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Historical Fires Induced Deforestation in Relict Scots Pine Forests during the Late 19th Century

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Abstract: Mountain forests are subjected to several pressures including historical land-use changes and climate warming which may lead to shifts in wildfire severity negatively impacting tree species with low post-fire growth resilience. This is the case of relict Mediterranean Scots pine (*Pinus sylvestris*) forests in the Sierra de Gredos mountains (central Spain). We reconstructed the historical fire regime of these forests since 1700 by using paleoecology, historical ecology and dendroecology. We detected an increase in charcoal accumulation rate and coprophilous fungi in peat bogs during the late 19th century when the pine pollen percentage sharply decreased, historical records of fire peaked and many trees showed growth suppressions. We inferred an increased wildfire incidence during the late 19th century, which could have shaped the current distribution of Scots pine forests. This shift in fire-forest interactions can be explained by the uncontrolled use of mountain forests and grasslands due to the dissolution of "Mesta", one of the major and lasting transhumance livestock associations in Europe. Integrating historical human and climate influences on fire regimes allows decomposing the resilience and conservation components of relict forests.

Keywords: dendroecology; growth suppression; historical ecology; paleoecology; *Pinus sylvestris*; resilience; Sierra de Gredos

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1. Introduction

Shifts in forest wildfire regimes are mainly triggered by changes in land use and climate, interacting with other causes [1,2]. Bridging paleoecological and historical reconstructions of fire recurrence and severity allow detecting those shifts and the interactive effects of land-use changes and climate and characterizing the historical range of variability of fire-prone forest ecosystems [3–5]. Reconstructing fire regimes is necessary to assess forest resilience through time in response to combinations of climatic, ecological and human drivers [6].

Mediterranean mountain forests have shown resilience to fire in terms of regeneration and growth dynamics [7]. However, rapid socioeconomic and land-use changes during the 20th and 21st centuries, including rural depopulation and abandonment of traditional landscape management, have enhanced forest expansion increasing the amount and continuity of fuel and leading to more frequent, large drought-driven fires [2,8]. It is unknown if Mediterranean forests will keep being resilient under future scenarios with abundant fuel loads and increased warming and aridification [7]. Detecting fire regime shifts through paleoecological and historical data allows determining the relative role of human-caused, historical burning in Mediterranean forests and assessing post-fire recovery [9–11].

According to several reconstructions, fire has contributed to rapid structural and compositional changes in Mediterranean forests at least for the past 2000 years [9–11]. For instance, the local demise of *Pinus nigra* Arn. in northern and central Spain has been attributed to recurrent human-caused fires occurring at a high frequency [12–14], and the low post-fire regeneration of this thin-barked species. Some of these Mediterranean pine forests are relict or isolated populations such as those formed by Scots pine (*Pinus sylvestris* L.) in the Sierra de Gredos mountains, central Spain (Figure 1a). The relict status of Scots pine in that region may be related to shifts in the historical fire regime [15–19], with more recurrent fires than under "natural" regimes, since Scots pine is one of the most vulnerable European pine species to fire damage [20].

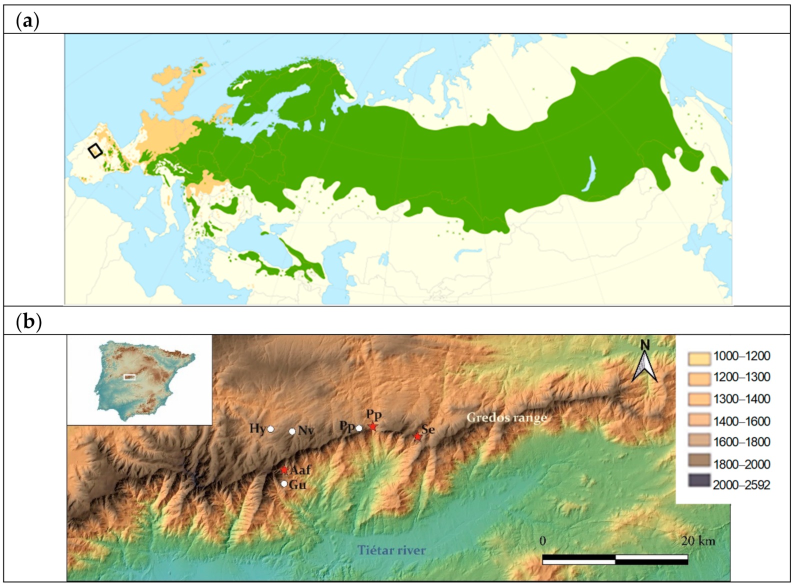

Figure 1. (**a**) Distribution area of Scots pine (*Pinus sylvestris*) across Eurasia showing native (green patches) and introduced or naturalized stands (brown patches; source [21]). Dots indicate isolated Scots pine populations. (**b**) Location of four Scots pine forests (white circles) investigated in the Sierra de Gredos mountains, central Spain (Gu: Guisando; Pp: Puerto del Pico; Hy: Hoyos del Espino; Nv: Navarredonda) and pollen/charcoal records (red stars: Pp, Puerto del Pico; Se, Serranillos; Aaf, Arroyo de Aguas Frías). Elevation is given in m a.s.l.

Here we reconstruct fire regimes during the past 300 years in the Sierra de Gredos to assess their role as historical factors leading to the current relic status of Scots pine in this region. We reconstruct fire incidence by combining palaeoecological (charcoal) and dendroecological (sharp growth suppressions) data and comparing them with historical fire records (archival sources). We hypothesize that a high fire frequency reduced the cover and density of Scots pine forests in the Sierra de Gredos.

2. Materials and Methods

2.1. Study Area and Tree Species

The study area is located in the Sierra de Gredos, central Spain (Table 1, Figure 1).

The climate of this mountainous region is Mediterranean with continental influence, characterized by cold-wet winters, wet springs and warm-dry summers. Mean annual temperature is 14.5 °C, mean maximum and minimum temperatures are 30.1 °C and 0.0 °C, respectively, and total annual precipitation is 1483 mm (data from "Arenas de San Pedro" meteorological station; 5°5′28″ W, 40°12′31″ N, 510 m a.s.l.). Drought may last from May to September. Geological substrates are dominated by granites, and soils are moderately deep at mid-elevation but rocky and thin in high-elevation Scots pine stands [22].

Table 1. Site information on the forests where tree-ring chronologies were developed. Diameter (Dbh) and age values are averages, and their ranges are shown between parentheses. The two ITRDB chronologies were developed by Klaus Richter, and Dbh and age data are not available for them.

Site (Code)	Source	Latitude N	Longitude W	Altitude (m)	No. Trees (No. Cores)	Dbh (cm)	Age at 1.3 m (years)
Puerto del Pico (Pp)	This study	40.31	5.02	1600	21 (45)	60.8 (28.5–110.5)	149 (76–265)
Navarredonda (Nv)	ITRDB-spai034	40.30	5.08	1470	12 (26)	-	-
Hoyos del Espino (Hy)	ITRDB-spai033	40.31	5.11	1465	12 (25)	-	-
Guisando (Gu)	This study	40.24	5.10	1175	24 (45)	53.8 (8.0–180.0)	53.8 (18–284)

The vegetation of the study area includes forests, shrublands and also sparse pine woodlands on rocky slopes, and includes oaks (*Quercus ilex* subsp. *ballota* (Desf.) Samp., *Quercus pyrenaica* Willd.) from 600 to 1600 m, and shrubs (*Cytisus oromediterraneus* Rivas Mart.) above 1600 m and pines. The resin tapping industry has favored planting *Pinus pinaster* Ait. at low to mid elevations, whereas scattered Scots pine stands appear at high elevations from ca. 1200 up to 1800 m [17]. In this area, pine woodlands have burnt (Figure 2) disproportionately more than other vegetation types since the 1970s after the abandonment of traditional land use and grazing practices associated with small fires affecting high-elevation scrublands [23].

Figure 2. Views of burnt Scots pine trees in a stand located in the study area affected by a fire in 2009 (stand situated near Puerto del Pico site, see Figure 1).

Scots pine is a long-living, thin-barked, non-serotinous and shade-intolerant species that can survive low-severity surface fires, but is less tolerant to mid-severity fires than the thick-barked, fast-growing *P. pinaster* [20,24].

2.2. *Field Sampling of Scot Pine Forests and Dendroecology*

We selected relict Scots pine stands situated near the sites of paleoecological records and in areas historically burnt (Figures 1b and 2) but subjected to different climate conditions. We sampled two Scots pine stands located at high (Puerto del Pico) and at low (Guisando) elevation (Table 1). In each stand, we sampled living Scots pine trees with diameter at breast height (Dbh) above 10 cm and located in a ca. 0.5 ha large area. Due to the conservation measures of these relict Scots pine forests, we discarded obtaining partial cross sections from living trees, and we took cores at 1.3 m using 5-mm Pressler increment borers perpendicular to the maximum slope.

Dendrochronology was applied to cross-date the tree-ring width series [25]. Cores were air-dried, glued onto wooden supports and polished with sandpaper until rings were clearly visible. Then, samples were visually cross-dated and tree-ring widths were measured to the nearest 0.01 mm using a binocular scope and a LINTAB measuring device (Rinntech, Heidelberg, Germany). Cross-dating was checked using the COFECHA program [26].

Individual tree-ring width series were detrended to remove non-climatic, size-related growth trends [25]. We applied a power transformation and then a cubic smoothing spline with 50% frequency-response cut-off was fitted to obtain ring-width indices. These indices were subjected to autoregressive modeling to remove most first-order autocorrelation. Finally, site chronologies were obtained by averaging the residual ring-width indices on a yearly basis using a bi-weight robust mean. We obtained two types of chronologies for each of the two study sites: (1) standard, non-pre-whitened or preserving serial autocorrelation; and (2) residual, pre-whitened chronologies. For the chronology construction, we used the ARSTAN software [27]. To characterize each tree-ring series, we calculated the mean and first-order autocorrelation, a measure or similarity between consecutive rings, of raw ring-width data, and the mean sensitivity, a measure of relative change in width between consecutive rings and correlation of trees with site mean chronology of standard chronologies [25]. The two study sites' chronologies were compared with tree-ring data of the same species and from two nearby sites (Navarredonda, Hoyos del Espino; Table 1) gathered from the International Tree-Ring Data Bank (ITRDB) webpage [28] and measured by Klaus Richter in 1985. We also considered previous chronologies developed in the study area for Scots pine and other pine species to check our cross-dating [13,14,29,30].

We calculated the differences between the standard and residual chronologies following [14] to assess short-term changes in growth. According to these authors, post-fire growth declines should be characterized in stands historically burnt, and these growth suppressions should not be related to other stress factors such as pests, diseases or droughts which differently affect tree growth [4,14]. We considered the standard chronology of the observed post-fire growth values, and the residual chronology of the predicted values after removing the temporal autocorrelation influence. We assumed that an abrupt decrease in growth following a fire (growth suppression) was related to a loss of photosynthetic biomass or deterioration of cambium because of high temperatures as has been observed in boreal Scots pine forests where post-fire growth suppressions lasted from 1 to 5 years [31].

Finally, we reconstructed pine recruitment in 20-year classes based on estimated age at 1.3 m. Age was estimated by counting rings in cores with pith or by calculating pith-offset estimates in cores without pith. This was achieved by fitting a geometric pith locator to the innermost rings and converting the distance to the theoretical pith into the number of missing rings [32]. We estimated tree age as the maximum number of tree-rings in each individual summed to the number of years from the base to the coring height (1.3 m). The time to grow from the base to 1.3 m was estimated to be 6 years based on the equation fitted to trees from the Guisando site: height = 0.347 age$^{0.736}$, R^2 = 0.85.

2.3. Paleoecological Methods

To reconstruct the regional forest history during the period 1700–2000, three pollen and charcoal records from the study area were selected corresponding to three cored mountain peat bogs (Figure 1): one situated at mid elevation (Arroyo de Aguas Frías, 1120 m a.s.l.) and two located at high elevation (Puerto del Pico, 1395 m; Serranillos, 1700 m). The processing and dating of samples have been described elsewhere [16–18,33–36]. These procedures are explicitly documented for the Arroyo de Aguas Frías site in the Supplementary Material. Here we only consider the percentage values of the main taxa identified in the pollen records related to fire (Scots pine, pyrophytic broom communities of Genisteae shrubs), the relative abundance of coprophilous fungi associated with grazing activity, as well as fire events related to peaks in charcoal accumulation rates.

2.4. Historical Fire Records Obtained from Archives

Historical fire records were obtained through systematic research in national (National Historical Archive, General Archives of the Administration, Archives of the former Ministry of Agriculture, Spanish Military Police Archive, Spanish National Library), regional or provincial (Province Historical Archives, Forestry Administration Archives, private archives) and municipal archives. This allowed reconstruction of the fire history for the Sierra de Gredos mountains (n = 1094 records) from the year 1497 until 2013. Three types of archival sources were considered: administrative documents from administrations with fire use regulation and land management power since the 16th century, judicial and police sources including court registers and police reports since the 17th century and printed press (official journals, newspapers, books) [10,37]. Historical fire records were georeferenced with three different levels of increasing accuracy (municipality, site or area without specified boundaries and forest or plot with accurate limits of property) depending on the historical source. The historical fire database includes comprehensive information on fire occurrence with data on: date, location, land ownership, land cover/use, burnt area, fire duration, fire cause, suppression resources, losses, etc. [1]. We acknowledge the statistical limitations of the archival sources [1,10], but they still provide relevant qualitative information on historical fire regimes.

3. Results

3.1. Paleoecology: Late-19th-Century Shift in Fire Regime and Reduction of Scots Pine Forests

Several proxies indicate a reduction of Scots pine forests during the past three centuries in the study sites with an abrupt shift in the late 19th century when the fire regime changed. For instance, in the Arroyo de Aguas Frías site, there is an abrupt drop in Scots pine pollen during the late 19th century which coincided with an increase in Genisteae pollen and coprophilous fungi indicating an increase in pastoral pressure (Figure 3). This change is also documented between the second half of the 19th century and the early 20th century in the Serranillos site, where the abundance of coprophilous fungi increased.

The changes in Scots pine pollen from the range of 50–70% during the 18th century and most of the 19th century to 10–30% values after the late 19th century and afterward indicate a shift from more extensive pine forests to scattered, fragmented stands. In the Puerto del Pico site such a decrease in pine pollen was not observed, but coprophilous fungi increased in the mid-19th century and in the 20th century.

Charcoal analyses indicate that the abrupt deforestation of pine forests observed in the late 19th century in the Arroyo de Aguas Frías is related to fire events in the late 19th century (1886 and 1893; Figure 3), despite a long-term increasing trend of pine pollen being observed until 2000. Fires occurred at Puerto del Pico in the 18th (1726, 1759), 19th (1814 and 1854) and 20th (1907) centuries, while in Serranillos, they are documented for the 19th century (1842, 1862 and 1879).

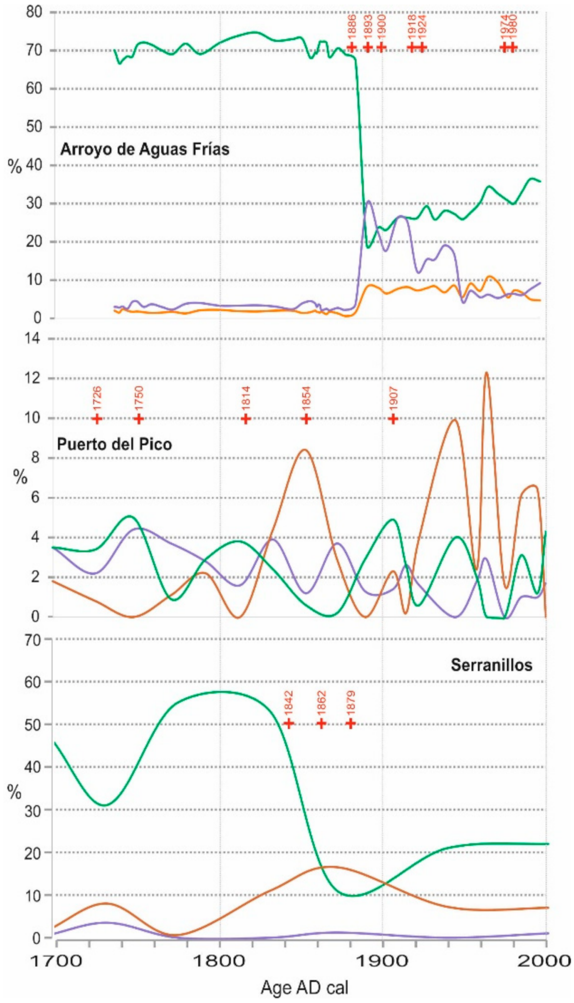

Figure 3. Percentage values of the main pollen and non-pollen palynomorphs morphotypes cited in the text (green line: *Pinus sylvestris*; violet line: Genisteae; brown line: coprophilous fungi) and inferred fire events based on charcoal analyses (red crosses).

3.2. Tree Growth

On average, radial growth was 1.97 mm (Table 2), with sites such as Guisando showing higher growth rates because of the presence of younger trees (Figure 4). The mean autocorrelation was 0.79 and the mean sensitivity was 0.26 indicating a high similarity between consecutive rings but also a high relative year-to-year variability in width. The mean correlation of trees with the site chronology was 0.61 confirming a high common signal, probably controlled by climate variability.

Table 2. Tree-ring data and statistics for the common period 1920–1985. Values are means ± standard deviations. Different letters indicate significant ($p < 0.05$) differences between sites according to Mann–Whitney tests.

Site (Code)	Timespan	Tree-Ring Width (mm)	First-Order AutoCorrelation	Mean Sensitivity	Correlation of Trees with Site Mean Chronology
Puerto del Pico (Pp)	1761–2018	1.92 ± 0.57	0.85 ± 0.07b	0.23 ± 0.03	0.54 ± 0.09a
Navarredonda (Nv)	1769–1985	1.88 ± 0.60	0.78 ± 0.09b	0.28 ± 0.05	0.64 ± 0.09ab
Hoyos del Espino (Hy)	1813–1985	1.82 ± 0.38	0.83 ± 0.08b	0.29 ± 0.05	0.73 ± 0.09b
Guisando (Gu)	1744–2015	2.28 ± 1.07	0.69 ± 0.05a	0.26 ± 0.06	0.51 ± 0.08a

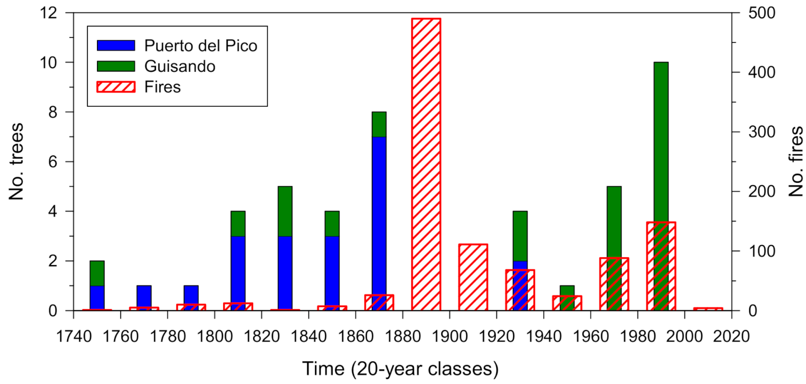

Figure 4. Scots pine recruitment (grey bars) reconstructed considering 20-year age classes in the two study forests (Puerto del Pico, Guisando) and historical records of fires (red bars with diagonal lines). The number of fires corresponded to historical records of fire events in the Sierra de Gredos mountains.

During the best-replicated period common to all tree-ring series (1920–1985), the two ITRDB series were highly correlated with them (Pearson correlation, r = 0.76, $p < 0.001$) and also with the Puerto del Pico series (r = 0.25–0.37, $p < 0.05$) but not with the Guisando series which showed lower correlations with the ITRDB series (r = 0.23, $p = 0.07$). The series of the two sampled sites were positively correlated (r = 0.34, $p = 0.005$). These results indicate a slightly different climate-growth response in Guisando as compared to the other sites in agreement with its lower autocorrelation and lower correlation with the site chronology (Table 2).

3.3. Fire Proxies in Tree-Ring Records: Recruitment Patterns and Growth Suppressions

None of the sampled Scots pine trees were recruited from 1880 to 1920 when the frequency of historical fire records peaked according to archive sources (Figure 4). In the Guisando site, at least three age classes could be distinguished, with young trees (age at 1.3 m between 20 and 100 years, 51% of trees), middle-aged trees (age between 150 and 200 years, 45% of trees) and one old tree of 284 years (age between 280 and 300 years, which represent 4% of all sampled trees). In the Puerto del Pico site, middle-aged trees were also abundant (45% of individuals), and 68% of trees were established to be from 1800 to 1880. In this site, there was a negative but not significant correlation between the log-transformed number of fire events and the frequency of recruited trees (Spearman correlation, $r_s = -0.44$, $p = 0.10$). Overall, we found a dominant cohort of middle-aged pines recruited in the first half of the 19th century.

In the Guisando site, we detected very low values of the differences between standard and residual indices in the mid (1861) and late 19th century (1888, 1891, 1895) and also in the early 20th century (1922, 1944, 1947, 2006) (Figure 5). The growth suppressions observed during the 1880s and 1890s in this site coincided with the peak of fire records. Similar years of low difference values were also observed in the Puerto del Pico site, but they did not surpass the 0.05 lower threshold (dashed line in Figure 5). The series of differences between the standard and the residual chronologies of the Guisando site was negatively related to the number of fires ($r_s = -0.21$, $p = 0.007$, period 1850–2013).

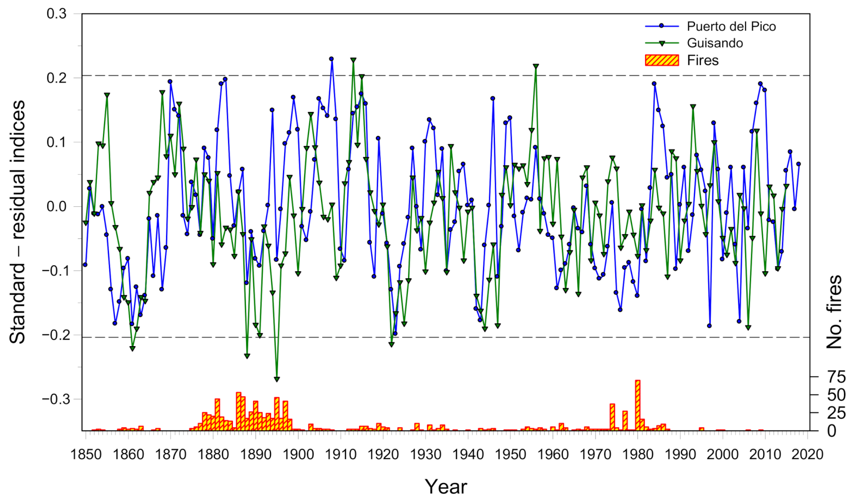

Figure 5. Differences between the standard and residual indices of the two Scots pine sites (Puerto del Pico, Guisando; lines with symbols) for the period 1850–2018 and annual frequency of fires according to archive sources (bars, right y-axis). The dashed lines show the mean of standard minus residual indices ± 2.96 times the standard deviation indicating the 95% confidence intervals.

4. Discussion

Our findings confirm our hypothesis supporting that a high fire frequency reduced the abundance of Scots pine in the Sierra de Gredos mountains. This corresponded to an abrupt shift in the fire regime cascading on feedbacks between wildfire, vegetation and human use of mountain forests, shrublands and pasture. We found a peak in wildfires during the late 19th century according to several proxies (charcoal accumulation rates, archive sources; Figures 3 and 4), which coincided with a reduction in Scots pine pollen in several sites (Arroyo de Agua Frías, Serranillos), a lack of tree establishment (Figure 4) and growth suppressions in the Guisando site (Figure 5). Nevertheless, there could be lagged responses of pine forests to the change in fire regime or dating uncertainties of fire events, which could explain why after several fires in the late 19th century, pine pollen steadily increased during the 20th century in the Arroyo de Agua Frías site. This trend could also reflect the recovery of pine forests in the study area after the reduction of the number of fire events during the mid-20th century (Figure 4).

In the study region, the last 300 years are mainly characterized by the deforestation of high-elevation Scots pine forests [18] related to an increase of human pressure, that is, clearance of high-mountain pine forests by means of anthropogenic fires to obtain pastures related to transhumant pasture uses [17]. This is confirmed by the increase in post-fire shrubland (Genisteae) communities above the disturbed treeline and coprophilous fungi after the 19th-century fire regime shift (Figure 3), as illustrated by the Arroyo de Agua Frías site. This deforestation process was not related to any major timber harvesting during the late 19th century according to historical management plans [10], and the presented tree-ring data do not show growth releases suggesting the removal of trees and the reduction of competition in the sampled stands (Figure 5).

The data from Serranillos reflect the presence of more extensive pine forests from the mid-18th to the mid-19th centuries as inferred from the changes in pollen percentage; while a reduction of pollen record there and in the Puerto del Pico along its chronological trajectory would denote the existence of isolated high-mountain pines or scattered stands [38]. These data seem to suggest that the increase of human-mediated fires and livestock grazing was connected to the decline of Scots pine in high-elevation sites [9,20]. The lower percentage of Scots pine pollen in the Puerto del Pico record is explained because this area has been the main passage for transhumant cattle since the Middle Age, making it an open woodland with scattered stands [35].

The beginning of the Late Modern Period (1800 to the present) in the Sierra de Gredos mountains coincides with prominent socioeconomic and political changes such as the dissolution of the "La Mesta" system, one of the main transhumance livestock associations in European history [39]. The termination of "La Mesta" in the 19th century far from lightening the livestock pressure on mountain areas as the Sierra de Gredos, triggered the intensive use of pastures for sheep and cattle for local farmers [20,35]. This manifested as a further local expansion of high-mountain shrublands (e.g., Genisteae) and grasslands with the increase of proxies of pastoral pressure such as coprophilous fungi and minimum percentages of Scots pine pollen [18]. These changes suggest an increase in local grazed areas and grazing pressure in response to the abrupt increase in fire frequency and severity during the late 19th century [13,14]. Such a shift in the fire regime was the most plausible cause of reduced establishment (Figure 4), either because of low recruitment or high mortality rates or both and severe growth suppressions (Figure 5). We noted that both forest responses were site contingent since the recruitment signal was more evident in the high-elevation Puerto del Pico site, where severe fires are frequent (Figure 2), whilst the growth signal was recorded in the low-elevation Guisando site. It is also remarkable that some growth suppressions (e.g., 1960–1963) and fire scars (e.g., 1975) were dated in trees sampled in the Puerto del Pico site [40], during two decades with a high frequency of fires (Figure 5). This may be explained by the fact that the late-19th-century wildfires drastically reduced pine cover whereas recent fires occurred under the present fire exclusion policy when the landscape was more open. It is also interesting to note that other reconstructions of fire history found a high incidence of fires during the mid to late 19th century in several Mediterranean countries such as Greece [41,42], Spain [43] and Algeria [44]. Further research could investigate if the 19th-century shift in fire regime was linked to local socioeconomic changes or also influenced by regional changes in climate conditions such as increased aridification.

We consider that the 1890s growth suppression can be explained by widespread surface fires which differently affected trees with moderate to high diameter (we estimate Dbh between 15 and 25 cm in the 1890s of the largest trees). This fire regime primarily depended on human burning and secondarily on climate variability since warm spring conditions occurred during those decades [13]. Scots pine growth in the study area is enhanced by wet spring and summer conditions [29,45], and reconstructed summer precipitation in the 1890s showed the smallest range of variability since 1800 [46]. Surface fires of different intensity usually affect Scots pine forests, albeit lethal crown fires could occur in dense stands under drought conditions [20]. In the study case, a high frequency of mid- to high-severity surface fires could have triggered the decline of Scots pine forests.

The late-19th-century shift in the fire regime contributed to shaping the current distribution and structure of relict Scots pine forests in the Sierra de Gredos mountains. Such episodes of rapid socio-economic and ecological changes and loss of forest resilience may inform management policies based on prescribed burning to recreate pre-19th century disturbance regimes associated with smaller, frequent fires and a greater abundance of Scots pine mountain forests. In addition, these forests are located near the species' southernmost distribution limit and should be monitored, better investigated and preserved since climate warming could further threaten their persistence. Plantations with other Scots pine provenances or with the more flammable *P. pinaster* should be avoided near these relict stands to preserve their genetic uniqueness and promote their long-term post-fire recovery. From a scientific point of view, combining paleoecological, historical, dendroecological and ecological (tree census data, forest inventory plots) sources of information represents a unique opportunity to disentangle the roles played by humans and climate as long-term drivers of forest dynamics [5,30].

5. Conclusions

We documented a regime shift in fire-vegetation dynamics during the late 19th century. In this study, human-caused burning was the main driver of the reduction in cover and abundance of Scots pine, which currently forms relict scattered stands in the Sierra de Gredos mountains. Paleoecological (increase in charcoal, decrease in pine pollen, increase in Genisteae pollen and coprophilous fungi), historical (increase in archive records of fires) and dendroecological (decrease in recruitment, growth suppressions) proxies point out to the high frequency and severity of fires during the late 19th century as triggers of deforestation related to shifts in land use of the mountain landscape (dissolution of the "Mesta" transhumant livestock system, extensive anthropogenic wildfires to create woodlands more intensively grazed). The disturbance regime shifts in the late 19th century illustrate a severe loss of resilience of Scots pine forests with legacy effects, including the current structure and distribution of relict forests of the species in the Sierra de Gredos mountains.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/fire4020029/s1, Paleoecological Methods; Table S1: radiocarbon (AMS-^{14}C) data from Arroyo de Aguas Frías site.

Author Contributions: Conceptualization, J.J.C. and J.A.L.-S.; methodology, J.J.C., G.S.-B., C.M.-M., R.L.-L., P.O., M.G. and J.A.L.-S.; software, J.J.C.; validation, G.S.-B., C.M.-M., R.L.-L., P.O., M.G.; formal analysis, J.J.C. and J.A.L.-S.; investigation, J.J.C. and J.A.L.-S.; resources, J.J.C., C.M.-M., M.G. and J.A.L.-S.; data curation, J.J.C., C.M.-M., M.G. and J.A.L.-S.; writing—original draft preparation, J.J.C. and J.A.L.-S.; writing—review and editing, G.S.-B., C.M.-M., R.L.-L., P.O. and M.G.; visualization, J.J.C. and J.A.L.-S.; supervision, J.J.C. and J.A.L.-S.; project administration, J.J.C., C.M.-M., M.G. and J.A.L.-S.; funding acquisition, J.J.C., C.M.-M., M.G. and J.A.L.-S. All authors have read and agreed to the published version of the manuscript.

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References

1. Montiel-Molina, C.; Vilar, L.; Sequeira, C.R.; Karlsson, O.; Galiana-Martín, L.; Madrazo-García de Lomana, G.; Palacios-Estremera, M.T. Have historical land use/land cover changes triggered a fire regime shift in central Spain? *Fire* **2019**, *2*, 44. [CrossRef]
2. Pausas, J.G.; Fernández-Muñoz, S. Fire regime changes in the western Mediterranean Basin: From fuel-limited to drought-driven fire regime. *Clim. Chang.* **2012**, *110*, 215–226. [CrossRef]
3. Swetnam, T.W.; Allen, C.D.; Betancourt, J.L. Applied historical ecology: Using the past to manage for the future. *Ecol. Appl.* **1999**, *9*, 1189–1206. [CrossRef]
4. Conedera, M.; Tinner, W.; Neff, C.; Meurer, M.; Dickens, A.F.; Krebs, P. Reconstructing past fire regimes: Methods, applications, and relevance to fire management and conservation. *Quat. Sci. Rev.* **2009**, *28*, 555–576. [CrossRef]
5. Abrams, M.D.; Nowacki, G.J. Global change impacts on forest and fire dynamics using paleoecology and tree census data for eastern North America. *Ann. For. Sci.* **2019**, *76*, 8. [CrossRef]
6. Seidl, R.; Spies, T.A.; Peterson, D.L.; Stephens, S.L.; Hicke, J.A. Searching for resilience: Addressing the impacts of changing disturbance regimes on forest ecosystem services. *J. Appl. Ecol.* **2016**, *53*, 120–129. [CrossRef]
7. Keeley, J.E.; Bond, W.; Bradstock, R.; Pausas, J.; Rundel, P. Fire in the Mediterranean Basin. In *Fire in Mediterranean Ecosystems*; Keeley, J.E., Bond, W.J., Bradstock, R.A., Pausas, J.G., Rundel, P.W., Eds.; Cambridge University Press: London, UK, 2012; pp. 83–112.

8. Chergui, B.; Fahd, S.; Santos, X.; Pausas, J.G. Socioeconomic factors drive fire regime variability in the Mediterranean Basin. *Ecosystems* **2017**, *21*, 619–628. [CrossRef]
9. López-Sáez, J.A.; Vargas, G.; Ruiz-Fernández, J.; Blarquez, O.; Alba-Sánchez, F.; Oliva, M.; Pérez-Díaz, S.; Robles-López, S.; Abel-Schaad, D. Paleofire dynamics in Central Spain during the late Holocene: The role of climatic and anthropogenic forcing. *Land. Degrad. Dev.* **2018**, *29*, 2045–2059. [CrossRef]
10. Montiel-Molina, C. Reconstrucción del régimen de incendios del centro de España durante los últimos quinientos años. In *Presencia Histórica del Fuego en el Territorio*; Montiel-Molina, C., Ed.; Ministerio de Agricultura, Alimentación y Medio Ambiente: Madrid, Spain, 2013; pp. 14–42.
11. Morales-Molino, C.; Colombaroli, D.; Valbuena-Carabaña, M.; Tinner, W.; Salomón, R.L.; Carrión, J.S.; Gil, L. Land-use history as a major driver for long-term forest dynamics in the Sierra de Guadarrama National Park (central Spain) during the last millennia: Implications for forest conservation and management. *Glob. Planet. Chang.* **2017**, *152*, 64–75. [CrossRef]
12. Morales-Molino, C.; Tinner, W.; García-Antón, M.; Colombaroli, D. The historical demise of *Pinus nigra* forests in the Northern Iberian Plateau (south-western Europe). *J. Ecol.* **2017**, *105*, 634–646. [CrossRef]
13. Camarero, J.J.; Sangüesa-Barreda, G.; Montiel-Molina, C.; Seijo, F.; López-Sáez, J.A. Past growth suppressions as proxies of fire incidence in relict Mediterranean black pine forests. *For. Ecol. Manag.* **2018**, *413*, 9–20. [CrossRef]
14. Camarero, J.J.; Sangüesa-Barreda, G.; Pérez-Díaz, S.; Montiel-Molina, C.; Seijo, F.; López-Sáez, J.A. Abrupt regime shifts in post-fire resilience are fueled by land use changes in Mediterranean pinewoods. *Int. J. Wildl. Fire* **2019**, *28*, 329–341. [CrossRef]
15. Génova, M.; Gómez, F.; Morla, C. (Eds.) *Los Bosques de Gredos a Través del Tiempo*; Junta de Castilla y León: Valladolid, Spain, 2009.
16. López-Merino, L.; López-Sáez, J.A.; Alba-Sánchez, F.; Pérez-Díaz, S.; Carrión, J.S. 2000 years of pastoralism and fire shaping high-altitude vegetation of Sierra de Gredos in central Spain. *Rev. Palaeobot. Palynol.* **2009**, *158*, 42–51. [CrossRef]
17. López-Sáez, J.A.; Sánchez-Mata, D.; Alba-Sánchez, F.; Abel-Schaad, D.; Gavilán, R.G.; Pérez Díaz, S. Discrimination of Scots pine forests in the Iberian Central System (*Pinus sylvestris* var. *iberica*) by means of pollen analysis. Phytosociological considerations. *Lazaroa* **2013**, *34*, 191–208.
18. López-Sáez, J.A.; Abel-Shaad, D.; Pérez-Díaz, S.; Blanco González, A.; Alba-Sánchez, F.; Dorado, M.; Ruíz Zapata, B.; Gil-García, M.J.; Gómez González, C.; Franco Múgica, F. Vegetation history, climate and human impact in the Spanish Central System over the last 9000 years. *Quat. Int.* **2014**, *353*, 98–122. [CrossRef]
19. López-Sáez, J.A.; Alba-Sánchez, F.; Sánchez-Mata, D.; Luengo-Nicolau, E. *Los Pinares de la Sierra de Gredos. Pasado, Presente y Futuro*; Institución Gran Duque de Alba: Ávila, Spain, 2019.
20. Fernandes, P.M.; Vega, J.A.; Jiménez, E.; Rigolot, E. Fire resistance of European pines. *For. Ecol. Manag.* **2008**, *256*, 246–255. [CrossRef]
21. Caudullo, G.; Welk, E.; San-Miguel-Ayanz, J. Chorological maps for the main European woody species. *Data Brief* **2017**, *12*, 662–666. [CrossRef]
22. Gallardo, J.F.; Cuadrado, S.Y.; González-Hernández, M.I. *Suelos Forestales de la Vertiente sur de la Sierra de Gredos*; VII Anuario del Centro de Edafología y Biología Aplicada de Salamanca: Salamanca, Spain, 1980; pp. 155–168.
23. Moreno, J.M.; Viedma, O.; Zavala, G.; Luna, B. Landscape variables influencing forest fires in central Spain. *Int. J. Wildl. Fire* **2011**, *20*, 678–689. [CrossRef]
24. Tapias, R.; Climent, J.; Pardos, J.A.; Gil, L. Life histories of Mediterranean pines. *Plant. Ecol.* **2004**, *171*, 53–68. [CrossRef]
25. Cook, E.R.; Kairiukstis, L.A. (Eds.) *Methods of Dendrochronology: Applications in the Environmental Sciences*; IIASA: Dordrecht, The Netherlands, 1990.
26. Holmes, R.L. Computer assisted quality control in tree-ring dating and measurement. *Tree-Ring Bull.* **1983**, *43*, 69–78.
27. Cook, E.R. *Turbo Arstan Software: Version 36. Lamont–Doherty Earth Observatory*; Palisades: New York, NY, USA, 2002.
28. International Tree-Ring Data Bank (ITRDB). Available online: https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring (accessed on 1 February 2021).
29. Génova, M. Anillos de crecimiento y años característicos en el Sistema Central (España) durante los últimos cuatrocientos años. *Bol. R. Soc. Hist. Nat. Sec. Biol.* **2000**, *96*, 33–42.
30. Génova, M.; Moya, P. Dendroecological analysis of relict pine forests in the centre of the Iberian Peninsula. *Biodiv. Cons.* **2012**, *21*, 2949–2965. [CrossRef]
31. Niklasson, M.; Granström, A. Numbers and sizes of fires: Long-term spatially explicit fire history in a Swedish boreal landscape. *Ecology* **2000**, *81*, 1484–1499. [CrossRef]
32. Duncan, R.P. An evaluation of errors in tree age estimates based on increment cores in kahikatea (*Dacrycarpus dacrydioides*). *N. Zeal. Nat. Sci.* **1989**, *16*, 31–37.
33. López-Sáez, J.A.; Alba-Sánchez, F.; Robles, S.; Pérez-Díaz, S.; Abel-Schaad, D.; Sabariego, S.; Glais, A. Exploring seven hundred years of transhumance, climate dynamics, fire and human activity through a historical mountain pass in central Spain. *J. Mount. Sci.* **2016**, *13*, 1139–1153. [CrossRef]
34. López-Sáez, J.A.; Sánchez-Mata, D.; Gavilán, R.G. Syntaxonomical update on the relict groves of Scots pine (*Pinus sylvestris* L. var. Ibérica Svoboda) and Spanish black pine (*Pinus nigra* Arnold subsp. *salzmannii* (Dunal) Franco) in the Gredos range (central Spain). *Lazaroa* **2016**, *37*, 153–172.

35. López-Sáez, J.A.; Abel-Schaad, D.; Luelmo-Lautenschlaeger, R.; Robles-López, S.; Pérez-Díaz, S.; Alba-Sánchez, F.; Sánchez-Mata, D.; Gavilán, R. Resilience, vulnerability and conservation strategies in high-mountain pine forests in the Gredos Range, central Spain. *Plant. Ecol. Div.* **2018**, *11*, 97–110. [CrossRef]
36. López-Sáez, J.A.; Blanco-González, A.; Abel-Schaad, D.; Robles-López, S.; Luelmo-Lautenschlaeger, R.; Pérez-Díaz, S.; Alba-Sánchez, F. Transhumance dynamics in the Gredos range (central Spain) during the last two millennia. Environmental and socio-political vectors of change. In *Historical Archaeologies of Transhumance across Europe*; Costello, E., Svensson, E., Eds.; Routledge: London, UK, 2018; pp. 233–244.
37. Valdés, C.M. La presencia histórica de los incendios forestales en el centro y este peninsular. Fuentes, metodología y resultados. In *Incendios Históricos: Una Aproximación Multidisciplinar*; Araque, E., Ed.; UNIA: Baeza, Spain, 1999; pp. 63–110.
38. Broothaerts, N.; Robles-López, S.; Abel-Schaad, D.; Pérez-Díaz, S.; Alba-Sánchez, F.; Luelmo-Lautenschlaeger, R.; Glais, A.; López-Sáez, J.A. Reconstructing past arboreal cover based on modern and fossil pollen data: A statistical approach for the Gredos Range (Central Spain). *Rev. Palaeobot. Palynol.* **2018**, *255*, 1–13. [CrossRef]
39. Klein, J. *The Mesta: A Study in Spanish Economic History 1273–1836*; Harvard University Press: Cmabridge, MA, USA, 2013.
40. Génova, M.; Ortega, P.; Sadornil, E. The effects of fire on *Pinus sylvestris* L. as determined by dendroecological analysis (Sierra de Gredos, Spain). *iForests* **2021**, in review.
41. Christopoulou, A.; Fulé, P.Z.; Andriopoulos, P.; Sarris, D.; Arianoutsou, M. Dendrochronology-based fire history of *Pinus nigra* forests in Mt Taygetos, Southern Greece. *For. Ecol. Manag.* **2013**, *293*, 132–139. [CrossRef]
42. Sarris, D.; Christopoulou, A.; Angelonidi, E.; Koutsias, N.; Fulé, P.Z.; Arianoutsou, M. Increasing extremes of heat and drought associated with recent severe wildfires in southern Greece. *Reg. Environ. Chang.* **2014**, *14*, 1257–1268. [CrossRef]
43. Fulé, P.Z.; Ribas, M.; Gutiérrez, E.; Vallejo, R.; Kaye, M.W. Forest structure and fire history in an old *Pinus nigra* forest, eastern Spain. *For. Ecol. Manag.* **2008**, *255*, 1234–1242. [CrossRef]
44. Slimani, S.; Touchan, R.; Derridj, A.; Kherchouche, D.; Gutiérrez, E. Fire history of Atlas cedar (*Cedrus atlantica* Manetti) in Mount Chélia, northern Algeria. *J. Arid Environ.* **2014**, *104*, 116–123. [CrossRef]
45. Sánchez-Salguero, R.; Linares, J.C.; Camarero, J.J.; Madrigal-González, J.; Hevia, A.; Sánchez-Miranda, A.; Ballesteros-Cánovas, J.; Alfaro-Sánchez, R.; García-Cervigón, A.I.; Bigler, C.; et al. Disentangling the effects of competition and climate on individual tree growth: A retrospective and dynamic approach in Scots pine. *For. Ecol. Manag.* **2015**, *358*, 12–25. [CrossRef]
46. Luterbacher, J.; Dietrich, D.; Xoplaki, E.; Grosjean, M.; Wanner, H. European seasonal and annual temperature variability, trends and extremes since 1500. *Science* **2004**, *303*, 1499–1503. [CrossRef]