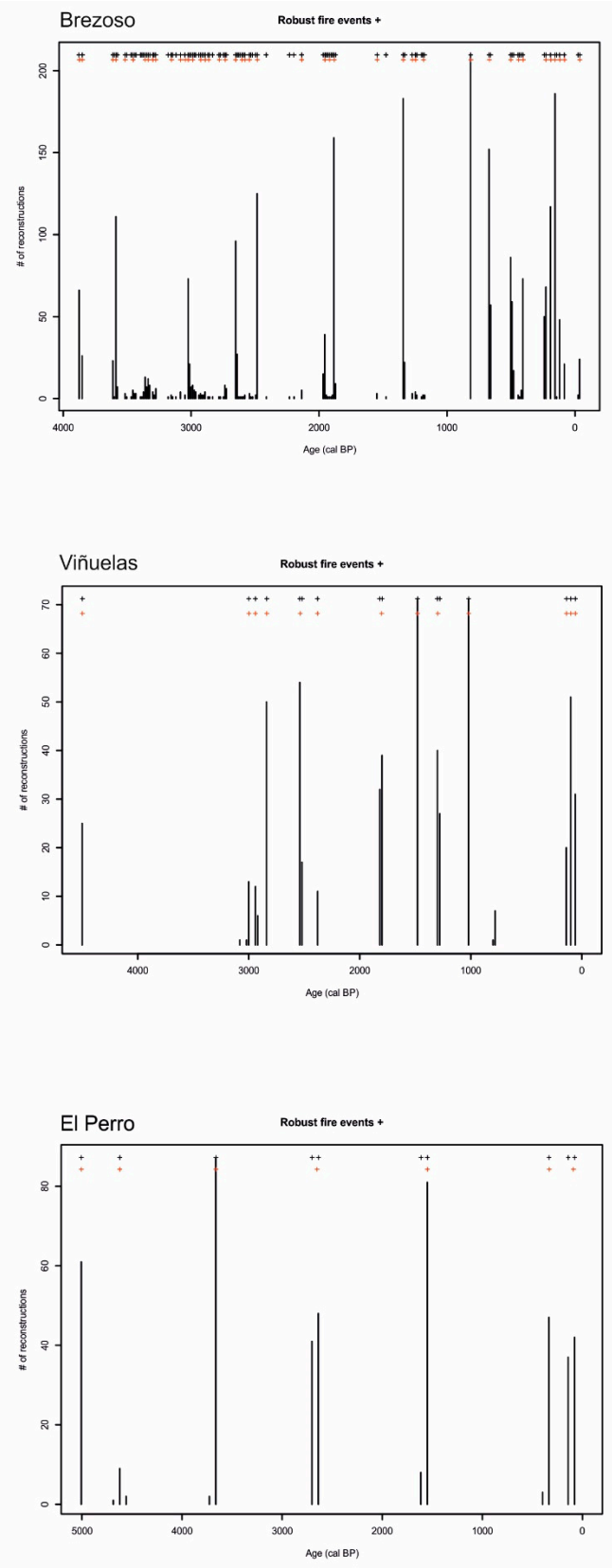

Figure A2. Fire densities and Robust Fire Events in the selected mires (red crosses): Brezoso, Viñuelas, El Perro.

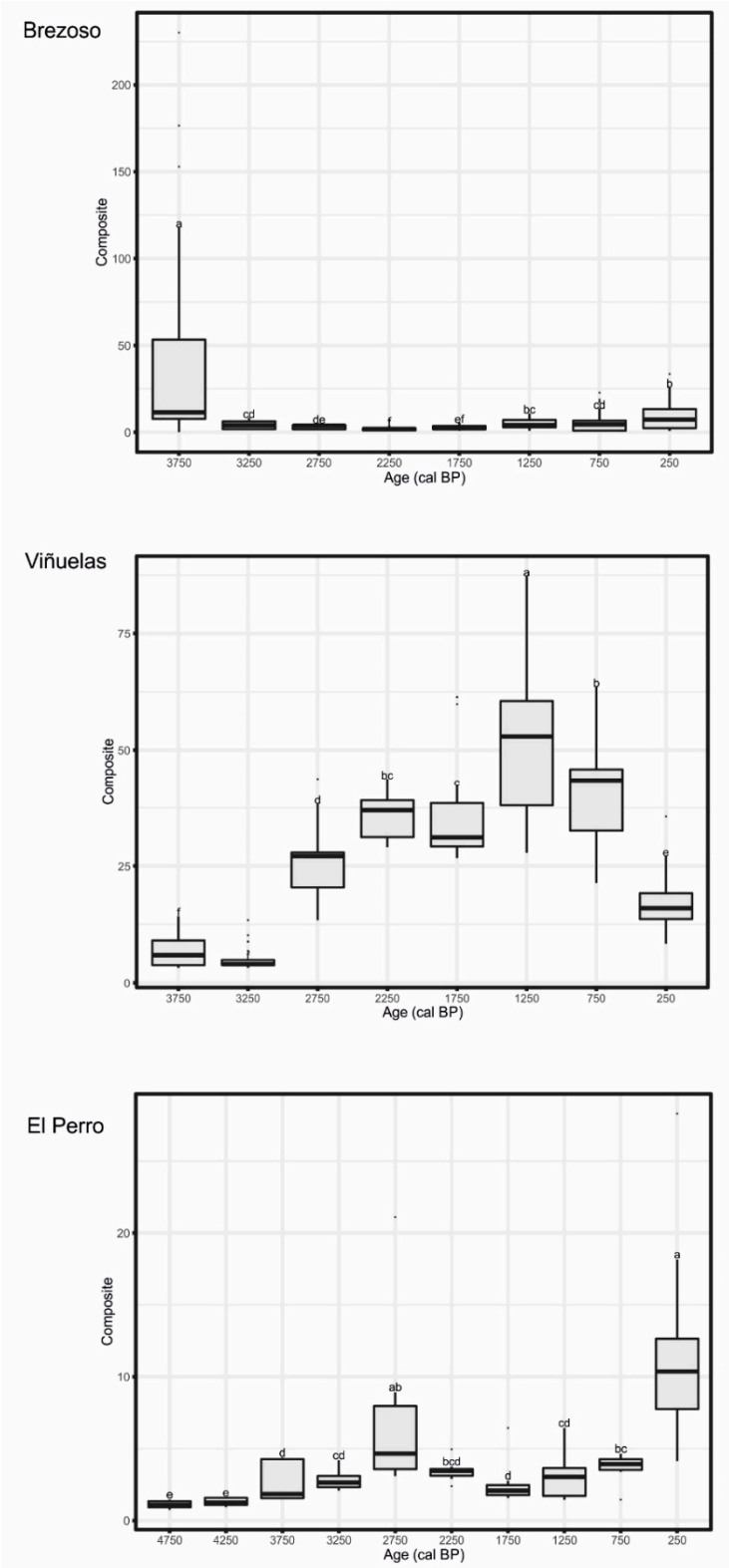

Figure A3. Kruskal–Wallis test from the studied sites.

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