History of fires and vegetation since the Neolithic in the Cantabrian Mountains

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Abstract

Fire has been one of the main causes of disturbance of vegetation over time, and since the Neolithic has become an irreplaceable tool for the opening of forest spaces and maintenance of pastures. Previous studies showed that the intensity and effects of wildfires are related to the biomass and controlled by climate factors. However, in regions such as Cantabria, where agriculture and livestock have spread throughout the territory since prehistory, fires should also be closely related to human land uses. The aim of this paper was to investigate the history of fires and vegetation since the Neolithic in the Cantabrian Mountains, using sedimentary charcoals and pollen data to study the role of human activities in the processes that have shaped ecosystems throughout the Holocene. The asynchrony and quantitative differences in the results obtained at different sites indicate significant variations in fire patterns at regional scale since the Neolithic, although the type and size of each basin also had a strong influence on charcoal accumulation. Maximum values for charcoal accumulation rate (CHAR) at La Molina were observed between the Neolithic and the Bronze Age, but occurred after about 3500 cal years BP at El Cueto de la Avellanosa. At El Sertal, low CHAR values were observed, probably because the sequence begins in a space that already had been cleared; the maximum values occurred during the most recent millennium. These data provide evidence that fire has been a key factor in forest retreat and in maintaining open landscapes since the Neolithic.

Key words: sedimentary charcoal, pollen, fire, climate, Neolithic, Cantabrian Mountains

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INTRODUCTION

Fire as an ecological factor

In recent decades, research in ecosystems throughout the world has shown sedimentary charcoals to be a useful proxy helping to explain the role of fire as a key ecological factor (Whitlock & Larsen C, 2001; Power *et al*., 2008; Feurdean *et al*., 2012; Beffa *et al*., 2015). The impact of fire on the landscape during the Last Glacial and since the beginning of the Holocene has been analyzed in relation to climatic episodes and to the availability of biomass in various parts of the world, including central and southern Europe (Carcaillet *et al*., 2012; Gil-Romera *et al*., 2014; Rius *et al*. 2014; López-Sáez *et al*. 2017).

Fire signal and pollen data facilitate an understanding of historical disturbances in the landscape (Burjachs & Expósito, 2015; González-Pellejero *et al*., 2014). As Conedera *et al*. (2009) report, the creation of effective land management approaches requires a sound understanding of past forest stands and of landscape dynamics. A well-grounded knowledge of the natural range of variability in the disturbances and processes that shaped ecosystems before the rapid intensification of human action in recent times is indispensable to achieve appropriate land management.

This knowledge can help researchers separate signs of climate change from human action by considering biomass availability, among other factors (Carcaillet *et al*., 2007) and understand the relationship between fire history and elevation-dependent parameters, biomass, and land management (Vannière *et al*., 2016).

Analysis of the deposition of sedimentary charcoal particles provides information on fuel availability, the extension of a historical fire, and the estimated distance between the fire and the coring site (Higuera *et al*., 2011; Ali *et al*., 2012). The fire regime can be inferred from the total number of charcoal particles per unit of sediment, which is proportional to the total biomass burned in a given site's surroundings (Marlon *et al*., 2006; Thevenon *et al*., 2004). Thus, sedimentary charcoals (≥150 µm) have been used in the study of long-burning fire events (local scale fire, 500 m-1km) in mountain zones (Clark, 1988). Fires in European mountain zones have been studied in the Alps (Carcaillet *et al*., 2007), Pyrenees (Rius *et al*., 2011; Bal *et al*., 2011) and the Iberian Central System (López-Sáez *et al*. 2017). Considering the available evidence since the Neolithic period, fire appears to be a great ally for the opening of forest spaces and the maintenance of open landscapes (Cunill *et al*., 2012, Feurdean *et al*., 2012, Gil-Romera *et al*., 2014; Colombaroli *et al*., 2014, García-Amorena *et al*. 2017), a practice that survives in Cantabria to the present day (Carracedo, 2015).

In Cantabria, only one study of historical fires has been based on sedimentary charcoals (Pérez-Obiol *et al*., 2016); it points out the importance of fire since Neolithic times in one of the Iberian regions most affected by fires in forests and pasture lands. The region also has some of the richest and best known prehistoric archaeology in Europe (Moure Romanillo, 1995; González-Morales & Estévez, 2004).

At present in Cantabria, fires are generally intentional and mainly burn scrub (Carracedo, 2015); previously, tree biomass was involved but controlled by climate factors. For example, Bond cycles (Bond *et al*., 2001) associated with quasi-periodic climate fluctuations have sometimes coincided with cooling periods or dry periods (Burjachs and Expósito, 2015); in Cantabria, dry climatic phases coincided with Bond cycles 3 and 4 (Pérez-Obiol *et al*., 2016), which could favor greater recurrence of fires.

Although it has been assumed that fire synchronicity is linked to climate, there may be a correlation with a human factor linked to land use. The type of landscape at each site and the role of biomass in fire history can be assessed by pollen analysis. The main objective of this study was to analyze the history of fires and vegetation since the Neolithic in the Cantabrian Mountains using sedimentary charcoals and pollen data in core samples obtained from three peat bogs (La Molina, El Sertal and el Cueto de la Avellanosa). In order to make reliable comparisons, the synchronicity of fire episodes and the observed differences associated with altitude, as well as topographic factors and human activities, were included in the analysis.

Study area

The peat bogs analyzed are located in the central-western sector of Cantabria, in northern Spain (Fig.1). The Cantabrian Mountains are an obstacle to the prevailing winds of maritime origin and give rise to a strong climatic dissymmetry. The northern slope has a temperate and rainy oceanic climate with seasonally distributed annual precipitation totals ranging from 1000 to 1600 mm (Cfb, in the Köppen-Geiger classification), while the southern slope shows continental Mediterranean traits (Csb) with cold winters and a water deficit in the summer. The highest sectors have a narrow, intercalated strip of mountainous climate (Dfc / Dsb / Dsc), with annual precipitation –occurring in the form of snow for much of the year– that may exceed 2000 mm (AeMet, 2011).

The Cantabrian Mountains mark the border between the Euro-Siberian and Mediterranean biogeographical regions (characterized by deciduous broad-leaved and evergreen forests, respectively), which in turn have different features depending on the vegetation floor or local substrate. On the oceanic slope, the vegetation of the lower zones is drawn from a mixed thermophilous forest dominated by *Quercus robur*, although on the limestone substrate there are also *Q. ilex* subsp. *ilex* forests and numerous Mediterranean taxa such as *Phillyrea latifolia*, *Pistacia terebinthus*, *Olea europaea,* and *Viburnum tinus*. Above 500 or 600 m.a.s.l., *Quercus pyrenaica* and *Q. petraea* occupy the southern slopes; on the northern slopes, *Fagus sylvatica* dominates at this altitude. The highest forests, which reach 1700 m.a.s.l. in altitude, include *Quercus petraea, Ilex aquifolium,* and *Betula pubescens*. On the Mediterranean side, the potential natural vegetation is dominated by semi-deciduous forests and sclerophyllous formations (*Q. pyrenaica* and *Q. ilex* subsp. *rotundifolia*). At present there are no natural coniferous forests in Cantabria, although several pine species have been planted and are now common in the region (Fig. 2).

La Molina peat bog (43º15'38'' N-3º 58'37'' W; ETRS89) is located at 484 m.a.s.l. in the municipality of Puente Viesgo, 20 km from the Cantabrian coast. It occupies a topographical concavity oriented to the North in the Pas-Besaya divide, currently dominated by minerotrophic wetlands and some small ombrotrophic areas. Moist Atlantic heaths of *Erica ciliaris* and *E. tetralix* are predominant, although *Quercus robur* remains with *Betula pubescens* and *Alnus glutinosa* are preserved on the slopes. **El Sertal** (43 ° 13'0.23" N 4 ° 26'16" W) is located on a small mountain range, at 940 m.a.s.l., near Peña Sagra. The peat bog is in a mountain pass, in an elevated, well-ventilated area without lateral protections (Mariscal, 1986). Communities of *Nardus stricta* dominate locally, and nearby are moist Atlantic heaths with *E. ciliaris* and *E. tetralix* and some remains of *Quercus pyrenaica* and *Q. robur*. **El Cueto de la Avellanosa** (43º 06 '50" N 4º 21' 52" W) also lies in a mountain pass, located at 1320 m.a.s.l. on the northern slope of the Cordel range. It rests on a substrate of impermeable sandstone, forming weak aqueous layers in which *Sphagnum* grows (Mariscal, 1983). At present, the communities of *Nardus stricta* and oro-Mediterranean and dry European heaths dominate, while on the slopes there are forests of *Fagus sylvatica* and *Betula pubescens.*

Archaeological context

The archaeological heritage of Cantabria is exceptionally rich and provides us with abundant information on the ways of life and the use of the territory in the region throughout the period between the Late Palaeolithic (late Pleistocene s.l.) and the end of Prehistory (Fig. 1).

Most of the remains dating to the Palaeolithic have been found in low valleys and coastal areas but this situation changes in the Neolithic, throughout the sixth millennium B.P., with the appearance of the first groups of herders and farmers who quickly colonized most of the regional territory (see Table 1). Subsequently, an economy based on cattle ranching and the exploitation of mountain areas was consolidated, leading to an effective system of spatial and productive organization that is considered the direct antecedent of the one that has survived until the contemporary period (Ortega, 1984). Knowledge about this historical process of cultural evolution and colonization of the territory provides a large amount of proxy data of great value for understanding the results obtained in relation to the use of fire and the evolution of the vegetation in the region.

Copper and tin deposits are very scarce in Cantabria; the region was relatively isolated from the new cultural currents and no important economic or social changes occurred during the Bronze Age (Blas and Fernández, 1992). However, we know that during this period (ca 3800 - 2700 cal years BP), peasant societies continued their consolidation and agricultural and livestock farming activities experienced strong growth, which encouraged the occupation of new areas (Arias, 1999).

Archaeology of the Iron Age is also very limited in this region (Arias, 1999; Blas and Fernández, 1992). There is evidence of large deforested areas at mid-mountain summits. The population was distributed throughout the region in small fortified nuclei situated in easy-to-defend positions, such as hydrographic boundaries or high points that allowed a good control of the territory. This settlement system was likely the most common until Roman times (Peralta, 2000; Cisneros *et al.*, 2008).

Along the entire coastal strip of the region, numerous deposits of goethite, pyrite, hematite, limonite and other iron ores have been exploited uninterruptedly from the beginning of the Iron Age to the contemporary era. This activity was particularly intense and widespread during Roman times (Mantecón, 2000) and much later, between the 16th and 19th centuries. In addition, various lead and zinc minerals (mainly galena and sphalerite) were likely mined, and mining of other metals and metallurgy (especially iron) also occurred, with extractive and processing activity concentrated in the east, south of the Bay of Santander and the Cartes area, very close to La Molina peat bog.

Finally, in historical times and until the nineteenth century, both extraction and charcoal smelting required enormous amounts of wood. This was another of the causes of forest retreat and transformation in the wake of the Iron Age (Ceballos, 2001).

MATERIAL AND METHODS

Coring, samples, and chronology

Samples were collected manually at La Molina and El Sertal by driving a 3-m PVC tube, 110 mm in diameter, to a depth of 260 cm and 50 cm, respectively. At El Cueto de la Avellanosa, it was possible to take advantage of the vertical cut that remained accessible after exploitation of the peat bog was abandoned to a depth of 406 cm. Cores from La Molina and El Sertal were cut into 302 and 57 samples, respectively, below the centimeter. At El Cueto de la Avellanosa, the core was sampled every seven centimeters for a total of 58 samples.

The chronology of the present study was based on 11 AMS ^{14}C dates (Beta Analytic Inc.) (Table 2, A-C), calibrated at 2σ from the INTCAL13 database (Reimer *et al*., 2013) using Calib Rev. 7.0.4. At La Molina, the dating did not respond to parametric adjustment. Therefore, an age-depth model was developed using Clam modeling software (Blaauw, 2010) with the R statistical software platform (R Core Team, 2015). Models for El Sertal and El Cueto de la Avellanosa underwent polynomial adjustment to obtain age-depth models (Fig. 3).

Macroscopic charcoal analysis and organic matter content

All samples from each site were used for the analysis of sedimentary charcoal and organic matter, for a total of 302 from La Molina, 57 from El Sertal, and 58 from El Cueto de la Avellanosa. To identify fire events, the number of charcoals ≥150 µm was estimated (Carcaillet *et al*., 2001) in the Physical Geography laboratory of the Geography Department at the Universitat Autònoma de Barcelona. This charcoal particles approach does not allow taxonomic identification but does establish the relative magnitude of fire events. The standard protocol (Carcaillet *et al*., 2001, 2007), as adjusted by Pérez-Obiol *et al*. (2016), was followed. KOH was used as a deflocculant solution, and 15% NaClH as a bleaching solution (Finsinger *et al*., 2014). Samples were heated to 70° C for 90 minutes and sieved with a 150 µm mesh. The number of macroscopic carbon particles was estimated under a stereomicroscope at 40x. The surface area of charcoal fragments was estimated using an ocular grid with 100 squares of 0.0625 mm2 each. Charcoal fragments were classified into exponential size-classes according to their area. (Carcaillet *et al*., 2007). The sedimentary charcoals concentration (CHAC, mm^2/g) was used to obtain the charcoals accumulation rate (CHAR, mm^2/g/yr), based on the sedimentation rate estimated by age-depth models for each site (Fig. 3, Fig. 4, and Fig. 5). Due to the high resolution of La Molina sedimentary charcoals, the CharAnalysis software (Higuera *et al*., 2009) was used to calculate fire frequency values for a 1000-year window, along with charcoal peak distribution and magnitude. The resulting interpolation value was 17 years. Low-frequency CHAR was modeled using a 1000-year running mean with a LOWESS smoothing function. Charcoal peaks were identified as peaks exceeding the 99th percentile of the noise distribution.

To allow a comparison of the three sites, their CHAR values were rescaled (Fig. 6) according to Power *et al*. (2008) using a minimax transformation. Briefly, this method rescales charcoal values from a given site record to range between 0 and 1 by subtracting from each charcoal value the minimum charcoal value found in the record, and dividing by the range of values.

Loss on ignition (LOI) analysis was carried out in the Physical Geography laboratory of the Geography Department at the Universitat Autònoma de Barcelona, modifying the standard procedures to achieve combustion at 550ºC for 4 hours (Dean, 1974 and Heiri *et al*., 2001).

Palynology

Information from La Molina (Pérez-Obiol et al., 2016) and El Cueto de la Avellanosa (Mariscal, 1983) allowed us to obtain a complete and comparative view of vegetation changes. The pollen diagram was based on the 57 samples from El Sertal and the 151 samples taken from the top of La Molina.

In El Sertal peat bog, on the basis of the pollen data provided by Mariscal (1986), a new pollen analysis (adding NPP data) was done in order to obtain a better resolution of changes in that landscape. Sediment samples were prepared in the Palynological Analysis Laboratory, Department of Animal Biology, Plant Biology, and Ecology (BAVE) at the Universitat Autònoma de Barcelona according to standard chemical procedures (Moore *et al*., 1991), including treatment with 10% HCl / 10% KOH / 70% HF to remove carbonates and silicates, followed by mounting with glycerol. Pollen was identified under an optical microscope using reference collections and codes (Reille, 1992 and 1998). The results were expressed in relative percentages, excluding aquatic plants and spores from the total sum. The pollen diagram was constructed using TILIA and TILIAGRAPH software (Grimm, 1991).

RESULTS

Charcoal analysis and fire regime

All three of the peat bogs have charcoal particles from the base (7000 cal years BP) up to the top layer. The presence of charcoals is almost uninterrupted at El Cueto de la Avellanosa and La Molina. At El Sertal, there was much more discontinuity in charcoal sediment. The highest CHAR values were observed at La Molina (a maximum of 2.63 mm^2/g/yr), while at El Sertal the maximum was 0.010 mm^2/g/yr and at El Cueto de la Avellanosa, 0.326 mm^2/g/yr (Fig. 4, 5 and 6).

At La Molina (Fig. 4), the CHAR record was separated into five patterns: 1) From 6500 to 5800 cal years BP, the CHAR was initially low, generally under 0.5 mm^2/g/yr, with only one distinguishable peak and fire frequency not exceeding 2 fires/1000 yr; 2) The highest number of fires of the study period (>3 fires/1000 yr) occurred between 5800 and 3500 cal years BP, with seven CHAR peaks and CHAR values exceeding 1.5 mm^2/g/yr; 3) From 3500 to 2100 cal years BP, the fire frequency oscillated between 2 and 3 fires/1000 yr, with 4 char peaks but a lower CHAR value, not exceeding 0.5 mm^2/g/yr; 4) Between 2100 and 600 cal years BP, charcoal sediments decreased, with only two isolated CHAR peaks, low CHAR values, and a mean frequency of about 2 fires/1000 yr; 5) From 600 cal years BP until the present, the frequency of fires has increased notably, to 4 fires/1000 yr; CHAR values again reaching 0.5 mm^2/g/yr, with two CHAR peaks.

In El Sertal (Fig. 5A), the lack of continuity and resolution in the charcoal sediment record impeded the establishment of a clear pattern for the last 7000 cal years BP. Testimonial evidence of charcoal presence was observed for 7000, 6400, 4900, 4300, 2800, 2150, 1800 and 1000 cal years BP, with a maximum presence during the Middle Ages and a strong presence during the most recent 400 years. CHAR values very slightly refined the CHAC results.

On the other hand, the presence of charcoals at El Cueto de la Avellanosa (Fig. 5B) was nearly uninterrupted throughout all the samples and the following patterns could be established : 1) From 7000 to 6300 cal years BP, mean CHAR values were 0.1 mm^2/g/yr, comparable to those observed since the Middle Ages; 2) From 6300 to 5800 cal years BP, CHAR values were very low (the lowest of the entire sequence for this register); 3) From 5800 to 3600 cal years BP, CHAR values were low, with some secondary blips between 4800 and 5000 cal years BP; 4) From 3600 to 1000 cal years BP, the CHAR was the highest in the entire sequence, with a maximum peak of 0.326 mm^2/g/yr in 2650 cal years BP and CHAR values were often clearly above 0.10 mm^2/g/yr. There was a secondary peak in the CHAR at c. 1700 cal years BP; 5) The most recent 1000 cal years BP were characterized by an increasing trend and higher mean CHAR values, compared to the rest of the study period. The highest values in this period were observed in the latest sample.

A comparison of all the sequences (Fig. 6) showed a fire pattern that was differentiated but coincided with the main points when changes in trends were observed. This framework of trends was established between 3000 and 4200 cal years BP.

Pollen analysis

The pollen diagram for El Sertal (Fig. 7) indicates the main vegetation changes since Neolithic times. The arboreal pollen curve showed a decreasing trend throughout the entire sequence.

From 6700 to 4600 cal years BP, despite the highest values for arboreal pollen (mean value of 74%) and a large *Corylus* presence, high percentages of Poaceae (up to 32%) and *Pteridium,* as well as the presence of cereals, provided evidence of Neolithic human impact. Pine (probably *Pinus sylvestris*) was always less than 15% of the pollen values, which would not indicate the presence of pine forests in the vicinity.

Later on, at around 4600 cal years BP, the presence of *Alnus* increased, while hygrophilous taxa such as Cyperaceae found in the peat bog could be indicative of a lentic ecosystem. Cereals disappeared from the sequence until 3300 cal years BP. A continuous decline in tree cover and *Corylus* was observed.

Fagus sylvatica appeared about 3000 cal years BP and showed low percentage values (less than 2%) for more than 2000 years. Arboreal pollen percentage values then continued to decrease, with a continuous curve of cereals, important *Plantago* values and rising values of Ericaceae.

In the past millennium, there was a strong increase in *Fagus*; this expansion of beech occurred at a time of decline in other trees and of increased human pressure in the Cantabrian Mountains (Muñoz-Sobrino *et al*., 2009). At the same time, anthropic pollen indicators acquire very high values. During the most recent centuries, an open landscape has dominated at the sites analyzed in the present study, with maximum Ericaceae, cereals, and *Plantago* values. The considerable *Glomus* values indicate erosion processes nearby, and *Corylus* has the lowest percentage values observed in the last 6700 years.

DISCUSSION

Patterns of charcoal accumulation and relationship with type of basin

The charcoal sediment records obtained allow a characterization of each site and show great variation on a regional scale in the patterns of fires since the Neolithic period. Sedimentologically, the three sites did not show abrupt changes during the Holocene. In La Molina and El Sertal, there are significant inflections in the quantity of organic matter that could reflect periods of erosion and produce major changes in the numerical values of the charcoals (Thevenon *et al*., 2003). However, in our data, the charcoal peaks did not normally coincide with greater energy in the sediment inputs to the basin (Fig. 3). In La Molina, there was an inverse proportion between the recent Holocene erosion processes and the sedimentary charcoal values.

The quantitative differences between the three sites may be due to several factors: basin type and size, patterns and rate of deposition, number of woody plants burned, and anthropic factors (Rius *et al*., 2011). In the present study, basin type seems to have a lot of weight. Macroscopic charcoal is usually not carried more than a few hundred meters and therefore is mainly a local fire proxy (Whitlock and Larsen, 2001; Higuera *et al*., 2007; Ohlson and Tryterud, 2000; Clark, 1988). The concave La Molina topography could have contributed to the quantitative results of charcoal particle deposits, both locally and on the slopes that form the basin. However, El Sertal and El Cueto de la Avellanosa occupy two hills and have almost no basin to receive particles from nearby slopes. This difference shows the sensitivity of the sedimentary records to the morphology of each site, along with the importance of considering likely potential biases (Higuera *et al*., 2005).

Fire regime

Several Mediterranean and Pyrenean studies (Rius *et al*., 2009; Mercuri and Sadori, 2014; Sadori *et al*., 2015; Beffa *et al.*, 2015) illustrate the main trends of interlaced forces acting on the development of the landscape during the Holocene. Joint actions of climate oscillations, increasing dryness, and human impact are hard to disentangle, and this becomes particularly true after the mid-Holocene onset of Bronze Age cultures (Rius *et al*., 2009; Vannière *et al*., 2011; Mercuri, 2014). Nevertheless, other studies found human impact on fire regime and frequencies since the Neolithic (8000 cal BP) (Vannière *et al*., 2008). Thus, the existence of dissimilar chronological patterns between the three peat bogs makes it difficult to interpret the data based solely on climate factors. However, the Cantabrian Region has been characterized by the predominance of broad-leaved forests since the beginning of the Holocene and by a large and sustained human presence since the Late Glacial period, which suggests that human control has been a major factor in the region's fires since the Neolithic.

At La Molina, the maximum fire values occurred between the Neolithic and the Bronze Age, when fire events would have been of great severity due to the availability of wood for fuel. Given the large number of charcoals and the high resolution of this record, fire peaks and their magnitude have been understood as providing a clearer visualization of fire events, indicating either high intensity or proximity.

Significant fire events were identified from the very base to the end of the sequence, with the highest frequency and intensity between 5800 and 3500 cal years BP (Fig. 4), coinciding with the highest arboreal pollen values. These data agree with studies carried out in a subcoastal area in the NW Iberian Peninsula, where there is evidence of frequent fires during the last 6300 years (Carrion *et al.*, 2010). After 5500 cal years BP, the percentage of arboreal pollen decreased and Ericaceae pollen increased along with the opening of new agricultural spaces and episodes of "cultural" fires. The first part of the Bronze Age still shows pollen evidence of significant fire events.

The probability of fires is much greater if fuel, in the form of vegetal biomass, is combined with dry climatic conditions, so the oscillations associated with Bond cycle 4 (ca. 5500 cal years BP) could have favored the fires of the Neolithic period and those of Bond cycle 3 (ca. 4200 cal years BP), the fire episodes of maximum frequency. The mid-Holocene (around 8.0–4.2 ka BP) was a time of great instability due to increasing climate variability and cultural changes in many regions of the world (Mercuri and Sadori, 2014).

Despite a lower fire frequency during the last 3500 cal years BP, an increase was again observed during the most recent millennium. The pollen curve decreased steadily until about 2800 cal years BP, about the time that fires were being used to maintain open agricultural spaces and there were fewer local fires with wood fuels. According to Pérez-Obiol *et al*. (2016), the increase in Poaceae and cereals since pre-Roman times is closely related to the absence of trees or shrubs as fuel for fires in the adjacent zones. In the final part of the sequence (Fig. 7), various anthropic or fire indicators (Ericaceae, Cerealia and *Plantago*) attest to pastures and crops dominating the landscape, as they do now.

The fire events detected at El Sertal and El Cueto de la Avellanosa (Fig. 5 and Fig. 6) appear to follow a different pattern, although the inflection and trend change points are the same as at La Molina. At El Cueto de la Avellanosa, CHAR increased ca. 3600 cal years BP and the maximum is seen at ca. 2650 years cal BP, coinciding with Bond cycle 2. The low CHAR values of El Sertal could be explained by an open space already present at the base of the sequence and the charcoal particles coming from woody fuel burning some distance away from the sampling point. Situated on a hill, it would only receive contributions from nearby fires. The highest CHAR values were found during the most recent millennium, when there has been a greater local and regional anthropic pressure.

From 3000-2800 cal years BP, the percentage of Ericaceae pollen increased and arboreal pollen decreased simultaneously, a pattern very similar to El Cueto de la Avellanosa (Mariscal, 1983). At this site, the increase in sedimentary charcoals was more coincident with indicators of the opening of the landscape, which suggests either that the fires were closer to the site or that its basin better reflects the events. Mariscal (1983) points out the development experienced by the paraclimatic communities of areas deforested by human action as the most remarkable feature.

The period of transformation represented by the Bronze Age seems to correspond to a global pattern in mountain areas where the dominant vegetal landscape consisted of open spaces, with a predominance of vegetation of anthropic origin and pastures for livestock (Carozza *et al*., 2005; Ruiz Alonso *et al*., 2011). The signs of human pressure become even clearer thereafter, beginning 2800 cal years BP. This model of general intensification of anthropic pressure on high mountain environments is well documented for the Pyrenees and the Basque Country and seems to respond to a global pattern in the whole northern part of the Iberian Peninsula (Galop *et al*., 2007; Bal *et al*., 2011; Pèlachs *et al*., 2011; Gassiot *et al*., 2014).

Fire and landscape dynamics

The first fire episodes are inextricably linked with the important percentages of Poaceae and *Pteridium* as well as the presence of cereal pollen grains (between 6000 and 5000 cal years BP) stand out as indicating open spaces (Fig. 7). These agricultural practices are also evidenced by the presence of naked wheat grains in El Mirón cave during the Neolithic period (Peña-Chocarro *et al.*, 2005). In Monte Areo, Asturias, the first evidence of human landscape transformation dates back 7300 years (López-Merino *et al*., 2010) and the appearance of a cereal-type pollen occurs between 6735-6495 cal years BP. The disappearance of cereals between 4800 and 3300 cal years BP could be explained by local changes of the bog because a regional explanation for their absence has not been found.

The climate conditions during the studied period would induce a major biomass production facilitating the expansion of mesophytic communities that grow faster than conifers (Gil-Romera *et al*., 2014). Likewise, the low values of *Pinus* would not suggest a presence of pine forests in the vicinity. This observation is confirmed in other diagrams of the Iberian Atlantic coast (García-Amorena *et al*., 2008; Moreno *et al*., 2011) and coincides with the absence of pine macroremains in nearby caves (Peña-Chocarro *et al*. 2005). Rubiales *et al*. (2008) suggest that deciduous taxa would have been favored over coniferous species because of the temperate and humid climate, creating a remarkable cover of flammable fuel necessary for fires.

It is important to keep in mind that fire linked to agricultural activities has had great influence on the configuration of the environment intensify continuously between the Bronze Age and the Roman period (Arias, 1999). The continuous decline in tree cover is associated with the presence of pastures and alternating burnings on the near slopes that favored the development of Ericaceae. Some parallelisms are found at Mediterranean sites. During the mid-Holocene, the vegetation around Stagno di Sa Curcurica (Sardinia, Italy) was characterized by dense *Erica scoparia* and *E. arborea* stands, which were favored by high fire activity (Beffa *et al*., 2015).

The intensification of fire activity in the last 1000 years in El Sertal represents an interesting point as regards the development of certain tree populations. That is the case of *Fagus*, it appears in the zone around 3000 cal yr BP and reaches its maximum from around c. 1000 cal yr BP. This episode is evidenced in most of the sequences of the Iberian Peninsula (Muñoz-Sobrino *et al*. 2009). Fire could have helped to create the conditions necessary for *Fagus* expansion while total tree pollen percentages fell and heathland began to expand.

CONCLUSIONS

The comparisons between the three sequences provide evidence that fire has been a key factor in the retreat of the forest and subsequently in the maintenance of open landscapes since the Neolithic. Over the past 7000 years, the intensity and chronology of fire events was unequal at the three sites studied, which can be interpreted as the result of asynchronous human activity in the high and low mountain areas and, at the same time, of the type of fuel involved in each zone.

The patterns of fires have varied significantly on a regional scale since the Neolithic period. In La Molina, the maximum values occurred between 5800 and 3500 cal years BP, whereas in El Cueto de la Avellanosa they were observed between 3600 and 1700 cal years BP. At El Sertal, the fire events occurred mainly during the past millennium, although open spaces are evident in the record from the very base of the sequence.

The phases of decline in organic matter, which could reflect more erosive periods, do not seem to be directly related to the rates of sedimentary charcoal accumulation. The catchment area at La Molina quantitatively favored the deposition of local charcoal as well as that from surrounding hillsides. At El Sertal and El Cueto de la Avellanosa, the peat bogs are located on hills and provide a much more local reflection of fire events.

At both El Sertal and El Cueto de la Avellanosa, the increase in Ericaceae around 3000 cal years BP is synchronous with the reduction in arboreal cover. At El Cueto de la Avellanosa, this landscape transformation coincides with an increase in sedimentary charcoals, defining a model of anthropic pressure intensification related to the use of fire.

Even though much of the Neolithic control of Cantabrian fires was basically human, we cannot rule out synergies with the climate and its influence in the processes of human adaptation to mountain areas. Two major climatic moments have been identified, in 4200 and 2800 cal years BP, which coincide with the transition to the Age of Metals (Bronze and Iron). The presence of human activity since the Neolithic period would have enhanced the effects of the drought cycles of the mid-late Holocene, increasing fire activity.

Forest fires induced by human activity can be identified from plant taxa that indicate fire and recurrent human presence at different historical moments. In Cantabria, the most important of these are Poaceae, *Pteridium*, Ericaceae and *Plantago*. The important presence of secondary communities of species such as *Corylus* should also be emphasized. The increase of *Fagus* in the last thousand years is another response to anthropic forest clearing. The study of the history of the vegetation in the Cantabrian Mountains reveals the direct relationship between the use of fire and the agro-livestock system, in particular cereal cultivation, from its origins.

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Table 1. Cultural stages and chronology in the Cantabrian Region

Cultural stages	**Chronology (cal ka BP)**	**Main characteristics of human presence in the territory**	**References**
Middle and Upper Palaeolithic (Late Pleistocene s.l.)	> 10	Groups of hunter-gatherers, mainly in the low valleys and coastal area.	González Morales *et al.*, 2004
Epipalaeolithic-Mesolithic	10 to 7	Hunter-gatherers mainly on the coast, although the mountain area is frequented.	Fano *et al.*, 2013 Álvarez Fernández, 2015
Neolithic	7 to 5.6	The emergence of grazing in the Neolithic period radically changed this pattern of occupation of the territory by encouraging the exploitation of all mid-mountain areas.	González Morales *et al.*, 2004 Cubas *et al.*, 2016 Peña Chocarro *et al.*, 2005 Arias *et al.*, 2013
Chalcolithic	5.6 to 3.8	Intensification of the producer economy in mid-mountain areas. First settlements.	Arias *et al.*, 2006 Ontañón, 1995 and 2003
Bronze Age	3.8 to 2.7	Strong growth of agricultural and livestock farming activities. Occupation of new areas.	Blas and Fernández, 1992 Arias, 1999
Iron Age	2.7 to 2.1	Fortified settlements and large deforested areas at the summits of mid-mountain areas. Mining and metallurgy of iron in the coastal area	Peralta, 2000 Cisneros *et al.*, 2008 Mantecón, 2000
Roman and Early Middle Ages	2.1 to 1.1	Small towns, agriculture, and active metallurgy in coastal areas. Livestock and a few fortified settlements in mountain areas.	Mantecón, 2000 Aja *et al.*, 2008
Middle Ages to Precontemporary	1.1 to 0.15	Increasing agricultural and livestock pressure. The productive space of the villages covers the whole territory. Overexploitation of forests to meet the demands of the naval, steel and coal industries.	Ortega, 1984 Ceballos, 2001

Table 2: Radiocarbon data for the peat bog cores analyzed.

A. La Molina

Laboratory code	Sample depth (cm)	Material dated	13C/12C (o/oo)	Conventional radiocarbon age	Age used for chronological model [cal yr BP]
Documentary data	14	*Pinus/Eucalyptus* plantations			0 (1950 AD)
Beta-371859	40	Peat	-27.5	650 ± 30	580
Beta-385973	68	Peat	-27.3	3340 ± 30	3575
Beta-371860	113	Peat	-25.9	3480 ± 30	3800
Beta-371861	186	Peat	-26.6	4130 ± 30	4760
Beta-360118	260	Peat	-27.7	5910 ± 30	6740

Source: Pérez-Obiol *et al*. (2016) *Quaternary Science Review* **135**: 65-78.

B. El Sertal

Laboratory code	Sample depth (cm)	Material dated	13C/12C (o/oo)	Conventional radiocarbon age	Age used for chronological model [cal yr BP]
Beta-424743	17.5	Plant material	-29.3	1520 ± 30	1404
Beta–448487	26.9	Organic sediment	-28.9	2590 ± 30	2741
Beta-371862	38	Organic sediment	-28.3	4520 ± 30	5158

C. El Cueto de la Avellanosa

Laboratory code	Sample depth (cm)	Material dated	13C/12C (o/oo)	Conventional radiocarbon age	Age used for chronological model [cal yr BP]
Beta-410651	56	Plant material	-24.7	1410 ± 30	1317
Beta-410652	196	Plant material	-28.1	3260 ± 30	3489
Beta-371855	399	Organic sediment	-28.2	6120 ± 40	7005

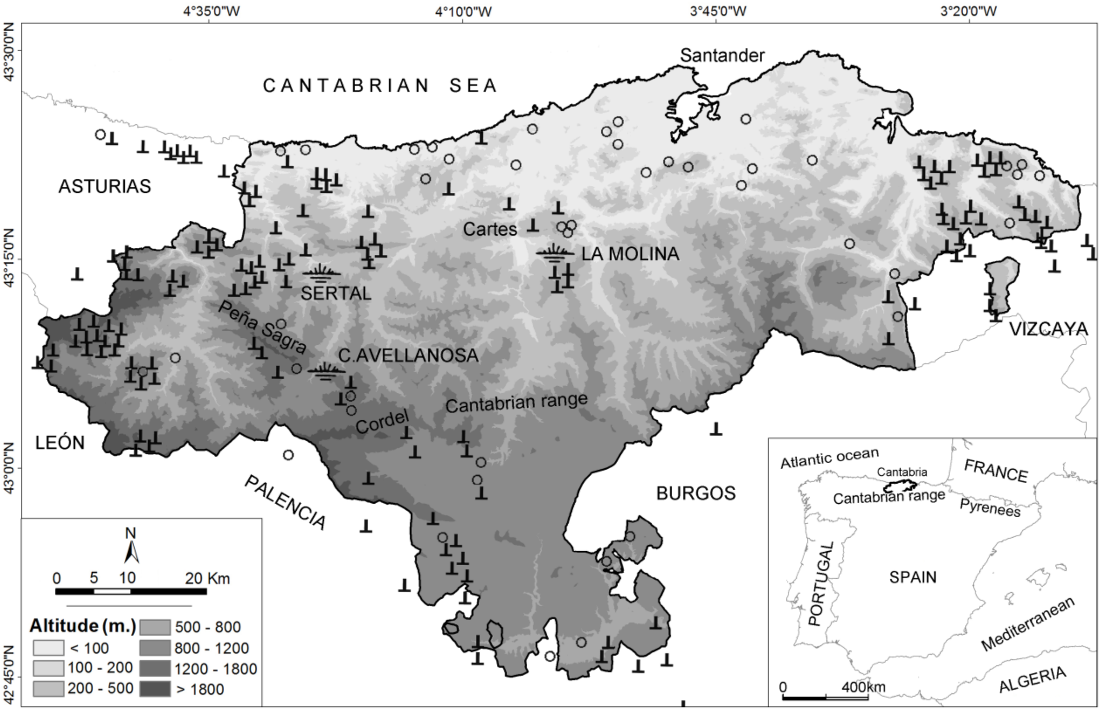

Fig. 1. Location of the peat bogs and of the main archaeological remains from the recent prehistory of Cantabria (inverted T = megaliths; Circle = Chalcolithic to Bronze Age sites).

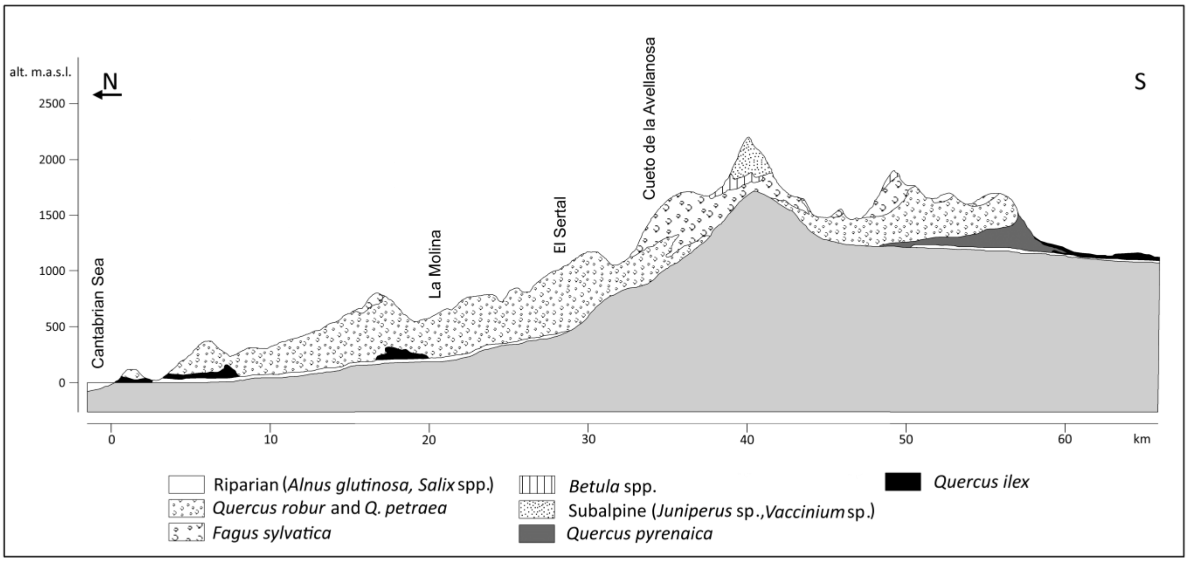

Fig 2. Altitudinal zonation of the Cantabrian mountains and location of the peat bogs studied.

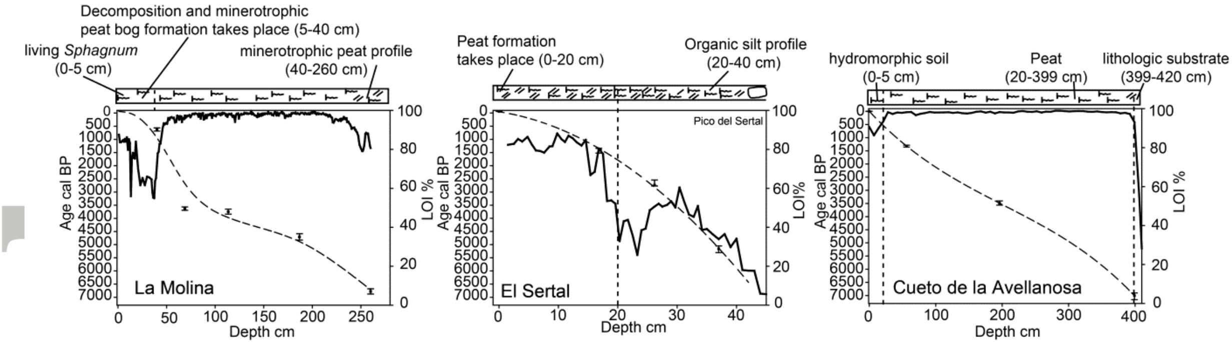

Fig. 3. Age-depth models with location of the radiocarbon samples, values for organic matter, and description of sediment. The main lithology of La Molina is peat. At El Sertal, there are three main sediment units (peat, organic silt, and silt). At Cueto de la Avellanosa, the peat lies above the lithological substrate (comprising Permian lutites and sandstones with large blocks of siliceous conglomerates of the same age). NOTE: 14C dates for these sequences are shown in Table 2.

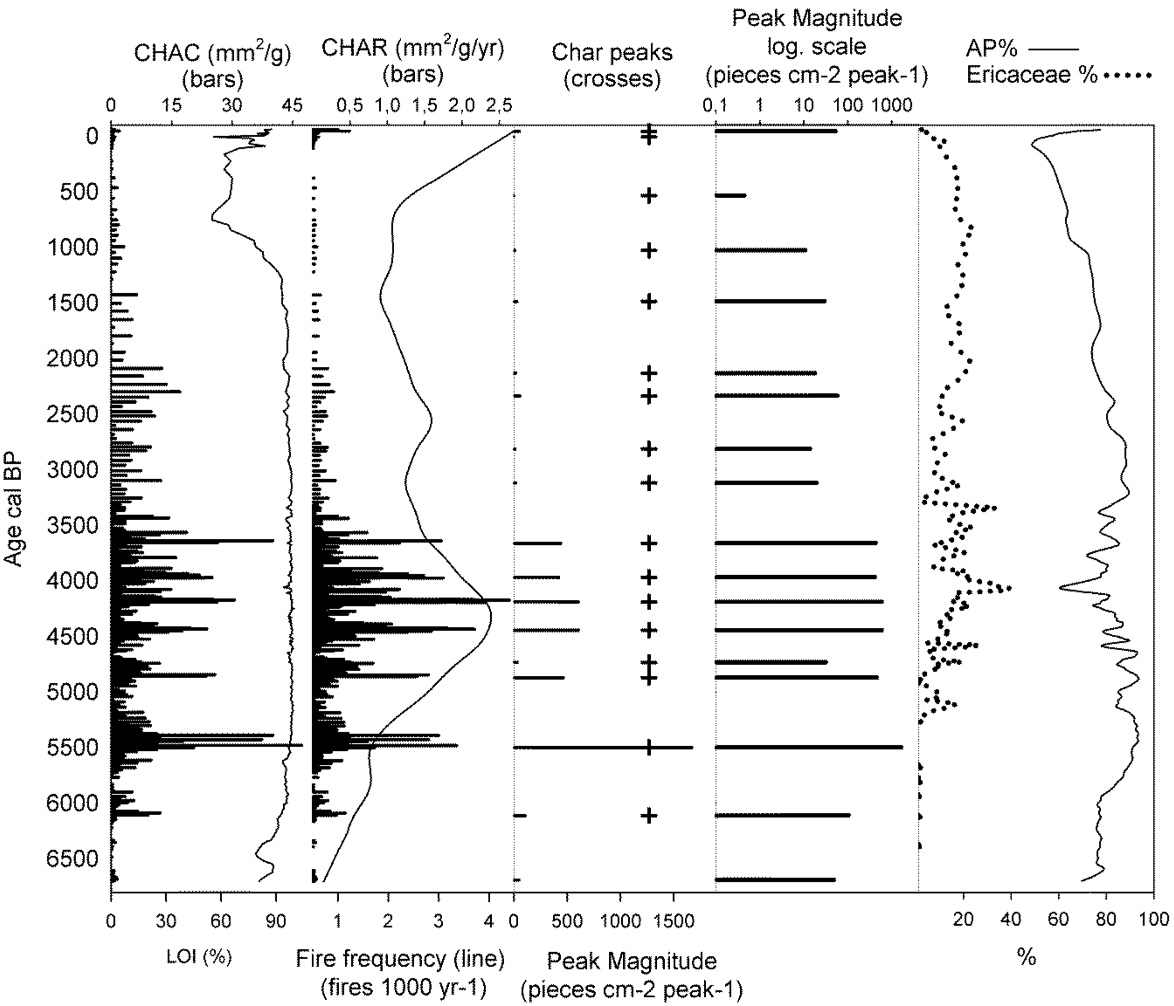

Fig. 4. CHAC, LOI, CHAR, Fire frequency, CHAR peaks, Peak magnitude (1000-year window) and changes in arboreal and Ericaceae pollen at La Molina. The most intense fires coincide with the highest arboreal pollen values. Significant fire events were identified from the very base to the end of the sequence; the highest frequency and intensity occurred between 5800 and 3500 cal years BP, when there was also a dense forest cover.

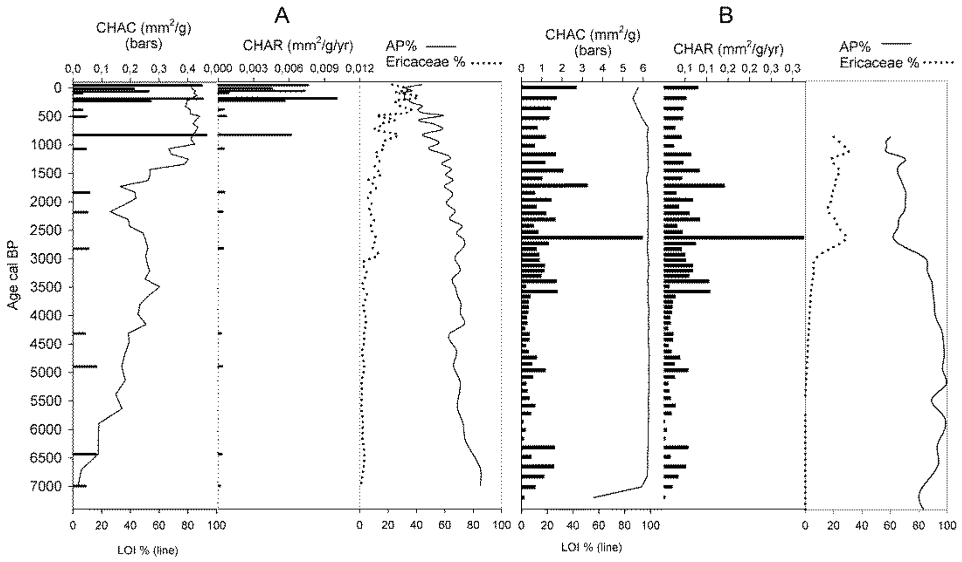

Fig. 5 CHAC, LOI, CHAR and changes in arboreal and Ericaceae pollen at El Sertal (A) and El Cueto de la Avellanosa (B). The pollen values at El Cueto de la Avellanosa have been redrawn based on Mariscal (1983). The fire events detected at El Sertal and El Cueto de la Avellanosa appear to follow a different pattern. At El Cueto de la Avellanosa, CHAR increased ca. 3600 cal years BP and the maximum is seen at ca. 2650 years cal BP, coinciding with Bond cycle 2. At El Sertal, the highest CHAR values were found during the most recent millennium, when there has been a greater local and regional anthropic pressure.

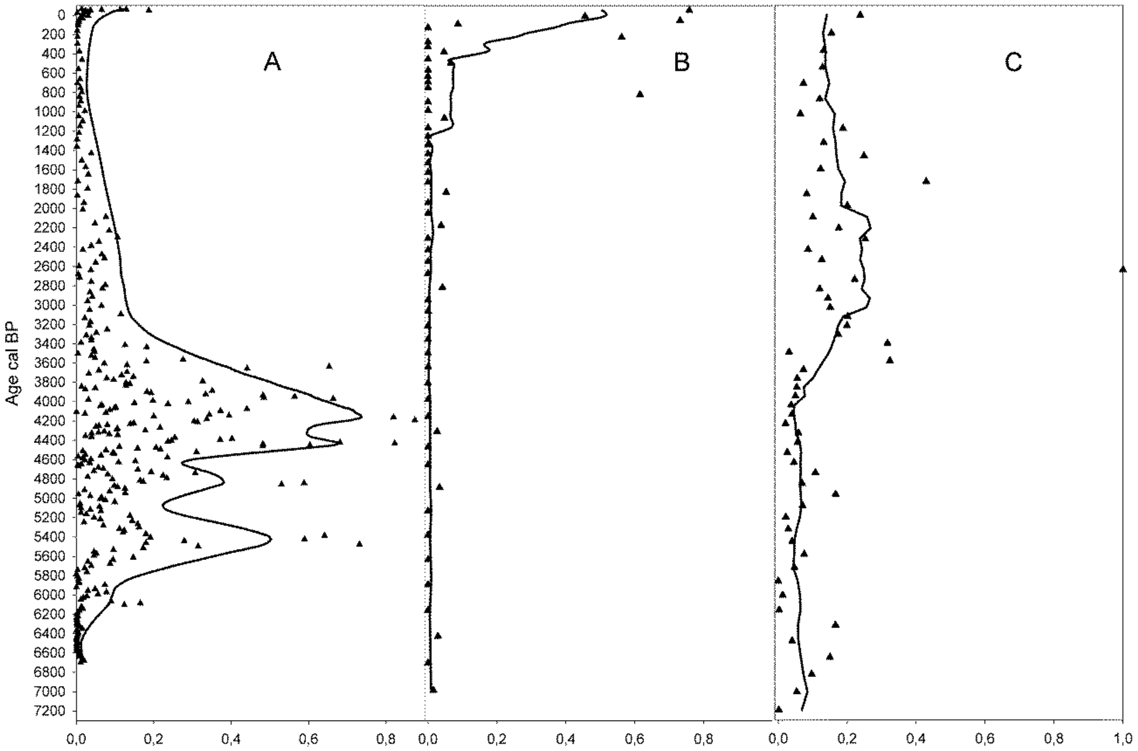

Fig 6. Comparison of CHAR values with rescaled and smoothed values from La Molina (A), El Sertal (B) and El Cueto de la Avellanosa (C). Over the past 7000 years, the intensity and chronology of fire events was unequal at the three sites studied, which can be interpreted as the result of asynchronous human activity in the high and low mountain areas and, at the same time, of the type of fuel involved in each zone.

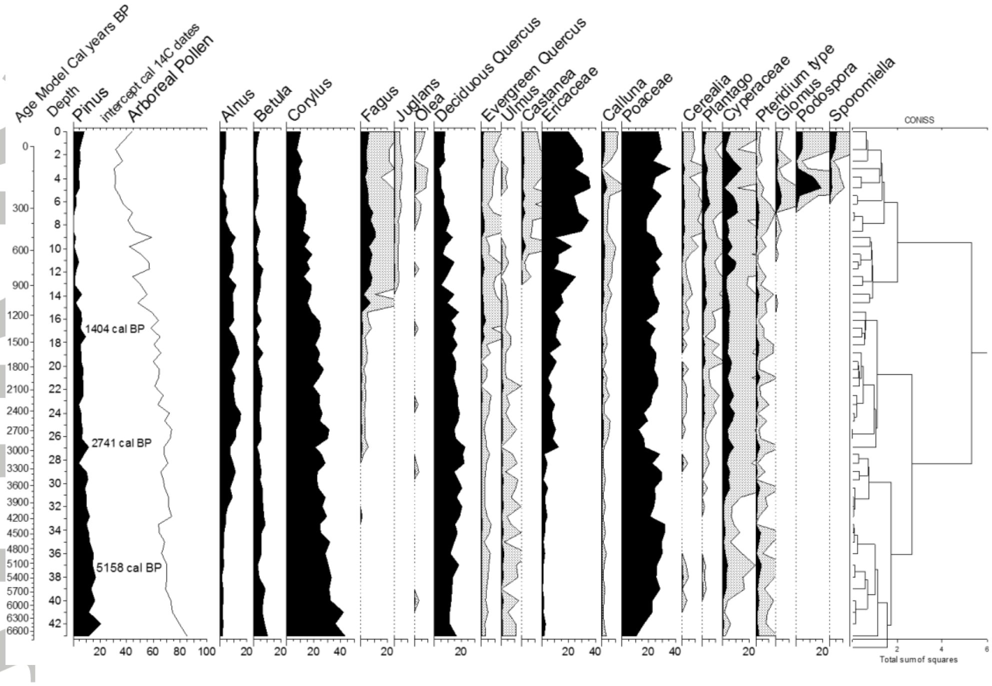

Fig. 7: Main taxa of the El Sertal pollen diagram. The pollen data revealed a continuous decline in forest cover since the Neolithic. Note the significant values of Poaceae, Pteridium, Ericaceae and Cereals, indicating different land management periods and types of human impact. The intensification of fires in the last millennium could well have led to the considerable increase in Fagus.