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Fire history in the serpentine-soil Spanish firs of Sierra Bermeja

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Abstract

Background *Abies pinsapo* Clemente ex Boiss. is a species classified as endangered and currently occupies a very small and fragmented area of distribution in the southwest of the Baetic System. The uniqueness of these relict forests has motivated their study from different perspectives: phytogeography, faunal and floristic communities or biotic and abiotic risks. However, the paleoecological characterisation of this fir is still clearly deficient. Consequently, there is hardly any information on the impact that fire has had on this conifer during the Holocene nor the real effect that this disturbance has had on the Spanish fir in recent decades. To fill this knowledge gap, the present research uses the pedoanthracological network developed over the last 10 years in Sierra Bermeja, one of the natural habitats of the Spanish fir forest most affected by fire. This discipline is based on the analysis of the charcoals present in the natural soils, which are an unexplored resource and particularly useful for the reconstruction of paleo-fires and the knowledge of the dynamics of the vegetation. This paleoecological approach has also been complemented by the mapping of recent forest fires. Both approaches constitute the methodological body of this study.

Results The identification of *Abies* charcoal in places where this taxon is not present today supports the idea that the Spanish fir was more widely distributed in the past. Likewise, the available dates (between 9931–9616 and 294–102 years cal BP) have revealed the existence of up to 28 events of forest fires that have affected the Spanish fir during the Holocene. The recurrence of fire could have caused its local extinction in the Sierra Palmitera. This reduction of the distribution area of the Spanish fir as a consequence of fire, as can be inferred from the cartography carried out, has been particularly intense during the last few decades, with almost 4500 fir trees affected.

Conclusions Results report on the important role played by fire in the dynamics of the serpentine-soil Spanish firs of Sierra Bermeja from the Last Glacial Maximum to the present day. This is a phenomenon that has intensified in recent decades, affecting the Spanish fir in a very worrying way. Consequently, we insist on the need to include the whole of Sierra Bermeja in the Spanish National Park Network to help ensure effective protection for the most important serpentine-tolerant ecosystem in Spain.

Keywords Spanish fir, Paleofires, Recent fires, Pedoanthracology, Remote sensing, Serranía de Ronda

Resumen

Antecedentes *Abies pinsapo* Clemente ex Boiss es una especie catalogada en peligro de extinción que actualmente ocupa un área de distribución muy reducida y fragmentada en el suroeste del Sistema Bético. La singularidad de estos bosques relictos ha motivado su estudio desde diferentes perspectivas: fitogeografía, comunidades faunísticas y florísticas o riesgos bióticos y abióticos. Sin embargo, la caracterización paleoecológica de este abeto es aún claramente

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deficiente. En consecuencia, apenas se dispone de información acerca del impacto que el fuego ha tenido sobre esta conífera durante el Holoceno, ni sobre el efecto real que esta perturbación ha tenido sobre el pinsapo en las últimas décadas. Para cubrir este vacío de conocimiento, la presente investigación utiliza la red pedoantracológica desarrollada durante los últimos diez años en Sierra Bermeja, uno de los hábitats naturales del pinsapar más afectados por el fuego. Esta disciplina se basa en el análisis de los carbones presentes en los suelos naturales, que constituyen un recurso inexplorado y particularmente útil para la reconstrucción de paleoincendios y el conocimiento de la dinámica de la vegetación. Este enfoque paleoecológico también se ha complementado con el cartografiado de los incendios forestales recientes. Ambas aproximaciones constituyen el cuerpo metodológico de esta investigación.

Resultados La identificación de carbón de *Abies* en lugares donde este taxón no está presente en la actualidad sustenta la idea de que el pinsapo tuvo una distribución más amplia en el pasado. Asimismo, las dataciones disponibles (con fechas comprendidas entre 9931 – 9616 y 294 – 102 años cal BP) han revelado la existencia de hasta 28 eventos de incendios forestales que han afectado al pinsapo durante el Holoceno. La recurrencia del fuego podría haber provocado su extinción local en la Sierra Palmitera. Esta reducción del área de distribución del pinsapo como consecuencia del fuego, según se desprende de la cartografía realizada, ha sido especialmente intensa durante las últimas décadas, con casi 4500 pinsapos afectados.

Conclusiones Los resultados informan del importante papel desempeñado por el fuego en la dinámica de los pinsapares serpentinícolas de Sierra Bermeja desde el Último Máximo Glaciar hasta la actualidad. Se trata de un fenómeno que se ha intensificado en las últimas décadas, afectando al pinsapar de forma muy preocupante. En consecuencia, insistimos en la necesidad de incluir a la totalidad de Sierra Bermeja en la Red de Parques Nacionales de España para contribuir a la protección efectiva del ecosistema serpentínico más importante de España.

Palabras clave Pinsapo, Paleoincendios, Incendios recientes, Pedoantracología, Teledetección, Serranía de Ronda

Introduction

Throughout the Holocene, vegetation landscapes have undergone important transformations, with climate variability and increasing human activity over the last 10,000 years being the main factors driving this process (Alba-Sánchez et al. 2021; Carrión 2022; Jiménez-Moreno et al. 2023). The most affected areas include mountain forests, which fragile ecosystems have been severely transformed by humans in search of the resources they provide (Walsh et al. 2006; Ejarque et al. 2010). In the particular case of the Mediterranean region, it is also important to bear in mind that fire has been the dominant large-scale disturbance process affecting forests and woodlands. This is why wildland fires are regarded as important elements in Mediterranean landscapes and ecosystems (Fernándes 2013; Safford and Ramón-Vallejo 2019), as shown in research in different Mediterranean regions (Ajbilou et al. 2006; Gil-Romera et al. 2008; Tinner et al. 2016).

In recent decades, the statistics on forest fires seem to indicate that fires are happening more frequently and affecting larger areas than in the past (Tyukavina et al. 2022). Data associate the increase in episodes of this kind with Global Change and the climate crisis (Flannigan et al. 2006; Stephens et al. 2013). Climate change is projected to increase heat waves and drought in all the regions with a Mediterranean climate (Lionello et al. 2014). The associated increase in temperature and fall in precipitation will increase the risk of forest/rural fires (Safford and Ramón-Vallejo 2019; Misir and Misir 2021; Nunes et al. 2022). Different projections indicate that these climatic effects will lead to an increase in the number of fires if no further improvements in fire management are introduced (Turco et al. 2014). Fire-smart management, focused on mitigating fire severity and enhancing the resilience of forests to fire, is therefore essential for sustainability of many species in the Mediterranean region (Fernándes 2013).

Noteworthy in this section *Abies pinsapo* Clemente ex Boiss. (Spanish fir), an endangered species of high ecological value that makes up unique forests and environments in the Mediterranean basin (Linares and Carreira 2006; Linares 2011). *A. pinsapo* is an endemic species of the Rondeño and Bermejense biogeographic sectors in the Serranía de Ronda (Pérez-Latorre et al. 2021) and is currently only found in the Western Baetic System and more specifically in the Sierra de las Nieves and Sierra Bermeja in the province of Malaga and in the Sierra del Pinar and the Sierra del Endrinal in the province of Cádiz, where it forms meso- and supra-Mediterranean forests (Galán de Mera and Pérez-Latorre, 2021; Gómez-Zotano and Olmedo-Cobo 2021). These are mountainous areas with unique geo-ecological characteristics within the context of the Mediterranean Biogeographical Region. This ecological and biogeographical uniqueness allows the existence of optimal environmental conditions for the Spanish fir that have enabled its survival in southern Iberia during the Holocene (Linares and Carreira 2006; Jaramillo et al. 2010; Pardo-Martínez et al. 2021).

Within its small distribution area, this species is particularly endangered in the ultramafic massif of Sierra Bermeja, where the alarming current situation of isolation of its populations due to the fragmentation of its habitat is damaging the viability and the genetic exchange in the only serpentine-tolerant Spanish fir forests on the planet (Linares et al. 2009; Linares 2011; Guzmán et al. 2013). Soto (2006) reports that seven stands of serpentine-tolerant Spanish fir forests have disappeared as a result of fire in recent decades, reducing the current area of Spanish fir in Sierra Bermeja to only 35 ha.

Sierra Bermeja is well-known for the high risk and extreme intensity of its forest fires and has been identified as one of the most important *hotspots* on the Iberian Peninsula (García-Gómez 1999; Vega-Hidalgo 1999; Gutiérrez-Hernández et al. 2015). There are various natural factors that contribute to the start and spread of fires, such as dense, highly combustible biomass, a very uneven topography, strong winds or the high summer temperatures. However, there are also a range of social and economic factors at the root of these disasters: the poor returns from forest resources, depopulation of rural areas, excessive pressure from rural tourism, abandonment of farmland and land use change. Separately or in combination, all these factors result in the frequent appearance of fires, many of which are started deliberately (García-Gómez 1999; Gómez-Zotano 2006).

However, there is often a lack of information as to how much Spanish fir forests have been affected by fire. In this research, we reformulate the question by proposing that forest fires, as one of the main factors that may have led to the reduction of the distribution area of the Spanish fir, are an excellent opportunity to collect palaeoecological information, especially when reconstructing the historical geography of forest fires (Nelle et al. 2013; Carracedo-Martín et al. 2017). In view of this consideration, the main objective of this research is to improve the knowledge about fire history of the Spanish firs of Sierra Bermeja. For this, we use the pedoanthracological network developed by Gómez-Zotano et al. (2017), Olmedo-Cobo et al. (2017, 2019a, b, 2021) and Pardo-Martínez et al. (2021) over the last 10 years in southern Spain, focusing the attention on the genus *Abies* in the Sierra Bermeja subregion. In parallel to this paleoecological approach, we also analyse the main forest fires that took place in the second half of the twentieth century. To this end, we consulted various different documentary and oral sources, together with the data and the analyses obtained by remote sensing based on the processing of satellite images from 1975 onwards. This enabled us to georeference and map the area covered by the fires and determine the territorial and temporal recurrence thereof. This information, combined with floristic and phylogeographic data, could be a key asset in the future recovery of relict and threatened species such as *A. pinsapo*.

Methods

Study area

Sierra Bermeja is located in the Serranía de Ronda (SW Baetic System) and is one of the largest ultramafic outcrops on the planet (300 km^2) (Fig. 1).

Lithologically speaking, the Sierra is dominated by peridotites, a fact that affects almost all its abiotic and biotic characteristics——soils, modelling, plant occupation, fauna. This igneous rock is very dense and is composed of ferromagnesian minerals known generically as serpentines, once they have been altered by geochemical weathering processes (Walsh et al. 2006; Ejarque et al. 2010).

The serpentine soils derived from the peridotites are rich in heavy metals such as cobalt, chromium and nickel. They also lack essential elements such as calcium, potassium and phosphorus. Consequently, they are not very fertile and create an adverse litho-edaphic context for biological occupation (Hidalgo-Triana 2016). There is a sub-humid to humid Mediterranean climate, albeit with cryptoprecipitation in the summer due to low cloud cover associated with easterly winds. Three bioclimatic stages can be distinguished: thermo-Mediterranean (up to 800 m a. s. l.), meso-Mediterranean (800–1300 m a. s. l.) and supra-Mediterranean (over 1300 m a. s. l.) (Gómez-Zotano 2004; Olmedo-Cobo and Gómez-Zotano 2017). Within these there are two main types of forest: the *Pinus pinaster* forests on ultramafic rock that can tolerate unusually dry conditions and at higher altitude the *A. pinsapo* forest, whose growth on serpentine soils makes this Spanish fir forest a unique plant formation on the planet (Gómez-Zotano et al. 2014; Hidalgo-Triana and Pérez-Latorre 2016).

Although the geological characteristics of these mountains enable them to be clearly distinguished from their surrounding natural spaces, for this study, we selected a clearly defined study area whose boundaries coincide with the Special Conservation Area (ZEC) of the Red Natura 2000 "Sierras Bermeja y Real" (ES6170010) and the ZEC Los Reales de Sierra Bermeja (ES6170004), with a surface area of 1236 ha and 30,824 ha respectively. Within the natural forest systems associated with peridotites, the plant associations made up of species HIC 9520 (*A. pinsapo* Spanish fir forests) and 9540 (Mediterranean pine forests with endemic Mesogean pines) are of particular importance. This explains why the protection of these habitats and their ecological connectivity are the top conservation priorities set out in the management plan for the ZEC and the reason for the declaration of the Natural Site of Los Reales de Sierra Bermeja in 1989. Of

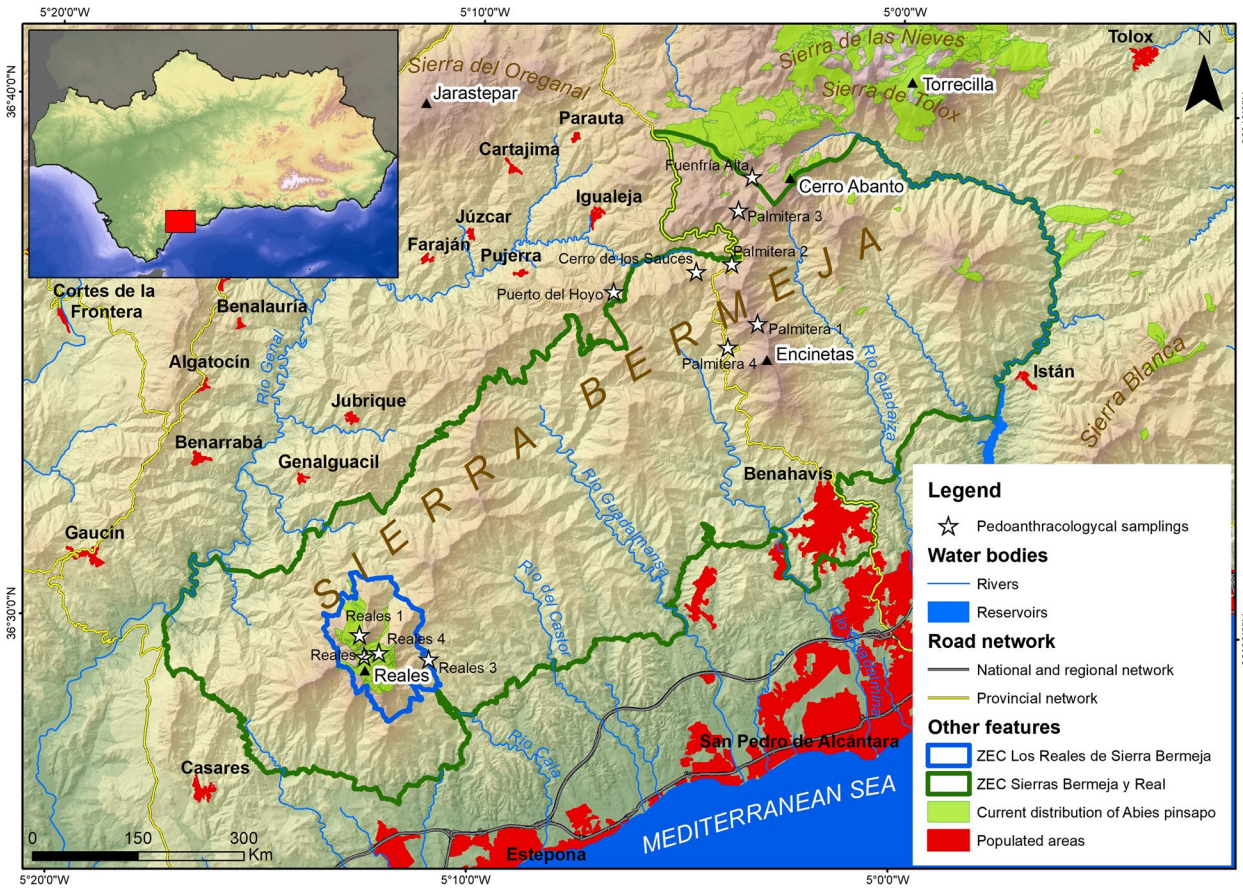

Fig. 1 Study area and location of the pedoanthracological samplings analysed during this research from data collected by Gómez-Zotano et al. (2017), Olmedo-Cobo et al. (2017, 2019a, b) and Pardo-Martínez et al. (2021)

all the various forest habitats, the most important is the HIC 9520. Due to their high natural value, they have also been included, albeit only partially, in the recently created Sierra de las Nieves National Park.

The special litho-edaphic characteristics of Sierra Bermeja have also favoured intensive forestry use, centred above all on its extensive resin-producing pine forests. Throughout the nineteenth and early twentieth centuries, these forests were a prime source of timber and resin. In fact, these mountains were considered one of the most important wood-production areas in the Iberian Peninsula under the auspices of the Spanish Resin-Producers Union (Unión Resinera Española) (Uriarte-Ayo 2000).

Methodology

Pedoanthracologycal analysis

Pedoanthracological analysis has been the main methodology used to carry out the palaeoecological approach. Specifically, the network of pedological sampling carried out by Gómez-Zotano et al. (2017), Olmedo-Cobo et al. (2017, 2019a, b) and Pardo-Martínez et al. (2021) in Sierra Bermeja has been used in this study. In the aforementioned works, the protocol established by Cunill (2010) and Cunill et al. (2013) has been followed. This consists of two stages of work: (1) fieldwork——a total of 11 soil pits were dug down to bedrock level, from which soil samples of between 3 and 15 kg per sampling level were taken (Fig. 1); (2) laboratory work——samples collected are wet sieved. After drying, the charcoal fragments were sorted from the sieved material. The anthracomass was then calculated and the selected charcoals (a total of 3565) were taxonomically identified using a reflected light optical microscope. Once identified, 28 charcoals fragments of *Abies* were selected for radiocarbon dating and calibrated with Oxcal v. 4.4 using the IntCal20 database (Reimer et al. 2020) to 2 sigma (95% probability). Finally, the palaeoecological information was analysed and interpreted.

Historical fire data

Our study of the large forest fires (LFF) in Sierra Bermeja is based on the analysis carried out by Martos-Martín

and Gómez-Zotano (2021), for which different documentary sources and news about fires were consulted from the 1950s onwards, following the method and sources detailed in that study, as well as remote sensing data from satellite image processing after 1975, to georeference and map the area covered by the fires. For the analysis of fires after 1975, these authors used the vector layers in the repository of the Andalusian Environmental Information Network (REDIAM) and found that one of the most serious LFFs in Sierra Bermeja and, in fact, in the whole province of Malaga was missing. This fire began on 17 November 1975 in Igualeja and affected a large part of the municipality of Benahavís (Gómez-Zotano 2004). A total of 10,218 ha were burnt in this fire, of which 9238 ha were forest, practically all serpentine-tolerant pine forests (Araque-Jiménez 2013).

Using remote sensing data, photointerpretation and georeferencing of other documentary data, these authors identify the area of this 1975 fire, thus completing the vector layers with which they carry out the analysis developed in this study, which covers the period 1975–2018.

To this research, the LFFs of Sierra Bermeja in 2021 and 2022 have been added to these vector layers using Geographic Information Systems (GIS), calculating the extent of the affected area and the severity of these fires using the dNBR index (Key and Benson 2006), based on remote sensing data.

Finally, we decided to geo-process the vectorial layers of fires that affected Sierra Bermeja over the period 1975–2022, generating a map of each LFF, and a map that compiles the various areas affected by more than one fire. The processing, image analysis and map generation were carried out using QGIS 2.18.24, ARCGIS 10.3 and GRASS 7.4.1. software and later versions thereof.

Results

Paleoecological approach

The paleoecological interpretation has been based on the statical analysis of 3565 charcoals. Of those, 765 fragments (21.5%) corresponded to *P. pinaster* (Fig. 2). This species appeared in all the sampling sites we analysed, with specific anthracomass values that oscillated between 14 295.2 mg/kg in Palmitera 1 sampling and 7.3 mg/kg in Palmitera 4 (see Gómez-Zotano et al. 2017; Olmedo-Cobo et al. 2017, 2019a, b; Pardo-Martínez et al. 2021).

After *P. pinaster*, the second most numerous taxa was *Quercus* with 679 charcoals identified, which was present in 7 of the 11 samplings. The specific anthracomass values for this genus ranged between 63 601.5 mg/kg for Palmitera 1 and 8.4 mg/kg for Reales 4 (Fig. 2).

A total of 144 charcoal fragments of *Abies* were identified. These were found in 4 of the 11 sampling sites (Fig. 2). The specific anthracomass values were 233.6 mg/kg in Palmitera 1, 37.5 mg/kg in Reales 2, 9.8 mg/kg in Fuenfría Alta and 8.4 mg/kg in Reales 1.

Together with these taxa, other taxonomic groups and categories were also identified, which in total made up 4.1% of the valid identifications.

Regarding radiocarbon dating, a total of 28 chronologies are available for the genus *Abies* in Sierra Bermeja from the research carried out by Gómez-Zotano et al. (2017), Olmedo-Cobo et al. (2017, 2019a, b) and Pardo-Martínez et al. (2021) (Fig. 3). These came from Palmitera 1 (15), Reales 1 (5), Reales 2 (5) and Fuenfría Alta (3), and

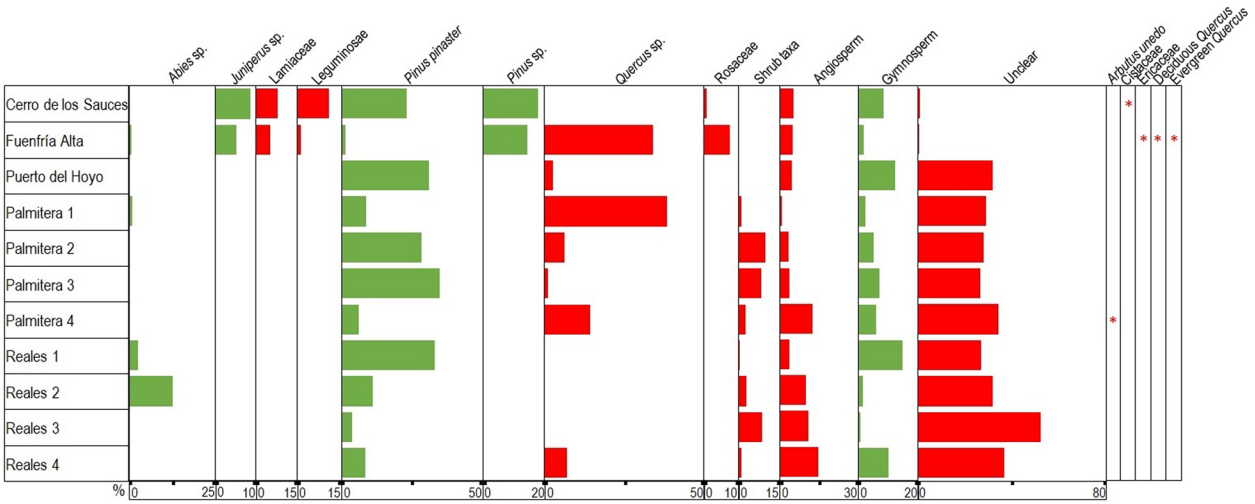

Fig. 2 Taxa identified in the different pedological samplings carried out in Sierra Bermeja from data collected by Gómez-Zotano et al. (2017), Olmedo-Cobo et al. (2017, 2019a, b) and Pardo-Martínez et al. (2021)

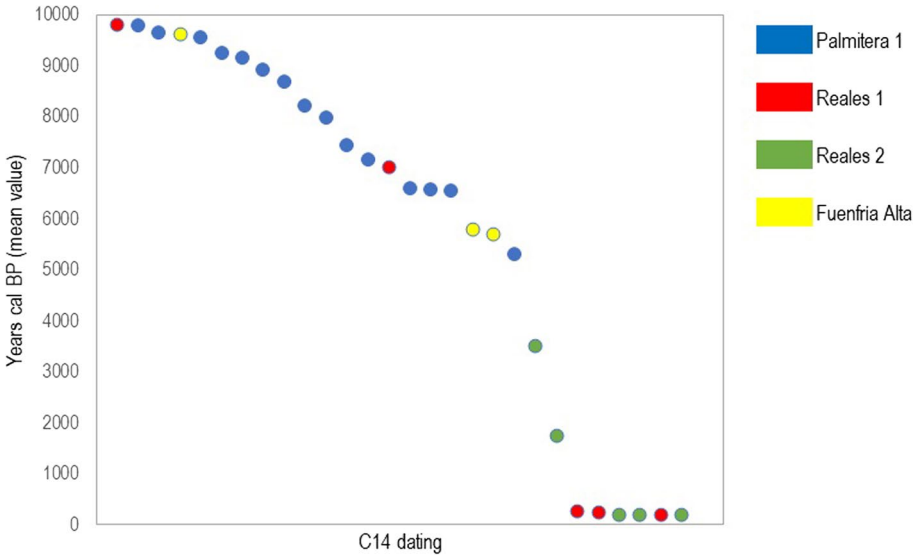

Fig. 3 Age values obtained from data collected by Gómez-Zotano et al. (2017), Olmedo-Cobo et al. (2017, 2019a, b) and Pardo-Martínez et al. (2021) for the 28 *Abies* charcoal fragments subjected to C^{14} radiocarbon dating

had chronologies ranging between 9931–9616 and 282–82 years cal BP.

Historical data

Since 1956, the study area has been affected by a total of 32 forest fires, 16 of which were LFFs (Table 1), making an average of one large forest fire every 4.125 years. These fires affected a total of 50,828 ha, of which 1916 ha were affected by "small" fires affecting less than 500 ha, and 48,912 ha were affected by LFFs. The fires that, by burned area, are considered most important are those of 1966 (4-8-1966), 1975 (17-11-1975), 1991 (7-8-1991), 2021 (8-9-2021) and 2022 (8-6-2022). According to fire severity, which includes, among other parameters, loss of biomass and high tree mortality rates (Keeley et al. 2009), the four fires of 1975, 1991, 2021 and 2022 stand out. This fire behaviour is related to the landscape structure, from the increase and continuity in forest cover due to rural depopulation (Pausas et al. 2012; Gutiérrez-Hernández et al. 2016). In addition to being severe fires, the 1975, 1991 and 2021 episodes had a high intensity fire behaviour, releasing a high rate of energy. Particularly intense was the 2021 fire, which spread through areas of high tree density and more continuous understory fuels. Both the length and the height of the flames were very prominent features of the 2021 fire, even producing pyrocumulus (pyroCu) (Gatebe et al. 2012).

The vast majority of fires are of anthropic origin, a finding in line with general statistics for Andalusia and for Spain as a whole, issued by the different administrations (Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente 2023).

Considering the recurrence of forest fires and therefore that the same area has been affected by fire up to four times, the total burnt area over the period analysed (50,828 ha) was higher than the total area of the study area (32,060 ha). After geo-processing all the fires since 1975 (LFFs——over 500 ha——and smaller fires) in order to identify which areas have been affected by more than one fire, we obtained the map in Fig. 4. This shows that the most frequently affected part of Sierra Bermeja is its western half, around the Los Reales de Sierra Bermeja Special Conservation Area, which includes the Los Reales Spanish fir forest. Almost 240 ha have been burnt on four occasions (1975, 1976, 1995 and 2021). However, the largest LFFs have been concentrated in the Centre and East of the study area (1975, 1991, 2021 and 2022).

The serpentine-tolerant Spanish fir forests have been affected by five forest fires in the last 66 years (1956, 1966, 1969, 1991 and 2021), in which a total of 4494 trees were lost. Of all these forest fires, the worst in terms of the numbers of trees lost was the fire in 2021, according to estimates made by Martos-Martin and Gómez-Zotano (2021).

Discussion

Paleoecological approach

This research has highlighted the fact that, at different times during the Holocene and since historical times, forest fires in Sierra Bermeja have been one of the main factors endangering the survival of *A. pinsapo*. In fact, *Abies*

Table 1 Forest fires in Sierra Bermeja over the period 1950–2022 and the number of Spanish firs affected

Date	Hectares	Large forest fire	Origin	Number of *A. pinsapo* affected
24-8-1956	20		Anthropic	500
4-8-1966	5000	Yes	Anthropic	429
20-4-1969	N/A		N/A	-
19-7-1969	1500	Yes	Anthropic	Unknown
1-7-1971	N/C		N/A	?
3-8-1971	1200	Yes	Anthropic	-
29-8-1971	400		N/A	-
30-8-1974	2500	Yes	Anthropic	-
1975	866	Yes	N/A	?
17-11-1975	9247	Yes	Anthropic	-
1976	258		N/A	-
25-7-1980	< 500		N/A	-
3-3-1987	33		N/A	-
11-10-1990	112		N/A	-
21-5-1991	921	Yes	Anthropic	-
7-8-1991	8157	Yes	Anthropic	565
10-8-1991	178		N/A	-
28-8-1992	545	Yes	Anthropic	-
16-7-1995	2319	Yes	Anthropic	-
4-9-1995	470	Yes	Anthropic	-
12-9-1995	101		N/A	-
4-7-1999	524	Yes	Anthropic	-
18-6-2000	179		N/A	-
2-1-2004	5		N/A	-
8-8-2004	86		N/C	-
9-9-2009	533	Yes	Anthropic	-
4-2-2012	798	Yes	Anthropic	-
20-8-2017	32		N/A	-
19-12-2017	12		Natural?	-
9-8-2021	?		Anthropic	-
8-9-2021	9731	Yes	Anthropic	3000 (approx.)
8-6-2022	4601	Yes	Anthropic	-
Total	**50,828**	**-**	**-**	**4494**

is widely known as a taxon that tends to be reduced by fire (no postfire regeneration mechanism, thin bark, does not resprout, canopy reaches the ground, etc.) (Furyaev et al. 1983; López-Quintanilla 2013). This is a multi-scale phenomenon that has also affected other mountain systems in central and southern Europe where the genus *Abies* is present, as reported by authors such as Wick and Möhl (2006) in the Alps and Cunill et al. (2015) in the Pyrenees.

Pedoanthracological studies revealed the existence of up to 28 fires in the serpentine-tolerant Spanish fir forests in Sierra Bermeja during the last 10,000 years. These paleodata demonstrate that fire is an ancient phenomenon in this mountain range, as revealed by other authors researching this subject in similar Mediterranean areas (Naveh 1974; Trabaud 1982; Pons and Thinon 1987). Evidence for these fires comes in the form of the anthracomass values, especially when contextualised with those for other charcoal samples found in other areas near the study area. A particularly high concentration of burnt wood was found in Palmitera 1, with an anthracomass value of 137,379.3 mg/kg, which is far higher than ever found in any other pedoanthracological analysis (Nelle et al. 2013; Pardo-Martínez 2020). Other locations in Sierra Bermeja also obtained very striking anthracomass values, including Palmitera 3 (7831.6 mg/kg), Palmitera 2 (7066.3 mg/kg), Reales 2 (2115.2 mg/kg) and Reales 1 (1965 mg/kg), with figures that were much higher than those calculated in other enclaves in the Serranía de Ronda (see Gómez-Zotano et al. 2017, 2023; Olmedo-Cobo et al. 2017, 2019a, b, 2021; Pardo-Martínez et al. 2021, 2023).

This long history of fire damage to Spanish fir forests may be the reason for its local extinction in places where it once existed. Various fragments belonging to *A. pinsapo* were identified in areas in which this taxon is no longer found, such as Palmitera 1 and Fuenfría Alta. These findings have made it possible, for the first time, to locate those specific sites where the Spanish fir was present in the past. These paleoecological data would also support the idea of a larger distribution area for Spanish fir indicated by the Euforgen database (Euforgen 2023).

The dating results for the 28 fragments of *Abies* enabled us to theorise as regards the possible local dynamics of *A. pinsapo* in Sierra Bermeja after the Last Glacial Maximum. There are up to 5 dates between 9931–9616 and 9552 years cal BP. This could inform about the existence of various episodes of fire during the first stages of the Holocene. These disturbances coincide with a period of maximum heat and dryness around 9500 years ago in the area surrounding the Sea of Alborán (Jalut et al. 2000; Cacho et al. 2001). Therefore, and considering the ecological requirements of this species (Linares and Carreira 2006), it seems plausible to think that the hypothetical decline of Spanish fir populations in this period would be essentially motivated by climatic factors. In this context, it is possible that *P. pinaster*, a species that has existed in the south of the Iberian Peninsula since the Pleistocene, took advantage of this retreat of fir forests (Mauri et al. 2015; Olmedo-Cobo et al. 2019a, b), as it is the most numerous taxon discovered in the pedoanthracological analysis and occupies a large number of ecological niches, including some ceded to it by the Spanish fir.

During the Holocene climate optimum (around 7800–5500 years cal. BP), the increase in temperature and the

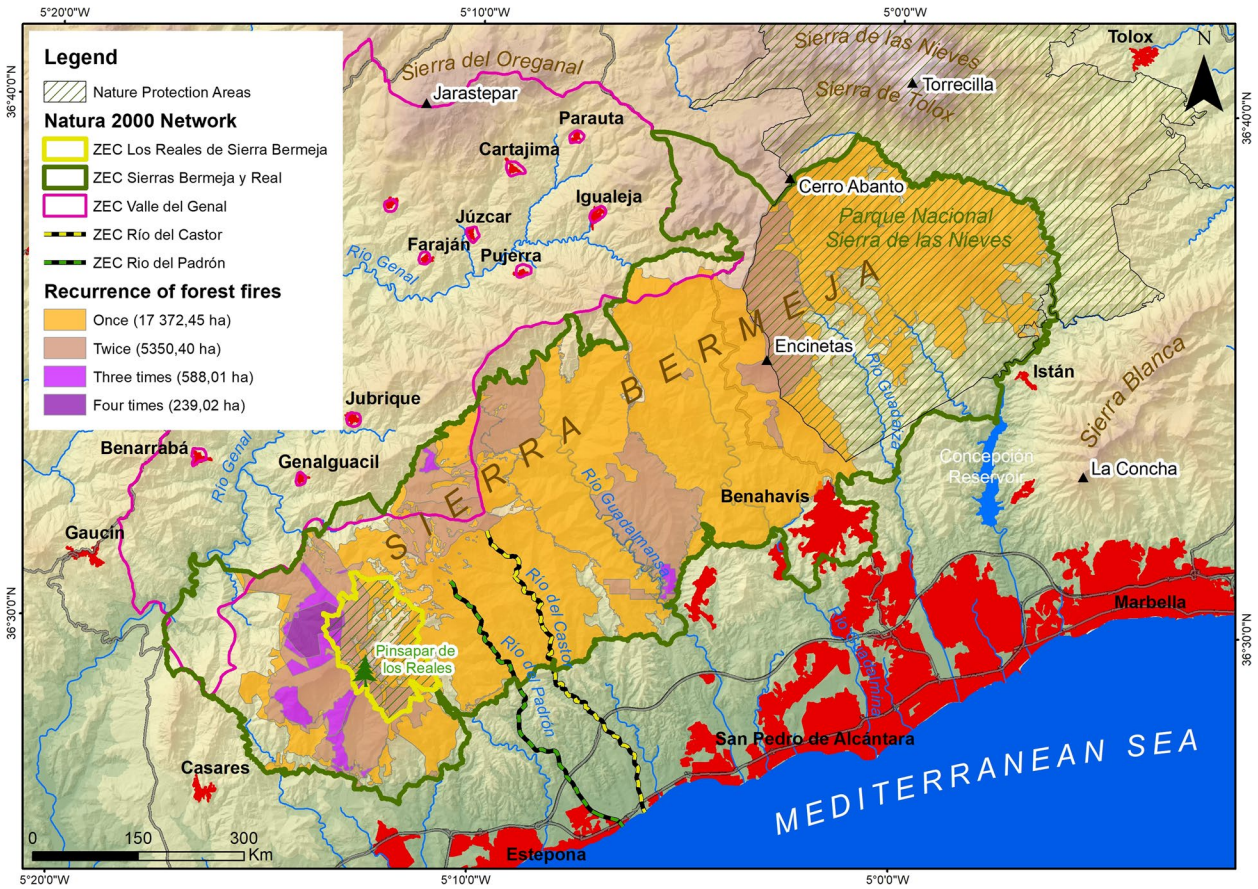

Fig. 4 Identification of the areas affected by fire on one or more occasions from 1975 to 2022

existence of recurring aridity events are noted (Schröder et al. 2019). This is a period that coincides with the start of the typically Mediterranean climate (Mauri et al. 2015), where natural conditions would be modelling an increasingly unfavourable scenario for the Spanish fir. Likewise, there is evidence of an increase in the prehistoric human population in the coastal area of the foothills of Sierra Bermeja, as noted by Ferrando de la Lama (1988) and Fernández et al. (2007). Despite the isolation, inaccessibility and toxicity of the soils of this peridodite massif (Asensi et al. 2004; Gómez-Zotano 2004), this mountain has played an important role as a source of abiotic resources for millennia (Martos-Martín et al. 2016). Since the late Neolithic (6000–5000 years cal. BP) and early Copper Age (5000–3800 years cal. BP), the human communities that occupied Sierra Bermeja would have made significant use of the mineral resources present in this mountainous massif (Navarro-Luengo et al. 1993). [[Both the management of forest resources——the use of pine resin, the coaling, the collection of both pine needles and wood——muleteering——through the opening of paths and roads——extensive livestock farming——mainly goats and cattle——and mining uses——through the opening of galleries, the deposit of mining waste or the creation of associated infrastructures, such as buildings or paths——have led to a management of the forest mass that has kept the levels of biomass available for fire to a minimum (Martos-Martín et al. 2016; Martos-Martín and Gómez Zotano 2021), thus leading to a low-intensity fire regime in the mountains and a smaller extension of the areas covered by fire. From the 1950s onwards, with the emergence of tourism as the main economic activity in the area, these traditional uses were abandoned, leading to an increase in the area of forest mass, mainly shrubs (Gutiérrez-Hernández et al. 2016). This biomass available for fire and its structure, where shrubs and the density of the tree canopy are particularly important, has increased the temporal recurrence, the extent of the areas covered by fire and its intensity (Martos-Martín and Gómez-Zotano 2021). This change in the fire regime associated with the abandonment of the rural world is a dynamic that has been observed throughout the Mediterranean peninsular area (Pausas and Fernández-Muñoz 2012).

Under this consideration, it is logical to think that both natural (determined mainly by the climate) and anthropogenic factors could have had a negative impact on the reduction in the vegetative cover, including the Spanish fir forests (Gómez-Zotano and Olmedo-Cobo 2021). This decrease in the area occupied by *A. pinsapo* has been accelerated over the last few centuries, as suggested by the five dated charcoal pieces in the most recent part of the record (Fig. 3). This trend has also been identified in other locations in the Serrania de Ronda, such as the Sierra de las Nieves (Alba-Sánchez et al. 2019; Pardo-Martínez et al. 2023).

This dynamic, which must be viewed within the framework of a profound phase of transformation of the dominant plant landscape in the south of the Iberian Peninsula (Carrión et al. 2008), benefited those conifers that were not very demanding and were better adapted to drier conditions such as the *P. pinaster*. The lack of charcoal remains of *Abies* in the last 5000 years, together with the progressive decline in *Abies* pollen in most of the fossil records from the southern part of the Iberian Peninsula (Carrión 2013, 2022), would help support this theory. It is therefore possible that the Spanish fir disappeared from both Palmitera 1 and Fuenfría Alta during the mid-Holocene, although further paleoecological research is required to be able to validate this hypothesis.

In any case, the paleoecological information obtained demonstrates once again the potential of pedoantracological analysis for finding out more about the composition and the ecological dynamics of the woody vegetation burnt over the last few millennia (Nelle et al. 2013). At the same time, for some years now, it has also proved to be a very useful method for enhancing our geohistorical knowledge of forest fires, especially when combined with other paleoecological sources (Carracedo-Martín et al. 2017; Ochando et al. 2023), over which it has a clear advantage, i.e. high spatial resolution (Talon et al. 1998).

Historical data

For their part, these historic and cartographic data regarding forest fires over the last 66 years show a very high recurrence of LFFs with an average of one large forest fire every 4.125 years over the period 1956–2022. Sixteen of the 32 fires identified in Sierra Bermeja affected over 500 ha. These statistics could indicate a tendency of the fires in this mountain range to become LFFs, extreme events which on various different occasions have affected the Spanish fir forest with important ecological consequences for this endangered species. One of these LFFs, which took place in September 2021, was a historical catastrophe in which over 9700 ha were destroyed by the fire.

This upward trend in the number of fires since the 1960s is the result of complex socio-territorial tensions generated on the nearby coastal tourist area, the Costa del Sol, and in the agricultural Genal Valley (Gómez-Zotano 2006; Martos-Martín and Gómez-Zotano 2021) (Fig. 5). From the mid-twentieth century, the traditional uses of the mountains were increasingly abandoned, thus converting Sierra Bermeja into the hinterland of the highly built-up Western Costa del Sol (Gómez-Zotano 2004). The rise in tourism coincided with the decline in traditional forestry uses in general and of resin-producing pines in particular, which had important territorial and landscape impacts. In the face of poor returns and shrinking markets for forest products, these forests were often abandoned. This became an environmental risk factor in that it led to an excessive densification of the plant cover and a large accumulation of easily flammable organic matter, which also served as a shelter for diseases and pests. This abandonment of forest-related businesses therefore had a negative impact on the frequency, extension, severity and intensity of forest fires, in which there was an alarming increase from the 1950s onwards, as noted by Gómez-Zotano (2004, 2006). This interpretation is supported by the conclusions reached by Vega-Hidalgo (1999), who, in his study on the fire history in Sierra Bermeja for the period between 1817 and 1997, argues that until 1950 the fires would have been of low and medium intensity.

The forest fire in Sierra Bermeja in September 2021 affected over 9700 ha of which almost half were tree-covered——with pine and Spanish fir forests——in the ZEC Sierras Bermeja y Real, the ZEC Los Reales de Sierra Bermeja, the ZEC Valle del Genal, the ZEC Río del Castor and the ZEC Río del Padrón. This was the greatest known loss of *A. pinsapo* as a result of fire with over 3000 trees destroyed, some of which were over 200 years old. This important depletion of the tree cover also enabled recent torrential rains to wash away more than 20 tonnes of soil per hectare, a fact that will almost certainly have negative effects on the regeneration of the plant cover (Gallegos-Reina 2023). The competent authorities have proved incapable of responding to this extreme, devastating event, preferring instead to argue that it is a fire without precedent in this area. However, as we have discovered in this research, this is not the first time that a fire of these characteristics has taken place in Sierra Bermeja.

Our data also suggest that the continued series of fires have played an essential role in the maintenance of the pine (*P. pinaster*) forest and more specifically in the creation of a structure of different age groups, although this claim should be taken with a great deal of caution. It is important to remember that unlike *A. pinsapo*, *P. pinaster* is one of the most flammable Spanish conifers,

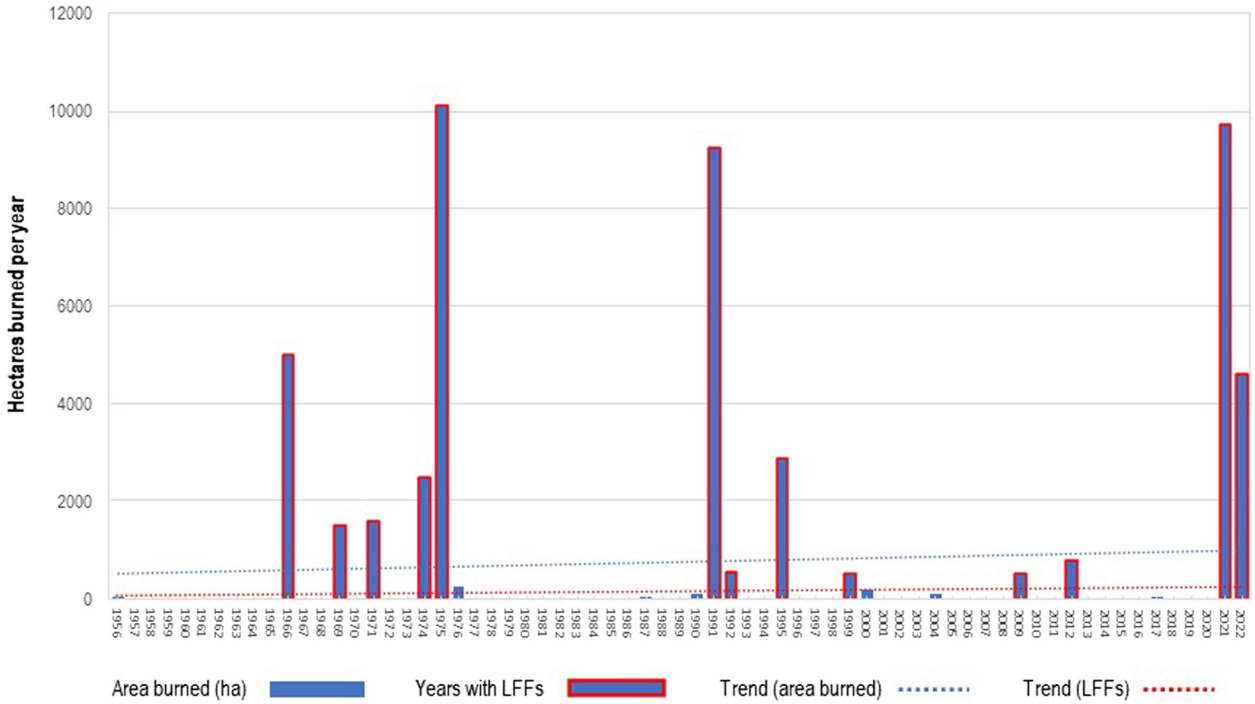

Fig. 5 Relationship between area burned and occurrence of LFFs per year

probably due to its high resin content (Ruíz de la Torre 1993). This characteristic helps both the start and spread of fire. It would also help to explain the high intensity and severity of some of the fires, especially during the summer months (Serrada 2011). At the same time, the subspecies present in the Sierra Bermeja, *P. pinaster* subsp. *Acutisquama*, has proved to be the most fire-resistant pines in the Iberian Peninsula (Vega et al. 2011). It is considered a pyrophyte species, being able to increase its number of individuals after the passage of fire. This is due to its serotinous character, a quality whereby the female pine cones break their dehiscence due to the heat generated by the fire, producing a massive dispersion of pine seeds, a great competitive advantage over *A. pinsapo* in a territory with a long history of recurrent fires (Pérez-Latorre 2022). This shows the importance of studying these phenomena in Sierra Bermeja, where a large part of the vegetation is composed of this autochthonous resin-producing pine forest.

Given the huge significance of fire in Sierra Bermeja over the course of history and its increasing frequency, severity and intensity over recent decades, more attention is required from those responsible for managing these forests. It is also vital that the entire massif be included within the Spanish National Park Network as the best example of serpentine-tolerant ecosystems in the country. Action is required even more urgently given the latest report from the United Nations Environment Programme (United Nations Environment Programme 2022), in which it warned that extreme forest fires will increase by 14% by 2030, by 30% by 2050 and by 50% by the end of the century due to the climate crisis.

Conclusions

Regardless of the time scale analysed, the data obtained in our research have confirmed the initial hypothesis, revealing that fire has played a leading role in the configuration of the plant landscape in Sierra Bermeja for millennia. It is even possible that fire may have been responsible for the local extinction of the Spanish fir in certain enclaves in Sierra Bermeja, as may be inferred from the pedoanthracological record, which has made it possible to identify charcoal from the *Abies* genus in places in which this taxon is no longer present, such as Palmitera 1 and Fuenfría Alta.

In parallel, the information obtained from documentary and oral sources and the data obtained via remote sensing have highlighted a worrying dynamic in forest fires over the last 72 years, a period in which this unusual mountain massif has become a fire hotspot of the first order at a national level. Many of these forest fires have significantly affected *A. pinsapo*, seriously threatening the viability of the planet's only serpentine-soil Spanish firs.

This increased frequency, severity and intensity of fires during recent decades highlights the need for this massif

to be included in the Spanish National Parks Network. It is furthermore important that the efforts made to restore and regenerate the Spanish fir forest, which have so far been based on historic sources, studies of current habitats and SDMs, many of which contain inaccuracies and uncertainties, should now also take the results of paleoecological studies into consideration.

These measures would help ensure effective protection for the most important serpentine-tolerant ecosystem in Spain, with particular attention being paid to the Spanish firs in Sierra Bermeja, in a bid to encourage the adaptative management of this endangered habitat in the context of Global Change, in which forest fires will become increasingly recurrent, severe and intense.

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Authors' contributions
JG conceived, designed and led the research. JG, RP and JAO carried out the fieldwork and collected field data. RP, JAO and JM analysed the data. JG took the lead in writing the manuscript. RP, JAO and JM assisted with analyses and writing the paper. RP and JM produced the figures. All authors reviewed the manuscript and contributed to the final draft.

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Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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