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The effects of fire on *Pinus sylvestris* L. as determined by dendroecological analysis (Sierra de Gredos, Spain)

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Iberian populations of Scots pine (*Pinus sylvestris* L.) have been declining since the late-glacial period; among those that remain, relict stands have great biological and ecological value. This paper investigates the effects of a 2009 fire on tree growth in one of these small populations in the Sierra de Gredos (Spain) by examining the responses recorded in the tree-ring width series of the surviving trees. The current status and distribution of these surviving trees reveal the severity of the fire; indeed most show scars or other evidence of fire damage. Dendroecological analysis revealed narrower tree rings, indicating negative pointer years for the year of the fire and the following year. A very significant reduction in growth was recorded for the years after the fire, both in terms of tree-ring width and basal area increment; incomplete and even absent rings were also recorded. No relationship was seen between these effects and climatic events. The dates and geographical extension of former possible disturbances were also investigated, using the data from these same trees plus information collected from others in the region. The vulnerability of these populations to past fires was evident. Lastly, given the problems affecting the regeneration of these relict populations, it is strongly suggested to urgently include all these populations in conservation and environmental management programs.

Keywords: Disturbances, Tree-ring Width, Growth Change, Absent Rings, Negative Pointer Years

Introduction

Forest fires are a serious ecological, economic and social problem in Spain. Year after year, the Province of Ávila has been one of the interior areas with the greatest number of such fires (Palacios 2013). The centre and south of the province are home to several ranges that belong to the larger Sistema Central. The highest of these ranges, the Sierra de Gredos, was declared a Regional Park in 1996. Summer thunderstorms and human activity in the area, which has been present for millennia (Génova et al. 2009, López-Sáez et al. 2019), have long rendered the Sierra de Gredos a hot spot for forest fires (Palacios 2013, Vázquez De La Cueva 2016). Moreover, the last 50 years have seen huge urban expansion, along with an increase in tourism and sporting activities, which together have led to a new urban-forest interface that increases the risk of fires and makes it more difficult to extinguish them (Galiana 2012). In July 2009, for example, a fire affected eight municipalities belonging to the Sierra de Gredos Regional Park. Apart from the lamentable loss of human life, it caused enormous ecological damage affecting over 4200 ha, of which 2600 within the Park itself. The municipality of Cuevas del Valle was particularly badly affected; indeed, 1500 ha were completely destroyed and the La Rubía Scots pine (*Pinus sylvestris* L.) forest, which lies within this municipality, was very badly hit.

The La Rubía forest, along with other woods and stands of Scots pine that still survive in the Sierra de Gredos, mark the southwestern limit of all natural populations of this species (Willkomm 1896, Gaussen 1949). Génova et al. (1988) mapped the distribution of Scots pine forests in the Sierra de Gredos, a work enhanced and updated some years later (Génova et al. 2009). Recently, López-Sáez et al. (2019) provided very detailed, specific and current information on the different sites where these stands are located. Though now reduced in size, the past extent and dominance of these forests is evident from the abundant *Pinus* pollen in the palaeopalynological sequences for different localities in the Sierra, as they also are from the dating of the numerous macroremains discovered therein (López-Sáez et al. 2014, 2016, Rubiales & Génova 2015).

A number of studies involving dendrochronological methods have provided information on *P. sylvestris* forests from different places within the Sierra de Gredos. Covering the period 1923-1977, F. H. Schweingruber analysed the first tree-ring width (TRW) data for the Sierra de Gredos (International Tree-Ring Data Bank [ITRDB], code SPAI058). Later, Richter (1988, Richter et al. 1991) built chronologies for this species for the municipalities of Navarredonda de Gredos and Hoyos del Espino (ITRDB, codes SPAI033 and SPAI034), as did García-

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Calvo (2004) and Génova et al. (2009) for Cuevas del Valle. Other tree-ring chronologies for pure Scots pine stands and for its mixed forest with *Quercus pyrenaica* – for 1839-2010 and 1844-2010, respectively – have recently been recorded for Hoyocasero (Gea-Izquierdo et al. 2015), and for Navarredonda de Gredos for the period 1805-2011 (Romero 2014).

Fire can damage trees to different extents depending on how the crown and trunk are affected. Dendroecological analysis are commonly used to estimate the harm caused to the growth of fire-surviving trees, to establish the extent of fires, or to draw up records of fires (Beghin et al. 2011, Mclauchlan et al. 2020). The frequency of fires has been determined *via* the dating of scars when the cambium dies (Niklasson & Granström 2000, Swetnam & Baisan 2003, Mclauchlan et al. 2020). However, this kind of damage is not always evident and sometimes does not occur; other data sources (proxies) that can indicate the disturbances caused by fire are therefore needed. Among these, changes in radial growth can be used, determined by measuring the TRWs or determining the absence of tree rings in surviving trees. Reductions in TRW measurements, along with interruptions in radial growth, can then be used to collate a record of the fires to which a tree has been exposed (Bond & Van Wilgen 1996, Ortloff 1996, DeBano et al. 1998, Beghin et al. 2011, Battipaglia et al. 2014). In Spain, a number of such studies have been undertaken using dendroecological techniques, including those of Vega-Hidalgo (2000), Fulé et al. (2008), Génova et al. (2008) and Rozas et al. (2011), and more recently those of Alfaro-Sánchez et al. (2018) and Camarero et al. (2018). These studies dated fire scars, absent tree rings, indicator rings (very narrow), and changes in the growth pattern, to establish records and estimate the frequency and geographical extension of fires. However, the direct consequences of known fires have only been examined by Rozas et al. (2011) and Alfaro-Sánchez et al. (2018).

In general, the available palaeobotanical data suggest *P. sylvestris* has suffered a reduction in its Iberian range since the late-glacial period. This fragmentation of the original range has left marginal, relict populations of great biological and ecological importance, among the most vulnerable of which are those of the Sierra de Gredos (Morla et al. 2009). Fire and the difficulty in regeneration are major factors of this vulnerability (Génova et al. 1988, Morla et al. 2009, and field observations in this study). Currently, the uncontrolled increase in the number of Iberian ibex (*Capra pyrenaica* subsp. *victoriae*) is all but preventing *P. sylvestris* stands from regenerating. Indeed, almost no saplings were located anywhere in the study area, a likely consequence of the ibex browsing. Although the ibex almost became locally extinct in the 20th century, the protection offered by the *Coto Real* in 1905 (when just 10 individuals were left), and the declaration of the Sierra as a Regional Park and a Regional Hunting Reserve in 1996, has allowed their population to climb to over 8000 (Alados & Escós 2017).

The aims of the present work were: (i) to examine the direct effects of the above-mentioned forest fire occurred in July 2009 on the growth of surviving *P. sylvestris* trees at the La Rubía site, using dendrochronological methods and dendrometic evidence; (ii) to detect other former environmental disturbances affecting these and other Scots pines across the Sierra de Gredos; and (iii) to use the information gathered to help document a regional and/or local fire record. A better understanding of how fire affects tree growth could be useful in plans to protect these threatened pine forests.

Materials and methods

Study area and tree sampling

The La Rubía Scots pine forest study site lies within the Sierra de Gredos Regional Park (in the south of the Province of Ávila, Spain) near the Puerto del Pico mountain pass (1390 m a.s.l. – Fig. 1). This pass is an important natural connection between the Northern and Southern Iberian *Mesetas*; it has been used since ancient times (Génova et al. 2009) and became key in transhumance systems (López-Sáez et al. 2016). Human use of fire (which favoured the appearance of pasture) and the commercial logging of the larger Scots pine trees, have together modified the structure and tree density of this area, and of all Scots pine forests in the Sierra de Gredos (Génova et al. 2009, López-Sáez et al. 2019).

This area was heavily damaged by a forest fire in July 2009. Its geographical extent was determined *via* visual analysis of aerial photographs taken before and after the event (material provided by the *Centro de Descargas del CNIG*, https://www.centrodedescargas.cnig.es – Fig. 1). The current status and distribution of the surviving trees indicate the severity of the fire; some old *P. sylvestris* trees remain, along with some younger trees, although most show scars or other evidence of fire damage. The area also has many burnt remains (Fig. 2).

In November and December of 2018, dendrochronological samples were taken using a Pressler borer from 23 surviving trees (young and mature) at the La Rubía site (altitude 1600 m a.s.l. – Fig. 1). At least two samples were taken from each tree, including samples from injured parts of the trunk. Dendrometric data were also recorded for each tree, along with any external evidence of fire damage.

Climate data

The meteorological records available for the region (AEMET, *Agencia Estatal de Meteorología, Gobierno de España*, 2021) were compiled, but since they were discontinuous and incomplete, mean annual temperatures and total annual precipitations were calculated for the 1950-2020 period using data from nearby meteorological stations (2818E, 2820, 2834, 3319D, 3405, 3407, 3416). These stations are located at different altitudes, so each series of climate data was standardized against their mean. Values exceeding the standard deviation were used to identify the most anomalous years (Fig. 3).

Effects of the 2009 fire on the sampled trees

Borer samples were prepared and sectioned for the visualization of tree rings, and the width of each ring determined to within 1/100 mm using a LINTAB measuring table. The synchronization and dating of the tree rings were determined by graphical and statistical analysis using TSAPWIN (Rinn 2011) and COFECHA (Holmes 1999) software. To establish the effect of fire on the radial growth of trees, the following items were recorded: (i) anomalies in tree growth, including scars, and incomplete and/or absent rings for the two years following the fire (2010 and 2011); all were detected during the synchronization process;

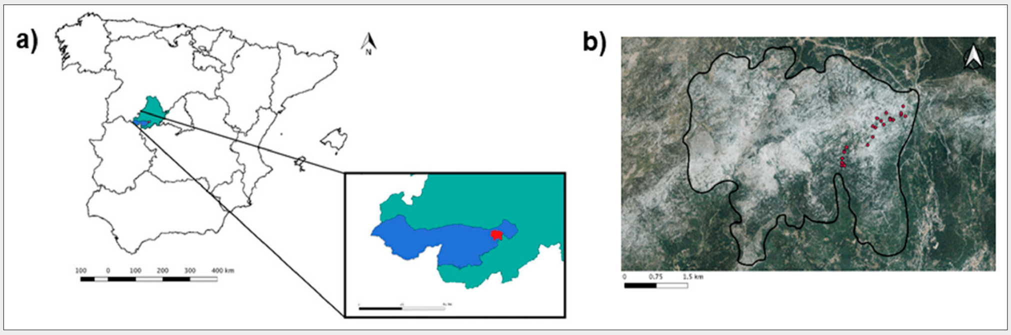

Fig. 1 - (a) Location of the study area (red) in the Sierra de Gredos Regional Park (blue) within the Province of Ávila (green); (a) study area marked on an aerial photograph taken in 2018 (http://www.centrodedescargas.cnig.es) nine years after the fire. The red dots show the location of the sampled trees.

(ii) narrower tree rings indicating negative pointer years for the year of the fire and the following year (2009 and 2010), *i.e.*, a TRW differing by ≥ 20% from the mean for the examined ring plus the immediately previous ring (Holmes 1992). Pointer years were recognised as such when shown by >75% of the TRW series examined; (iii) growth changes from 2009, both in terms of TRW and basal area increment (*BAI*). The BAI was estimated as (eqn. 1):

$$BAI=\pi\left(R_t^2-R_{t-1}^2\right) \quad (1)$$

where R_t and R_{t-1} are respectively the radii corresponding to the end and the beginning of the annual TRW for the year *t* (Biondi & Qeadan 2008). The percentage growth change (*GC*) was determined as (eqn. 2):

$$GC=\frac{M2-M1}{M1}\cdot 100 \quad (2)$$

where *M1* is the mean for *n* years prior to the fire, and *M2* the mean of *n* years after the fire (Nowacki & Abrams 1997). *M1* and *M2* were calculated for 5 and 10 years, according to Nowacki & Abrams (1997) and Camarero et al. (2018). The threshold for recognising a *GC* in a tree was a change of ≥25% (Nowacki & Abrams 1997), and ≥50% for sets of trees (Gea-Izquierdo & Cañellas 2014).

Detection of other environmental disturbances in Scots pines of the Sierra de Gredos

Other environmental disturbances reflected by the trees at the La Rubía site (this study), by the *P. sylvestris* TRW series for the Sierra de Gredos compiled from the ITRDB (codes SPAI033 and SPAI034), and from García-Calvo (2004), Génova et al. (2009) and Romero (2014), were also studied. For both the La Rubía and these raw series, negative pointer years and growth changes were recorded using the same methods indicated in the previous section, in this case for the common period 1900-2000.

Local chronologies were obtained by standardizing the raw series with spline models and using the robust mean, employing ARSTAN software (Cook & Krusic 2008). The expressed population signal (EPS) was determined for each of the indices of the chronologies. The EPS measures the statistical quality of the mean site chronology compared to a perfect, infinitely replicated chronology (Wigley et al. 1984); a value of >0.85 is the minimum required for selecting a representative period. For such periods, the intercorrelation (IT – Holmes 1999) and the cross-date index (CDI) between the chronologies were calculated to determine their cross correlation. The CDI combines the standard Student *t* values with the sum of the equal slope intervals (Rinn 2011).

The common negative pointer years for the chronologies were determined according to Génova et al. (2009), *i.e.*, through the growth indices that decreased in the way described above and through the reductions by one or more standard deviations with respect to the mean for the chronology.

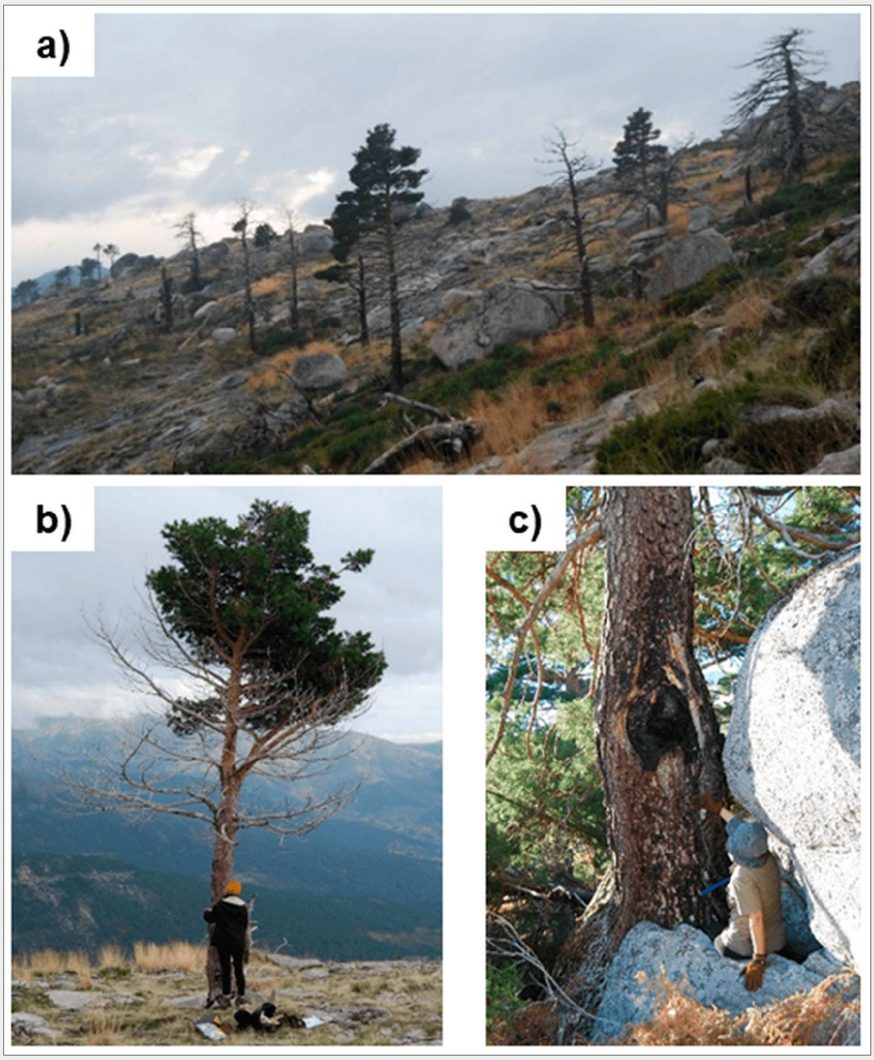

Fig. 2 - (a) View of the La Rubía site with dead (but standing) trees, and some survivors; (b) a surviving tree with over 50% of its crown lost; (c) tree with a large scar caused by a fire dating back to 1975.

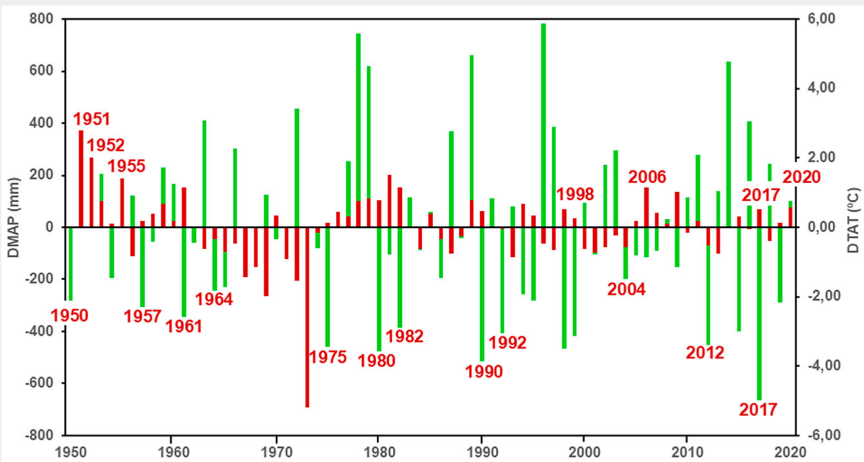

Fig. 3 - Differences in mean annual precipitation (DMAP, green bars) and total annual temperature (DTAT, red bars) with respect to the mean for the meteorological series of data analysed. The driest and warmest years (exceeding the standard deviation) are shown in the lower and upper parts of the graph, respectively.

Tab. 1 - Characteristics of the trees sampled at the La Rubía site. (ER): estimated trunk radius; (MSL): maximum sample length; (MNR): maximum number of tree-rings; (MTRW): mean TRW.

ID	External evidence	ER (cm)	MSL (mm)	MNR	MTRW (mm)	Time span
RU01	fallen tree over trunk	53.34	402.76	177	2.28	1842-2018
RU02	fallen tree over crown	21.82	194.86	44	4.43	1975-2018
RU03	fire scar, 50% crown defoliated	14.33	107.4	42	2.56	1977-2018
RU04	fire scar, 30% crown defoliated	32.48	223.68	79	2.83	1940-2018
RU05	fire scar, 30% crown defoliated	25.64	196.8	62	3.17	1957-2018
RU06	old fire scar	35.03	299.49	156	1.92	1863-2018
RU07	fire scar	18.31	138.97	53	2.62	1966-2018
RU08	fire scar, 30% crown defoliated	41.08	270.32	144	1.88	1875-2018
RU09	30% crown defoliated, roots exposed	19.11	151.58	37	4.10	1982-2018
RU10	fire scar	21.5	165.58	38	4.36	1981-2018
RU11	30% crown defoliated, roots exposed	17.04	116.52	31	3.76	1988-2018
RU12	none	28.98	229.66	35	6.56	1984-2018
RU13	20% crown defoliated	31.37	217.86	42	5.19	1977-2018
RU14	old fire scar	37.58	198.66	77	2.58	1942-2018
RU15	none	55.25	338.12	148	2.28	1871-2018
RU16	20% crown defoliated	49.52	311.07	211	1.47	1808-2018
RU17	none	22.93	152	34	4.47	1985-2018
RU18	fire scar	29.3	271.65	50	5.43	1968-2017
RU19	fire scar	25.8	209.11	54	3.87	1965-2018
RU20	fire scar	43.95	277.91	118	2.36	1901-2018
RU21	fire scar	24.04	289.01	147	1.97	1872-2018
RU23	fire scar	20.54	172.91	59	2.93	1960-2018

Results

Effects of the 2009 fire

During synchronization and dating, data from one tree was rejected (samples too damaged); data for 22 trees were therefore used in the following analyses (Tab. 1 and Tab. 2). The estimated radius of the trunk and the maximum number of rings were very variable, ranging from 14 to 55 cm and 31 to 211 rings, respectively. The mean TRW of each tree also varied widely, from 1.47 mm in the oldest tree to 6.56 mm in a young tree (Tab. 1). Nine years after the fire, external evidence of the damage was still visible, including wounds, scars and other traces revealing the trunk to have partially burned (seen in 59% of the examined trees), crown defoliation of 20-50% (seen in 36%), and difficulties in development due to having to sustain the weight of burned and fallen trees, or the exposure of roots due to post-fire erosion (Tab. 1).

Some 41% of the studied trees showed narrower rings in 2009, as did 86% in 2010. In addition, four trees formed no rings or incomplete rings in 2010 and/or 2011 (Tab. 2). Some 64% of the trees showed a significant, negative GC for the TRW series over the 5 years from 2009, as did 59% in *BAI* series (Tab. 2 and Fig. 4). These percentages were similar to those returned when examining the 10 years since the fire (68% and 55% respectively). Those trees for which growth was significantly affected suffered a mean reduction of 46% in TRW, and of 44% in *BAI*, over the five years since the fire, and of 40% and 35%, respectively, over the 10 years since the fire (Tab. 2). In general, the trees that suffered the greatest external damage showed a large reduction in growth, although in some cases a GC of over 40% was seen with no or little evidence of external damage (Tab. 1 and 2).

Other disturbances detected

According to the dated fire scars, two fires occurred at the La Rubía site before 2009: one in 1941 and one in 1975 (see Fig. 2 lower right, and Fig. 4). Moreover, taking into account the TRW series obtained in the present and previous studies (García-Calvo 2004, Génova et al. 2009) for the same area, two negative pointer years were identified: 1941 and 1960 (detected in 87% and 95% of TRW series, respectively). The GC values corresponding to 1941, 1960 and 1975 were significant only over the 5 years from 1960 (64% of trees).

In the additional TRW series of *P. sylvestris* examined (SPAI033, SPAI034 and NAVA – Fig. 5), negative pointer years were detected for 1913 (99% of the TRW series), 1951 (77%) and 1981 (76%). The GC was negative and significant from 1913 to 1923 for 65% of trees.

Four index chronologies were established from the TRW series examined (Tab. 3). The chronology for Cuevas del Valle (CUEV)

Tab. 2 - Tree-ring anomalies and growth changes for the trees sampled at the La Rubía site. (NR 09/10): narrower rings in 2009 and/or 2010; (a) absent or incomplete ring in 2010; (b): absent or incomplete ring in 2011; (GCW5): percentage change in tree-ring width over 5 years from 2009; (GCW10): percentage change in tree-ring width over 10 years; (GCB5): percentage change in basal area over 5 years; (GCB10): percentage change in basal area over 10 years; (*): indicates non-significant change.

ID	NR 09/10	GCW5	GCW10	GCW5	GCW10	ID	NR 09/10	GCW5	GCW10	GCW5	GCW10
RU03	no/yes[ab]	-74.21	-63.09	-71.33	-55.08	RU17	yes/yes	-38.63	-44.74	-29.53	-26.70
RU14	yes/yes	-60.34	-49.97	-58.94	-46.93	RU09	yes/yes	-28.40	-31.97	-23.02*	-18.11*
RU01	no/yes[ab]	-57.84	-44.79	-57.27	-43.16	RU16	no/yes	-26.19	-22.85*	-25.39	-21.24*
RU02	no/yes	-55.16	-45.00	-51.25	-37.10	RU04	no/yes[a]	-24.38*	-25.11	-21.25*	-19.35*
RU13	yes/yes	-47.80	-45.53	-44.90	-39.77	RU08	yes/no	-20.95*	-29.66	-18.75*	-26.31
RU19	no/yes[a]	-47.35	-41.18	-43.36	-32.35	RU23	yes/yes	-18.90*	4.96*	-12.11*	25.59
RU12	no/yes	-46.70	-42.78	-39.81	-25.08	RU06	yes/no	-6.67*	10.67*	-5.69*	13.07*
RU05	yes/yes	-44.60	-38.09	-41.64	-31.16	RU20	no/yes	-5.47*	-2.13*	-2.69*	3.13*
RU10	yes/yes	-41.67	-40.77	-36.10	-27.52	RU15	no/no	-2.09*	18.63*	-0.65*	22.49*
RU18	no/yes	-39.04	-29.78	-35.42	-21.35*	RU11	no/yes	7.55*	-2.20*	25.10	37.95
RU21	no/yes	-39.02	-29.49	-37.37	-25.93	RU07	no/yes	38.32	32.16	57.59	71.26

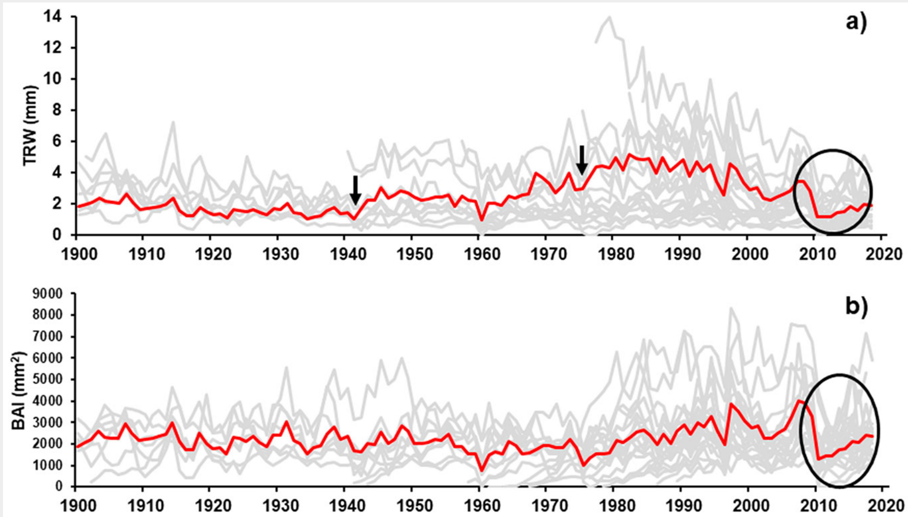

Fig. 4 - Tree-ring width series (TRW) for the La Rubía site for the period 1900-2018. (a) TRW and (b) basal area increments (*BAI*). Grey lines, individual series; red lines, means for the TRW and *BAI* series showing a reduction in growth over the five years since the fire. Red oval: indicates a steep growth change since 2009. Black arrows indicate dates for fire scars before 2009 (1941 and 1975).

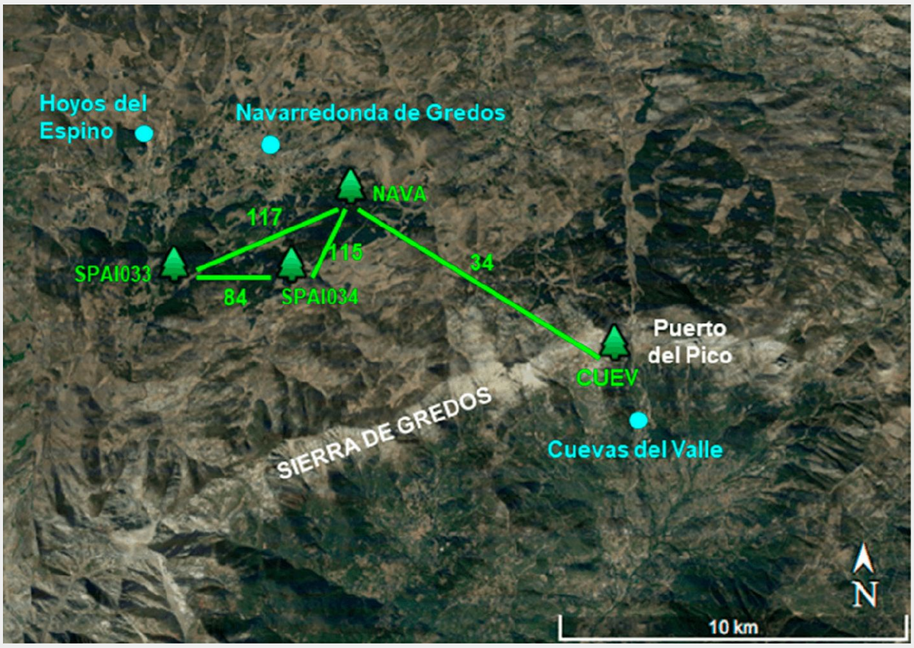

Fig. 5 - Location of *Pinus sylvestris* populations for which chronologies were established in the Sierra de Gredos range. The values between the chronologies are the cross-date index values for 1900-1985.

on the south side of the Sierra collects a long TRW series for the La Rubía site (from the present work) and from the work of García-Calvo (2004) and Génova et al. (2009). The four chronologies obtained are all representatives of the period 1900-1985, with the NAVA chronology extending to 2005 and the CUEV chronology to 2000. The three chronologies established for the northern part of the Sierra de Gredos (SPAI033, SPAI034 and NAVA) showed both high cross-correlation values and IT values (Fig. 5, Tab. 3). However, the chronology for the southern slope (CUEV) showed a lower IT with respect to the latter chronologies (in fact below the acceptance threshold of 0.33 indicated by Holmes 1999). However, the minimum value of 10 for the CDI (Rinn 2011) was reached in all cases, allowing all four chronologies to be considered synchronised.

During the 1900-1985 common representative period of the chronologies for the northern side (SPAI033, SPAI034 and NAVA), four negative pointer years were detected: 1913, 1950, 1951 and 1965. The narrower ring for 1913 was also followed by a negative and significant *GC* for the next 10 years. In contrast, the CUEV chronology (from the southern side) showed negative pointer years for 1941-1942 and 1960-1963, the first two coinciding with fire scars dated to 1941. The period 1960-1963 was a period of very much narrower TRWs, with 1960 returning the lowest chronology indices (Fig. 6). A significant, negative *GC* was also detected for 1960-1965. In general, the main environmental disturbances detected on the opposite sides of the mountain range did not match, although the 1996 negative pointer year was identified in the longest CUEV (south) and NAVA (north) chronologies (Fig. 6).

Tab. 3 - Available TRW series and chronologies for *Pinus sylvestris* in the Sierra de Gredos. (MA): mean altitude; (NT): no. of trees; (NS): no. of TRW series; (EPS): expressed population signal; (IT): intercorrelation for the period 1900-1985; (*): 9 trees from the 2018 sampling and 12 trees from previous samplings.

ID	Latitude (N)	Longitude (W)	MA (m)	NT/ NS	Time span	Time span EPS>0.85	IT
SPAI033 (ITRDB)	40.33	-5.17	1465	12/ 25	1812-1985	1900-1985	0.63
SPAI034 (ITRDB)	40.33	-5.13	1470	12/ 26	1769-1985	1900-1985	0.75
NAVA	40.35	-5.11	1500	32/ 68	1805-2011	1900-2005	0.75
CUEV	40.31	-5.02	1600	21*/ 45	1761-2018	1900-2000	0.19

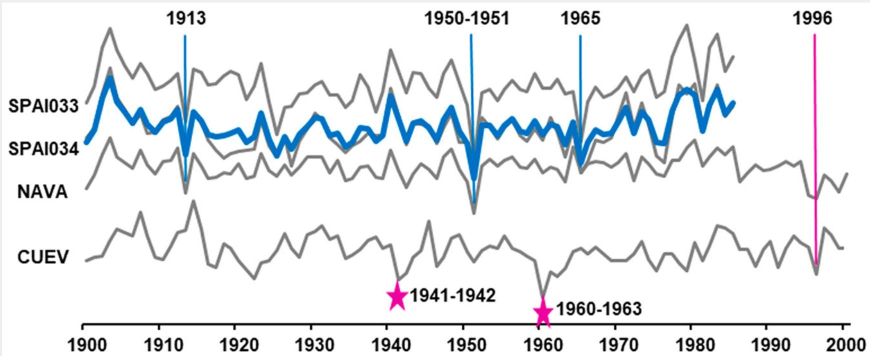

Fig. 6 - Chronologies of tree-ring indices for *P. sylvestris* in the Sierra de Gredos. Grey lines: local chronologies; blue line: mean chronology for the north side. Blue vertical lines indicate the negative pointer years common to the chronologies of the north side. Magenta vertical line indicates the negative pointer year in the two longest chronologies. Magenta stars mark the negative pointer years for the CUEV chronology (south side of the Sierra).

Discussion

The high mountain forests of *Pinus sylvestris* in the Sierra de Gredos, including those located in the Regional Park, have been strongly affected, both in terms of their structure and extension, by anthropic activity. Indeed, they have been reduced to small relict woods and stands over the last 2000 years, mainly due to an increase in the frequency of fires. The devastating fire of 2009 wiped out most of the remaining pines over a vast area of the Sierra; nearly all the survivors show external traces of fire damage.

Studies on *P. sylvestris* in northern Italy (Beghin et al. 2011), and on *P. canariensis* on the island of Tenerife (Rozas et al. 2011), show that incomplete and absent tree rings, such as those noted in the present work, are clear signs of a tree having suffered the effects of fire. While some authors indicate growth to be increased after a fire (Py et al. 2006, Alfaro-Sánchez et al. 2018), especially for trees growing in arid and semi-arid areas, other studies report that surviving trees may experience a reduction in growth (Peterson et al. 1991, Elliott et al. 2002, Beghin et al. 2011, Rozas et al. 2011, Guiterman et al. 2015), or even a mixed response (Peterson et al. 1994, Mutch & Swetnam 1995). Such growth increases might be explained by the reduced competition for water and nutrients after a fire, while the smaller photosynthetic capacity resulting from crown damage might cause reductions in growth. The extent of growth reduction might be expected to reflect fire frequency and/or the severity of damage suffered.

The present results indicate a marked and generalized reduction in growth after the 2009 fire. The significant, negative changes in growth since this year, as reflected by both the TRW and *BAI* data (not very different from each other), lasted for at least 10 years after the fire. They are also comparable to the results reported by Beghin et al. (2011) for *P. sylvestris*, and very similar (in terms of the percentage of damaged trees and the degree and duration of growth reduction) to those reported by Peterson et al. (1991) for *Pseudotsuga menziesii* and *Pinus contorta*. In addition, the negative pointer years recorded in the TRW series for the year of the fire and later – also used in dendroecological studies on the effects of forest fires by Niklasson & Granström (2000), Beghin et al. (2011), and Alfaro-Sánchez et al. (2018) – are here shown to be determinant in identifying the consequences of fire in *P. sylvestris*. Finally, it should be noted that none of the discussed findings appears to be related to any particularly anomalous climatic conditions between 2009 and 2010; the climate data analysed revealed no such anomalies existed (Fig. 3).

While keeping this dendroecological evidence of the effects of fire in mind, other evidence of disturbances prior to 2009 was sought in the TRW series available for *P. sylvestris* across the larger region. The chronologies for the north side of the Sierra de Gredos synchronise well with one another and provide evidence of different events compared to the south side. Indeed, the major disturbances that affected tree-growth on the two sides of the Sierra were often different. In part this is because the Sierra de Gredos forms a huge orographic barrier running east to west, which accentuates its action as a climatic and ecological frontier. On the north side, the year 1913 was the only negative pointer year to coincide with a negative GC in all the examined series and chronologies, indicating a possible forest fire. However, the 1950-1951 negative pointer years were not followed by growth changes; the climatic conditions over this two-year period (precipitation and temperature below and above average, respectively – Fig. 3) could have acted as a driver of growth reduction. On the south side, the fire scars from 1941 and 1975, and the 1941-1942 negative pointer years, perhaps indicate small local fires, even though no more conspicuous evidence was detected. The 1960-1963 period was also one of narrower TRWs; in fact, they were the smallest of the entire period of the south-side chronology (Fig. 6). However, significant changes in tree growth were only seen until 1965. The anomalies detected in 1940-1945 and 1960-1965 on the south side of the Sierra coincide with the negative pointer years identified for the entire Sistema Central by the chronologies of *P. sylvestris* and *P. nigra* (Génova 2000). In addition, the 1942 and 1996 negative pointer years have recently been identified in *P. nigra* chronologies from different sites in the Sierra de Gredos (Camarero et al. 2018), and in the present work the 1996 negative pointer year was also detected in the longest chronologies for both sides of the Sierra. These negative pointer years and periods might be related to adverse climatic episodes for the region (droughts in the early 1960s, 1975, and 1990s – Fig. 3), or for the Iberian Peninsula as a whole (droughts suffered in the 1960s and 1990s – Vicente-Serrano 2006, González-Hidalgo et al. 2018).

Evidence of other fires is also provided by the *P. nigra* trees of the region. In the chronology for Arenal (south side of the Sierra de Gredos), an abrupt reduction or halt in growth is indicated by the large number of incomplete or absent tree rings since 1926, especially for 1927 and 1928 (prolonged in some trees until 1950 – Génova et al. 2008, 2009). Camarero et al. (2018) also reported a relationship between the negative pointer years determined for the *P. nigra* chronologies and the increase seen in historical fires for the region at the end of the 19^{th} century, particularly during the 1880s and 1890s. These fires seem to have coincided with the increase in droughts, as seen for some periods in the present study.

Conclusions

Dendroecological analyses revealed the effects of a 2009 forest fire on the radial growth of *P. sylvestris* in the Sierra de Gredos; these effects are unrelated to any particularly adverse climatic conditions. Almost 70% of the analysed trees showed notable growth reduction since 2010, including old and young trees, and those with and without external evidence of fire damage. In some trees, incomplete or absent rings were also detected.

The major disturbances revealed by the TRW series and the chronologies for *P. sylvestris* did not coincide for the north and south sides of the Sierra. Indeed, the differing synchrony of the chronologies reveals the trees on either side to have been subject to different environmental conditions. Evidence of a possibly local forest fire in 1913 was found for the trees on the north side. Other local forests fires may also have occurred on the south side (in 1941 and 1975), although other evidence suggests the trees may have been responding to adverse climatic conditions.

The present results could be useful in

plans to protect the relict woodland and stands of *P. sylvestris* in the Sierra de Gredos. Given their great biological and ecological value, their vulnerability to forest fires, and the regeneration difficulties they face (owed not least to the browsing of saplings by ibex) suggest they should become an urgent focus of conservation and environmental management.

List of abbreviations

ITRDB: International Tree-Ring Data Bank; TRW: tree-ring width; BAI: basal area increment; GC: growth change; EPS: expressed population signal; IT: intercorrelation; CDI: cross-date index.

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This work is dedicated to our friend and colleague Fernando Gómez Manzaneque, who passed away during the execution of this work. As a tribute to his stature as a teacher and researcher, we offer the following paragraph written by him (here translated) from the book *Los Bosques de Gredos a través del Tiempo* (2009): "This publication cannot be deemed complete without a public and heartfelt expression of gratitude towards those who with their efforts, and sometimes with their lives, have fought the fires that have threatened these forest gems. It is their dedication that has so often saved the trees described in this book. Even as these lines were being penned, the forests of Puerto del Pico and the centuries-old trees of La Rubía were burning."

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