Abies pinsapo and forest fires: a long history of surviving extreme events in Sierra Bermeja (SW Baetic System)

José Gómez-Zotano
University of Granada: Universidad de Granada
Rubén Pardo-Martínez (rubenpardo@ugr.es)
University of Granada: Universidad de Granada https://orcid.org/0000-0003-4457-8536
José Antonio Olmedo-Cobo
University of Granada: Universidad de Granada
Javier Martos-Martín
Acaire

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Abstract

Background *Abies pinsapo* 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; 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 few years in one of the natural habitats of the Spanish fir forest most affected by fire: Sierra Bermeja. 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.

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 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 regressive dynamic of this fir as a consequence of fire, as can be inferred from the cartography carried out, has been particularly intense during the last few decades.

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. To help ensure effective protection for the most important serpentine-tolerant ecosystem in Spain it is essential to include the whole of Sierra Bermeja in the Spanish National Park Network.

Introduction

Throughout the Holocene, landscapes have undergone important transformations within a context of natural Global Change, in which climatic variability, paleoecological processes and increasing human activity over the last 15 000 years have played a defining role (Cunill et al. 2012, 2015). The most affected areas include mountain forests, whose 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 (Mouillot et al. 2003; 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). For example, 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 (Bedia et al. 2015; Safford and Ramón-Vallejo 2019; Morán-Ordóñez et al. 2020; 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* 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 endemism of the Rondeño and Bermejense biogeographic sectors in the Serranía de Ronda, 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 (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, currently occupying a small area (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 with steep slopes and numerous boxed-in valleys, almost constant battering by strong winds channelled in by the Strait of Gibraltar or the high temperatures reached in the summer months. However, these natural factors are not the only cause. There are also a range of social and economic factors at the root of these disasters. The growing incidence of forest fires is a clear reflection of the conflicts and tensions of various kinds in Sierra Bermeja: social marginality in the surrounding villages, the poor returns from forest resources, problems associated with the holding/ownership of mountain land, depopulation of rural areas, excessive pressure from rural tourism, abandonment of farmland, stubble burning, land use change, real estate speculation and the granting of planning permission on land on which development was previously forbidden. 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. That is why in this paper we reformulate the question by proposing that forest fires are an excellent opportunity to collect palaeoecological information at different levels, especially when reconstructing the distribution areas that certain plant taxa occupied in the past or to improve knowledge about the historical geography of forest fires (Nelle et al. 2013; Carracedo-Martín et al. 2017), knowledge that could be a key asset in the future recovery of relict and threatened species such as the Spanish fir. In this research we use the pedoanthracological network developed by Gómez-Zotano et al. (2017), Olmedo-Cobo et al. (2017, 2019a, 2019b, 2021) and Pardo-Martínez et al. (2021) over the last few 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 20th 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.

The paleobiogeographical and historical information obtained will enable new measures to be introduced to further the conservation and management of *Abies pinsapo*, a relict species in danger of extinction due to Global Change.

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). Running parallel to the coast of the Sea of Alborán, it could be classified as a medium-altitude mountain range (its highest peak is Cerro Abanto at 1508 m a. s. l.) (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 and create an adverse litho-edaphic context for biological occupation. 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: thermomediterranean (up to 800 m a. s. l.), mesomediterranean (800–1300 m a. s. l.) and supramediterranean (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 (part of the *Querco cocciferae-Pineto acutisquamae* vegetation series), and at higher altitude the *A. pinsapo* (*Bunio macucae-Abieteto pinsapo*) forest, whose growth on ultramafic 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. These areas were chosen because their boundaries are precisely defined by an official public body. In the maps generated during the course of this research, the study area is indicated as the area falling within the perimeters of these two ZECs. 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 Park of Los Reales de Sierra Bermeja in 1989. Of all the various forest habitats, the most important is the HIC 9520, which is classified in the Plan as very rare. The serpentine-tolerant Spanish fir forests are a relict plant community which is unique in the world (Cabezudo et al. 1989; Hidalgo-Triana and Pérez-Latorre 2016). 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 19th and early 20th 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).

From the mid-20th century, these traditional uses of the mountains were increasingly abandoned, so 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 inflammable 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 and intensity of forest fires, in which there was an alarming increase from the 1950s onwards (Gómez-Zotano 2004, 2006).

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, 2019b) 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 the following stages:

Fieldwork. A total of 11 soil pits were dug (Fig. 1, ESM). A sampling pit was dug at each site down to bedrock level, from which soil samples of between 3 and 15 kg per sampling level were taken. The geo-ecological characteristics of the various sampling sites are set out in Table 1.

Table 1
Geo-ecological characteristics of the sampling sites (Gómez-Zotano et al. 2017; Olmedo-Cobo et al. 2017, 2019a, 2019b; Pardo-Martínez et al. 2021).

Name	Geographic coordinates	Altitude (m. a. s. l.): thermotype and ombrotype	Sampling depth in cm (nº of sampling levels)	Orientation	Lithology/ type of soil	Geo-ecological environment
Cerro de los Sauces	36º36’49”N; 05º04’50”W	1104: Mesomediterranean sub-humid	54 (3)	N	Peridotite Regosol	Reforested pine forest on hillside
Fuenfría Alta	36º38’13”N; 05º00’23”W	1217: Mesomediterranean sub-humid	94 (4)	WNW	Gneiss Regosol	Reforested pine forest on hillside
Puerto del Hoyo	36º36’24”N; 05º06’45”W	938: Mesomediterranean sub-humid	137 (8)	SE	Peridotite Leptosol	Pine forest on hillside
Palmitera 1	36º35’53”N 05º03’21”W	1364: Meso-supramediterranean sub-humid	80 (5)	SE	Peridotite Regosol	Scrub at the bottom of endorheic basin
Palmitera 2	36º36’55”N 05º03’49”W	1202: Mesomediterranean sub-humid	90 (4)	W	Peridotite Leptosol	Pine forest on hillside
Palmitera 3	36º37’59”N; 50º03’50”W	1256: Mesomediterranean sub-humid	36 (2)	NW	Peridotite Leptosol	Pine forest with firs on hillside
Palmitera 4	36º35’20”N; 05º03’53”W	838: Mesomediterranean sub-humid	42 (3)	SSW	Peridotite Leptosol	Pine forest on hillside
Reales 1	36º29’43”N 05º12’36”W	1165: Mesomediterranean humid	105 (5)	N	Peridotite Leptosol	Fir-Pine forest on hillside
Reales 2	36º29’24”N 05º12’08”W	1247: Mesomediterranean humid	52 (4)	NNE	Peridotite Leptosol	Fir forest on hillside
Reales 3	36º29’17”N 05º10’56”W	638: Mesomediterranean humid	29 (2)	WSW	Peridotite Leptosol	Scrub with pines on hillside
Reales 4	36º29’23”N 05º12’05”W	1070: Mesomediterranean humid	86 (3)	SSE	Peridotite Leptosol	Pine forest on hillside

Anthracological (charcoal) analysis. The second stage took place in the laboratory and involved the following phases:

- The samples were wet sieved with mesh sizes of 0.8 mm, 2 mm and 5 mm. The soil fraction of the samples was gradually broken down, using water and a paintbrush, and poured through the sieve, leaving behind stones and possible charcoal fragments. The material collected by each of the three sieve sizes was left to dry in a space prepared for this purpose in the laboratory.
- The charcoal fragments were sorted from the sieved material and identified using a stereo microscope and the residual mineral fraction was then discarded. Before being discarded, all stone fragments of > 5 mm were weighed for subsequent inclusion in the calculation of the amount of charcoal (anthracomass).
- Anthracomass analysis. In this analysis, the weight of the charcoal found in the soil (in mg) is calculated as a proportion of the weight of the whole soil sample (in kg), in this way obtaining the absolute anthracomass (in mg/kg). We also calculated the specific anthracomass of *Abies* sp. in the samples in which it was found. For this calculation, the weight of the stony material trapped in the 5 mm mesh was subtracted from the initial weight of the soil sample.
- Taxonomic identification of the selected charcoals was performed using a Nikon SMZ445 stereo zoom microscope and reflected light optical microscopy using an Olympus BX51 at 10–200X. The taxa represented by the charcoal fragments were identified by consulting various atlases of comparative anatomy of wood (Schweingruber 1990; Vernet 2001), and by comparing them with the collection of carbonized wood fragments stored in the anthracotheque at the Terra Lab UGR of the Physical Geography Department at Granada University. The maximum number of pieces of charcoal in each sample varied between 70 and 1134 fragments and a total of 3565 pieces of charcoal were identified.
- Radiocarbon dating of 28 charcoal fragments of *Abies* sp. was conducted by the Poznań radiocarbon laboratory (Poznań, Poland) and the Alfred-Wegener-Institut (Bremerhaven, Germany) and calibrated with Oxcal v. 4.4 using the IntCal20 database (Reimet et al. 2020), to 2 sigma (95% probability).
- Finally, the palaeoecological information was analysed and interpreted.

Geohistorical analysis

For these purposes, Large Forest Fires (LFF) will be those affecting over 500 ha. For our study of the LFFs in Sierra Bermeja, we consulted several different documentary sources and news stories about fires from the 1950s onwards. We then had to decide exactly which area to study. After analysing the cartography, we decided that the most practical approach was to use the Special Conservation Areas (Sierras Bermeja y Real and los Reales de Sierra Bermeja) as the study area. We then went on to superimpose all the georeferenced information for its analysis using Geographic Information Systems (GIS). These produced a series of vectorial layers with the areas affected by fire between 1975 and 2022; the use of remote sensing enabled us to process satellite images for the respective years, from the repository of the Andalusia Environmental Information Network (REDIAM). This information was collated with the set of vectorial layers with data about the forest fires (of over 10 ha) in Andalusia between 2008 and 2022, drawn up by the Provincial Operating Centres (REDIAM), which means they are practically identical. However, for the period 1975–2008, in the data generated by remote sensing, we noted that one of the most serious LFFs in the Sierra Bermeja, and indeed in the entire province of Malaga, was missing, namely the fire that began on 17th November 1975 in Igualeja and affected a large part of the municipal area 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).

In order to identify the area affected by this LFF in 1975, which does not appear in the REDIAM database, we compared aerial photos generated by the images captured by the MSS sensor of the LANDSAT 2 satellite from 1975 and 1976 available in REDIAM (false colour image generated using bands 4, 5 and 6) in order to identify any differences between the two pictures. In the false-colour aerial photo from 1976 (after the fire), there is an area that looks noticeably different. This could be the burnt area covering parts of the municipal areas of Igualeja, Benahavís and Estepona.

With a view to be able to identify the area affected by this fire more precisely, we generated a Normalized Difference Vegetation Index (NDVI) to help determine a possible area from which to start and then identify the exact boundaries using photodetection by comparing the relevant images from the Series B American Flight (1956) and the Interministerial Flight (1977).

The NDVI is the most widely-used index for calculating the areas affected by the fire. It uses radiometric information about the vegetation provided by the red and near-infrared bands, so minimizing the effects of different solar angles and of the relief (Rouse et al. 1973; Mather and Koch 2010). In order to generate the NDVI, we processed the downloaded image, captured by the multispectral MSS sensor on the LANDSAT 3 satellite on 26 August 1978.

After calculating the NDVI with the red (5) and near-infrared (7) bands, we then assessed how closely it matched the possible affected area resulting from the comparison of the false colour aerial photographs from 1975 and 1976. This comparison shows that the NDVI reflects less plant cover in this area, in other words, less photosynthetic activity, either because the area had suffered a fire or because it was suffering more hydric stress, as might be expected given that the image was taken in August.

For photodetection purposes, in the area in question, we used the image from the Series B American Flight (1956) and the Interministerial Flight (1977). The resulting polygon was drawn on the basis of the three cartographic sources: comparison with false colour aerial images 1975 and 1976; NDVI 1978; comparison by photodetection for the years 1956 and 1977. This polygon was then used to make a topographic map in which various markers were placed in the areas referred to as being burnt in newspaper reports at the time or in oral accounts to see if they coincided with the proposed area affected by fire.

After discovering that this LFF from November 1975 was not included in the REDIAM database, we decided to collate all the areas indicated in the database as areas affected by fire between 1975 and 2022. In this way we detected another LFF that supposedly occurred in 1975 in the western part of Sierra Bermeja, in the municipal areas of Casares and Genalguacil, but which does not appear in any of the other sources consulted or in any news reports from the period. Even so, in our analysis of the recurrence of fires over the period 1975–2022, we decided to include this fire together with all the other fires affecting the Sierra Bermeja in this period.

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 y GRASS 7.4.1. software and later versions thereof.

Results

Paleoecological data

Taxon identification and anthracomass values

The paleoecological approach used in this research has been based on the pedoanthracological analysis carried out by Gómez-Zotano et al. (2017), Olmedo-Cobo et al. (2017, 2019a, 2019b) and Pardo-Martínez et al. (2021). Specifically, 3565 charcoal were statistically analysed for subsequent paleoecological interpretation. Of those, 765 fragments (21.5%) corresponded to *P. pinaster* (Fig. 2). This species appeared in all the samplings 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.

After *P. pinaster*, the second most numerous taxon 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.

A total of 144 charcoal fragments of *Abies* were identified. These were found in 4 of the 11 samplings. 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. Although it was impossible to discriminate at species level, it seems very likely that the fir fragments found belonged to *A. pinsapo* given its status as a relict taxon present in this area since the Tertiary.

Together with these taxa, other taxonomic groups and categories were also identified, which in total made up 4.1% of the valid identifications. These include *Pinus* (1.3%), labiatae (0.7%), *Juniperus* (0.5%), leguminosae (0.5%), rosaceae (0.4%), evergreen *Quercus* (0.3%), deciduous *Quercus* (0.2%), *Erica* (0.2%) and cistaceae (0.1%).

An additional 7.1% of the samples identified belonged to the angiosperm group, while gymnosperms accounted for a further 5.5%. Finally, we should also mention the large number of samples that proved impossible to identify. These made up 34.3% of all the charcoal fragments proposed for taxonomic identification.

Age of the charcoal fragments

A total of 28 chronologies are available for the genus *Abies* in Sierra Bermeja as a whole, obtained from the radiocarbon dating carried out by Gómez-Zotano et al. (2017), Olmedo-Cobo et al. (2017, 2019a, 2019b) and Pardo-Martínez et al. (2021). (Table 2). These came from Palmitera 1 (15), Reales 1 (5), Reales 2 (5) and Fuenfría Alta (3), and had chronologies ranging between 9931 – 9616 and 282 – 82 years cal BP.

Table 2
Age values obtained from data collected by Gómez-Zotano et al. (2017), Olmedo-Cobo et al. (2017, 2019a, 2019b) and Pardo-Martínez et al. (2021) for the 28 *Abies* charcoal fragments subjected to C^{14} radiocarbon dating.

Sampling	***Laboratory code***	***Conventional age (C14 years BP)***	***Calibrated age (years cal BP) (95%)***
Palmitera 1	5173.1.1	8707 ± 37	9931 – 9616
	5174.1.1	8573 ± 35	9719 – 9551
	5176.1.1	8549 ± 36	9552
	5175.1.1	8300 ± 40	9266 – 9206
	5177.1.1	8155 ± 39	9245 – 9076
	5170.1.1	8003 ± 128	9236 – 8615
	5171.1.1	8057 ± 111	8672
	Poz-83921	7300 ± 50	8342 – 8053
	5169.1.1	7142 ± 34	8001 – 7944
	Poz-78851	6480 ± 40	7516 – 7356
	5172.1.1	6239 ± 35	7224 – 7085
	Poz-78852	5710 ± 40	6651 – 6473
	Poz-83920	5840 ± 40	6607 – 6573
	Poz-83922	5770 ± 40	6553 – 6523
	Poz-83924	4605 ± 35	5441 – 5145
Reales 1	Poz-83919	8860 ± 50	9810
	Poz-83918	6160 ± 40	7014
	Poz-78858	200 ± 30	326 – 208
	Poz-78859	195 ± 30	325 – 143
	Poz-78885	60 ± 30	294 – 102
Reales 2	Poz-82525	3270 ± 30	3516 – 3476
	Poz-82527	1800 ± 30	1832 – 1674
	Poz-83914	45 ± 30	295 – 103
	Poz-83913	40 ± 30	295 – 103
	Poz-83912	110 ± 30	282 – 82
Fuenfría Alta	Poz-113780	8740 ± 50	9619

Sampling	*Laboratory code*	*Conventional age (C14 years BP)*	*Calibrated age (years cal BP) (95%)*
	Poz-113779	4970 ± 35	5897 – 5668
	Poz-113778	5015 ± 35	5726 – 5679

Historical data

Since 1956, the study area has been affected by a total of 32 forest fires, 16 of which were LFFs (Table 3), 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. In line with the model that classifies fires into different generations and in which the behaviour of the fire is related to the structure of the landscape, three of these fires could be considered "sixth generation fires". 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).

Table 3
Forest fires in Sierra Bermeja over the period 1950–2022 and the number of Spanish firs affected.

Date	*Hectares*	*LFF*	*Generation*	*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	6th	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	6th	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	-

Date	Hectares	LFF	Generation	Origin	Number of A. pinsapo affected
20-8-2017	32			N/A	-
19-12-2017	12			Natural?	-
9-8-2021	?			Anthropic	-
8-9-2021	9731	YES	6th	Anthropic	3000 (approx.)
8-6-2022	4601	YES	6th	Anthropic	-
TOTAL	50 828	-	-	-	4494

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. 3. 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-Martos and Gómez-Zotano (2021).

Discussion

Paleoecological approach

In general, *Abies* is widely known as a taxon that tends to be reduced by fire (no postfire regeneration mechanism, thin bark, doesn't resprout, canopy reaches the ground, etc.) (Furyaev et al. 1983; López-Quintanilla 2013). Authors such as Wick and Möhl (2006) reported on the decline of the genus *Abies* due to fire in the Alps during the last millennia. Cunill et al. (2015) also reported a decline of *Abies* populations in the Pyrenees, where human activities and fire played a major role. It is therefore a multi-scale phenomenon that affected different mountain systems in central and southern Europe. In southern Spain, however, there was still no contrasted information available on how fire has historically affected *A. pinsapo*. 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*.

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 contextualized 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; Olmedo-Cobo et al. 2017, 2019a, 2019b, 2021; Pardo-Martínez 2020; Pardo-Martínez et al. 2021; Gómez-Zotano et al. 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. In spite of the fact that a large amount of the gymnosperm charcoals identified in the study area belong to *P. pinaster*, 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 support the hypothesis that *A. pinsapo* occupied a larger geographical area in the past, extending far beyond its current enclaves in Sierra Bermeja and the western end of the Baetic Cordillera (Gómez-Zotano et al. 2017; Olmedo-Cobo et al. 2017, 2019a, 2019b, 2021; Pardo-Martínez et al. 2021). This theory, supported by fossil records of Circum-Mediterranean firs, was previously proposed by Gómez-Zotano (2004, 2006) and Linares (2011). Similarly, Alba-Sánchez and López-Sáez (2013) and Alba-Sánchez et al. (2018) detected pollen readings for *Abies* from the Holocene of over 3–5% in certain locations in the South and South-East of the Iberian Peninsula. The high spatial resolution provided by the pedoanthracological record has made it possible, for the first time, to locate those specific sites where the Spanish fir was present in the past. These paleoecological data are also in line with the results produced by the main Species Distribution Models (SDM) applied to *A. pinsapo* (Navarro-Cerrillo et al. 2006; Alba-Sánchez et al. 2010; Alba-Sánchez and López-Sáez 2013; Gutiérrez-Hernández 2018), and ultimately would 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*, together with those available for other tree taxa in the Serranía de Ronda (Gómez-Zotano et al. 2017; Olmedo-Cobo et al. 2017, 2019a, 2019b, 2021; Pardo-Martínez et al. 2021), enabled us to theorize as regards the possible local dynamics of *A. pinsapo* 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 pedoantracological 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 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 modeling an increasingly unfavorable scenario for the Spanish fir. Likewise, there is evidence of an increase in the prehistoric 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 and early Copper Age, 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). This intense mining activity was a complementary activity to the agro-livestock economy, which would be developed mainly in the valleys of the rivers that drain the peridotites, materials that help to form high quality soils (Martos-Martín et al. 2016). Under this consideration, it is logical to think that both natural and anthropic factors could have had a negative impact on the forest resources, including the Spanish fir forests (Gómez-Zotano and Olmedo-Cobo 2021), a regressive dynamic for the species that has been accentuated over the last few centuries, in line with what has occurred in other locations in the Serrania de Ronda, such as the Sierra de las Nieves (Alba-Sánchez et al. 2019).

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 weren't 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), 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 identification of Spanish fir charcoal in Palmitera 1 and Fuenfría Alta support the hypothesis that Sierra Bermeja may have played a very important role as a postglacial refuge for different mountain conifers during the Holocene (Olmedo-Cobo et al. 2017; Gómez-Zotano et al. 2023), which caused the reduction and fragmentation of the distribution ranges of species that were best adapted to temperate climates (Van der Veken et al. 2007; Alba-Sánchez and López-Sáez 2013). In addition, both these sites – Palmitera 1 and Fuenfría Alta– could have acted as a corridor linking the Spanish fir forest in the Sierra de las Nieves with the most southerly outpost of the serpentine-tolerant Spanish fir in the southern Iberian Peninsula in Sierra Bermeja (Gómez-Zotano et al. 2017; Olmedo-Cobo et al. 2017, 2019a, 2019b, 2021). For its part, the Sierra del Oreganal could have been the branch linking the Spanish fir forests in the Sierra de Grazalema Natural Park with those in the Sierra de las Nieves National Park (Pardo-Martínez et al. 2021). Alongside them, the presence for thousands of years of *P. pinaster* has helped resolve, to a large extent, the long-standing dynamics and ecological succession debate as to the suitability of broad-leaved or coniferous trees as potential vegetation on ultramafic substrates in Mediterranean climates (Olmedo-Cobo et al. 2019a, b). As a whole, this information reveals that over the last 10 000 years the conifers *P. pinaster* and *A. pinsapo* have been the climax vegetation on the serpentine-tolerant soils of Sierra Bermeja.

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), over which it has a clear advantage, i.e. high spatial resolution (Talon et al. 1998). Therefore, 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.

Historic and cartographic 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. 16 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 traumatic 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). 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 sixth-generation 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 inflammable Spanish conifers, perhaps due to its high resin content (Ruíz de la Torre 1993), which would explain the high intensity of some of the fires. At the same time, the subspecies present in the Sierra Bermeja, *P. pinaster* subsp. *Acutisquama*, has proved to be one of the most fire-resistant pines in the Iberian Peninsula, in that it is capable of withstanding various repeated fires at relatively short time intervals (Vega et al. 2011). This shows the importance of studying these phenomena in Sierra Bermeja, where a large part of the vegetation is composed of autochthonous resin-producing pine forest.

Given the huge significance of fire in Sierra Bermeja over the course of history and its increasing frequency 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

The data provided by pedoantracological record has enabled us to obtain information of great paleoecological interest with regard to the dynamics of mountain forests during the Holocene and in particular of the Spanish fir (*A. pinsapo*) forests. The data also reveal that fire has played a leading role in the configuration of the plant landscape in Sierra Bermeja since the Last Glacial Maximum. 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 identification of 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.

Our research also demonstrated the significant role played by fire during the prehistoric period in Sierra Bermeja, which together with the increased frequency and intensity of fires during recent decades, highlights the need for this massif to be included in the Spanish National Parks Network. 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 face of Global Change.

Declarations

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Contributions

JG conceived, designed and led the research. JG, RP and JAO carried out the fieldwork and colleted 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. R. 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.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Author details

[1]Departament of Análisis Geográfico Regional y Geografía Física, Facultad de Filosofía y Letras, University of Granada, Campus Universitario Cartuja s/n, 18011 Granada, Spain

[2]Acaire S. Coop. And. (www.acaire.es)

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Figures

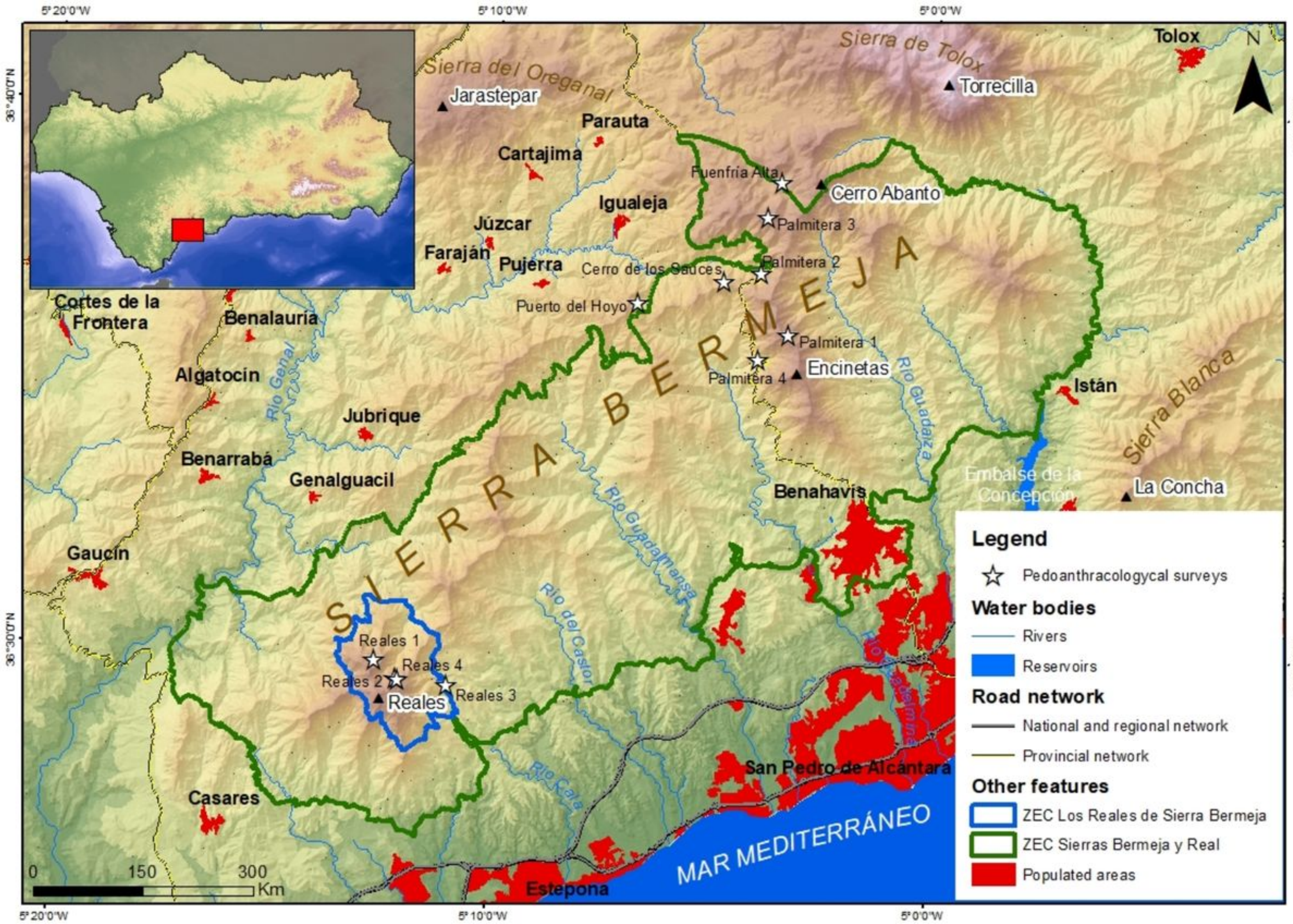

Figure 1

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, 2019b) and Pardo-Martínez et al. (2021).

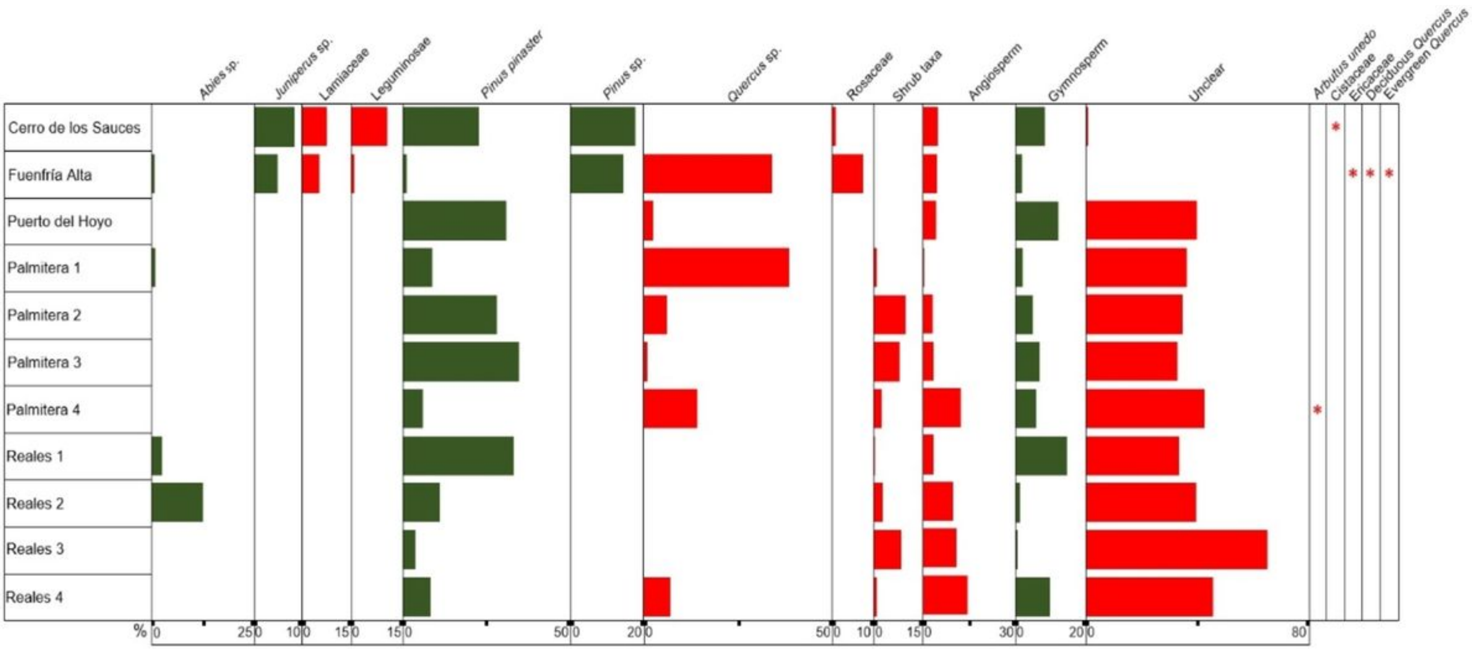

Figure 2

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, 2019b) and Pardo-Martínez et al. (2021).

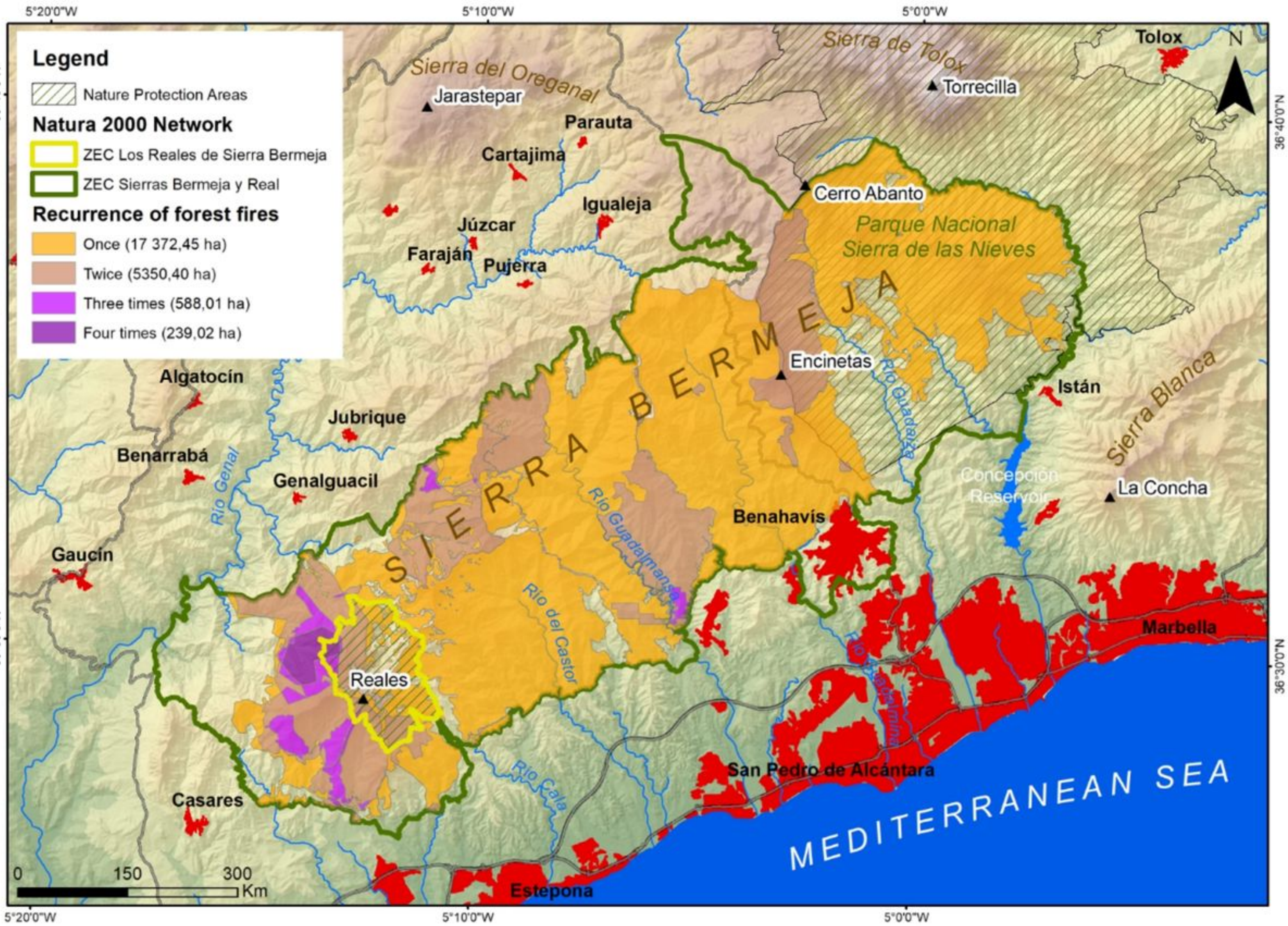

Figure 3

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