DENDRO-ANTHRACOLOGICAL TOOLS APPLIED TO MONTANE PINE FORESTS EXPLOITATION AS FUEL DURING THE MESOLITHIC-NEOLITHIC TRANSITION IN THE SOUTHERN CENTRAL PRE-PYRENEES (SPAIN).

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Abstract

This work focuses on the reconstruction of human firewood management during the Mesolithic-Neolithic transition in the southern central Pre-Pyrenees (Spain). The study combines wood charcoal identification with the application of dendro-anthracological approaches in the archaeological sequence of Esplugón (9.4-6.8 kyr cal BP) (Sabiñanigo, Huesca). Montane pine (Pinus sylvestris tp.) reaches in this record around 90% of exploited firewood in line with its abundance in the inner Iberia mountainous areas during the onset of the Holocene. The classification of pine wood fragments in anthraco-groups is based on the combination of different dendro-anthracological tools: i) pith location tool and wood diameter estimation based on trigonomethric method tool (ADmodel) ii) the study of growth rate based on the annual tree-ring width measurements iii) and a modern dendrological dataset. There are hardly any differences in the firewood management by the last hunter-gatherers and the first farmers in the long sequences from rock-shelters with recurrent human occupations. First results in this site suggest the exploitation of whole trees but a high use of small pine branches probably from the gathering of natural pruning.

1. INTRODUCTION

This work constitutes a holistic approach to Early-Middle Holocene archaeological wood charcoal assemblages from the southern central Pre-Pyrenees (Spain). Some of these assemblages are characterized by a very homogeneous composition, in which montane pines wood (*Pinus sylvestris* tp.) always reaches very high values, above 70%, despite the taxonomic diversity. Montane pines (*Pinus sylvestris* tp.) has been played an important role in Mediterranean vegetation since the Pleistocene which is reflected in its abundant presence in many wood charcoal assemblages of southern Europe (Alcolea, 2015; Alcolea et al., 2017a; 2017b; Allué et al., 2012, 2017a; 2017b; 2018; Allué and Mas, 2020; Aura et al., 2005; Badal et al., 2012a, 2012b; Badal and Martínez-Varea, 2018; Carrión et al., 2008; 2019; Mazo and Alcolea, 2019; Montes et al., 2016; Rubiales et al., 2010; Théry-Parisot, 2001; 2002; Théry-Parisot and Thiébault, 2005; Théry-Parisot et al., 2016; 2018; Vidal-Matutano, 2017; Vidal-Matutano et al., 2015, 2017, 2018).

Pinus sylvestris L. forests show a greater world distribution area nowadays although in the Iberian Peninsula are now restricted to the highest elevations in mountain areas (Costa et al., 2001). They are accompanied by *Pinus nigra* subsp. *salzmannii* (Dunal) Franco in the lowlands and *Pinus mug*o subsp. *uncinata* (Ramond ex DC.) that dominates the highlands. Unfortunately, these species can hardly be distinguished in the basis of their microscopic wood anatomy, so they are grouped in the taxon *Pinus sylvestris* tp. which refers to all these cryophillous pines that live in the Mediterranean mountains.

The abundance of *Pinus sylvestris* tp. wood in certain archaeological records for thousands of years implies an evident limitation in the interpretation of the archaeological record from the point of view of traditional wood charcoal analysis. But also, the large amount of available fragments from the same taxon constitutes an opportunity to apply innovative anthracological and dendro-anthracological tools to these contexts (Allué et al., 2009; Allué and Mas, 2020; Caruso-Fermé and Théry-Parisot, 2018; Caruso-Fermé et al., 2013; Dufraisse, 2006; Dufraisse and García-Martínez, 2011; Dufraisse et al., 2017; 2020; García-Martínez and Dufraisse, 2012; Henry and Théry-Parisot 2014; Paradis-Grenouillet et al., 2013; Thèry-Parisot et al., 2011; Théry-Parisot and Henry, 2012; Vidal-Matutano et al., 2017).

In this paper, the unpublished wood charcoal analysis of the whole archaeological sequence of Esplugón site (Huesca, NE Iberia) is presented in its Pyrenean context. In addition, we introduce the quantitative study of the wood charcoal alterations, as well as the first results of the application of dendro-anthracological tools to wood charcoal fragments, that allow to know the parts of the exploited plants. For the latter, it has been necessary to create a first specific modern dendrological dataset for montane pines (*Pinus sylvestris* tp.) in the southern central Pre-Pyrenees. All these approaches lead us to a better global understanding of the forest management by the human inhabitants of the site. The archaeological sequence of Esplugón, with a succession of Mesolithic and Neolithic occupations, allows a comparison of the firewood management between the last hunter-gatherers and the first farmers in the region. This work constitutes a starting point for future wood charcoal studies in Pleistocene and Holocene sequences in NE Iberia.

2. REGIONAL SETTING AND SITE DESCRIPTION

The southern central Pre-Pyrenees is a key region for understanding the Mesolithic-Neolithic transition in NE Iberia. The Pyrenean foothills, or Pre-Pyrenees (450-950 msnm), concentrate human occupations in rock-shelters and caves, some of them containing long sequences of human occupation, as Esplugón, Forcas, Artusia, Aizpea and Arba del Biel sites (Utrilla et al., 2016, Obón et al., 2019; Utrilla and Mazo, 2014; García-Martínez de Lagrán et al, 2017; Barandiarán and Cava, 2001; Montes et al., 2016; Laborda, 2019) (Figure 1). All the sites have many similarities as they contain recurrent and probably short-term occupations and their strategic location over the valley, controlling human and prey movements. Wood charcoal analysis has been recently performed in all of them (Zapata, 2001; Alcolea, 2015; Montes et al., 2016; García-Martínez de Lagrán et al, 2017).

The Esplugón site is the largest rock-shelter facing southeast in the southern central Pyrenees known so far for this chrono-cultural period (Figure 2). It is located in the middle transverse corridor of the Guarga valley (Huesca, NE Iberia) between Pre-Pyrenees and Pyrenees. The description of six Mesolithic and Neolithic archaeological layers makes it a reference site for understanding the neolithisation process in the Ebro basin (NE Iberia) (Utrilla et al., 2012; 2016; Berdejo and Obón, 2013; Berdejo et al., 2018; Obón et al., 2019). Regarding to the whole stratigraphy, 7 described archaeological layers are organized in 4 chrono-cultural stages of human occupation (Figure 3):

- Stage 1. Layer 1. A partially altered Chalcolithic layer, in which they have been recovered chalcolithic and sub-present materials.
- Stage 2. Layers 2 and 3 sup. An Early Neolithic occupation, in which lithic geometric microliths with abrupt retouching was recovered, as well as a scarce bone industry and pottery fragments with incised and cardial decorations.
- Stage 3. Layers 3 inf. and 4. A Geometric Mesolithic occupation, in which a rich lithic assemblage of geometric microliths was recovered, firstly triangles and afterwards trapezes.
- Stage 4. Layers 5 and 6. A Late Mesolithic occupation still without an accurate chrono-cultural definition. Although the scarce lithic materials recovered seem to fit with a Notches and Denticulate Mesolithic (layer 5) and a Microlaminar Epipaleolithic (layer 6), the available radiocarbon dating does not support the second ascription.

Radiocarbon dating has been obtained in 14 samples (Table 1 and Figure 4). They place the human occupation of the site (excluding phase 1) between 9.4 and 6.8 ka cal BP (Obón et al., 2019; Laborda, 2019). The Late Mesolithic stage occurs during the last millennium of the Early Holocene (9.4-8.5 ka cal BP). The Geometric Mesolithic or Early Mesolithic stage starts coinciding with the 8.4 and 8.2 arid events that gives rise to the Middle Holocene in the region (8.5-7.5 ka cal BP). Finally, the Early Neolithic stage occurs during Middle Holocene (7.3-6.8 ka cal BP).

Archaeological materials recovered at the site as well as the preliminary archaeozoological study suggest that hunting would be the main use of the settlement along the whole sequence. Recurrent use by short-term occupations is proposed during the Mesolithic while a more or less stable habitat by long-term occupations with various activities (scraping, drilling, mowing), besides hunting, have been proposed during the Neolithic (Utrilla et al., 2016; Obón et al., 2019). In any case, the hunted species are characteristic of a forested environment with prevailing red deer (*Cervus elaphus*), roe deer (*Capreolus capreolus*), and wild boar (*Sus scrofa*) (Obón et al., 2019). Despite the presence of some domestic animals only in layer 2, neither traces related to livestock sheltering and feeding nor storage structures have been found so far in the site (Laborda, 2019).

The site is located at 800 m asl. This area is currently characterised by a continental Mediterranean climate with long, dry summers, an average annual temperature between 12°C and 14°C, and 500 mm of annual precipitation. The vegetation is characteristic of the transitional zone between the meso-Mediterranean and oro-Mediterranean biogeographic belts (Rivas Martínez, 1982). Present-day flora is influenced by the altitudinal gradient, orography, calcareous lithology and the high levels of anthropic impact. Vegetation surrounding the site is dominated by degraded forest of deciduous *Quercus* (*Quercus faginea* Lam. and *Quercus cerrioides* Wilk & Costa). Scots pine (*Pinus sylvestris* L.) and mainly extensive plantations of Austrian pine (*Pinus nigra* subsp. *laricio* Maire) grow throughout the valley. Boxwood (*Buxus sempervirens* L.), hawthorn (*Crataegus monogyna* Jacq.), dogwood (*Cornus sanguinea* L.), and brooms (*Echinospartum horridum* (Vahl) Rothm), grow abundantly in the scrubland and forest edges. The proximity of the Guarga river defines the ample presence of riparian vegetation dominated by black poplar (*Populus nigra* L.) and willow (*Salix eleagnos* Scop.).

3. Materials and methods

3.1. Materials.

Archaeological works started in 2009. Specific strategies of sampling and recovery for archaeobotanical remains have been followed at Esplugón site during 2012, 2013 and 2017 fieldwork seasons. Archaeological layers are characterized by a greater density and good conservation of charred wood remains. Hand-picking of visible charcoal remains found during fieldwork was accompanied by a wet sieving of all the sediment through a 2-1 mm mesh size. Also, flotation tests with 0,5-0,1 mm mesh size of 20 litres of sediment per square meter and archaeological layer were performed by M. Alcolea in the Laboratory of Prehistory of the University of Zaragoza in 2018. It was not possible to document so far the presence of carpological remains in the archaeological deposit. Charred wood identified in this work corresponds to scattered charcoal in the sediment from samples recovered by hand-picking, wet sieving and flotation. Scattered charcoal is the result of consecutive combustion events reflecting successive collections of firewood (Chabal, 1997). It constitutes a valuable source of information about the surrounding vegetation of the site and the activities of human groups in the past (Chabal et al., 1999; Théry-Parisot et al., 2010).

3.2. Methods.

3.2.1. Wood charcoal analyses

Wood charcoal fragments were studied following the standard methods in wood charcoal analysis (Vernet, 1973). For the taxonomic identification the anatomical patterns of each fragment were observed along the three wood sections under magnification factors between x50 and x600, employing an incident light dark/bright field microscope Leica DM2700M property of PPVE research group of the University of Zaragoza (Spain). Botanical identification was possible by referencing wood anatomy atlases (Schweingruber, 1990, García Esteban et al., 2003) and current carbonized woods from the reference collection. Nomenclature follows the guidelines in *Tela Botanica* (https://www.tela-botanica.org/). No significant differences in the number of identified taxa have been documented from the screened and floated samples. The results have been organized in an anthracological diagram.

3.2.2. Charcoal taphonomy

Charcoal taphonomy in anthracological research provide additional information about plant growth, wood-gathering strategies and combustion and post-deposition processes (Chabal et al., 1999; Allué et al., 2009; Théry-Parisot et al., 2010; Vidal-Matutano et al., 2018; Caruso-Fermé and Théry-Parisot, 2018; Allué and Mas, 2020).

Alterations were quantified by a binomial system based on presence or absence. The percentages of alteration are calculated in relation to the number of charcoal fragments identified as *Pinus sylvestris* tp in the first three cases. Only in the case of vitrification, the percentages of alteration are calculated in relation to the total number of studied fragments since this alteration strongly conditions the number of undetermined charcoal fragments. For the application of dendro-anthracological techniques it has been necessary to select the charcoal fragments that present a low alteration level that not affect their wood structure.

3.2.3. Dendro-anthracological techniques

Dendro-anthracological tools allow to measure dendro-anthracological parameters based on morpho-anatomical criteria (Table 2). Dendro-anthracological techniques have been applied on selected *Pinus sylvestris* tp. wood charcoal fragments with the aid of a multizoom microscope (Nikon AZ100) that allows magnification factors from x4 to x500 and the NIS Element image analysis software. The measurements are based on the distance and the angle between two ligneous rays. They were obtained by using a semi-automatic system based on 4 landmarks integrated in the Nikon NIS Elements software. All measurements are taken in radial section. The selection of fragments was based on two criteria: size and status. In terms of size, a minimum of 4 mm^2 is required in transverse section. Regarding the status of preservation, the microscopic wood anatomy must not be deformed, particularly affecting ligneous rays and tree-rings boundaries.

3.2.3.1. The pith location tool and wood diameter estimation

Pinus sylvestris tp. is an appropriate taxon to apply dendro-anthracological techniques. Regarding microscopic wood anatomy features, the presence of visible ligneous rays makes them appropriate for measuring the charcoal pith distance applying the trigonometric method (Dufraisse and García-Martínez, 2011; Paradis-Grenouillet et al., 2013). On the other hand, is important that a modern reference dataset is already established for the measuring of calibres of pines in the framework of the DENDRAC project (http://dendrac.mnhn.fr/) (Dufraisse et al., 2020). The pith location tool is used to measure the distance between the charcoal fragment and the theoretical location of the missing pith. This tool is based on measurements of the angle and the distance between two ligneous rays and the application of correction factors (Dufraisse and García-Martínez, 2011; Dufraisse et al., 2020). The angle must be above 2 degrees and the distance must be above 2 mm for reducing the margin of error and improving results in archaeological applications (Dufraisse et al., 2017; 2020). The values were ordered into diameter classes chosen to be compatible with standards used in dendrometrical plans by foresters, 4 cm, 7 cm and 20 cm but adding some wood cuts. For *Gymnospermae* diameter classes chosen are [0-2] cm, [2-4] cm, [4-7] cm, [7-10] cm, [10-14] cm, [14-20] cm and >20 cm (Dufraisse et al., 2017).

3.2.3.2. The Analysis Diameter model (ADmodel)

The Analysis Diameter model has been developed as a tool dedicated to recompose unburnt wood diameter (UWD) in terms of volume based on the distribution of diameter classes obtained with the pith estimation tool (Dufraisse et al., 2017). It was developed, based on the fact (i) burnt, wood undergoes both mass loss and charcoal fragmentation and (ii) a trunk is biologically considered to be a stack of hollow cones whose thickness corresponds to the amplitude of the diameter classes (Dufraisse, 2006; Dufraisse and García-Martínez, 2011). A calculation table provides the respective distribution of these cones in terms of volume (Dufraisse et al., 2020). However, this model does not reconstruct the initially quantity of burnt wood (Dufraisse and García-Martínez, 2011, Dufraisse et al., 2017).

3.2.3.3. Tree-ring analysis and growth rate

The presence of clearly identifiable annual growth rings in transversal section makes *Pinus sylvestris* tp. an appropriate taxon for measuring tree-ring width. Tree-ring width, as well as early wood (EW) width and late wood (LW) width, has been measured in mm by NIS Element image analysis software (Nikon AZ100). Correction factors have been applied to reverse shrinkage effect in the tree-ring width during charcoalification (García-Martínez and Dufraisse, 2012). The results are plotted by R software (R Core Team, 2017).

In order to establish a discriminating threshold between slow growth rate and fast growth rate we have built a modern dendrological reference dataset in the southern central Pyrenees. Trunks and branches of three *Pinus sylvestris* L. (and three *Pinus nigra* subsp. *laricio* Maire) adult trees between 40 and 50 years from the Station 1, called Secorún (UTM 30T 734715 469813, 1047 masl), close to Esplugón site, have been sampled (Figure 1). Our goal is to know the intra-individual variability and establish the existence of different growth patterns between trunk and branches within the same tree. Trunk core discs are sampled at breast height, 1.30 m above ground, as is usual in dendrochronology. Apical trunks are sampled at an average height of 10.5 m at which they have a similar diameter to the sampled branches. Four primary branches regularly located along the trunk height have been sampled and measured for each tree. The samples have been measured to the nearest 0.01 mm with the TSAP-Win program and a LINTAB™ (Rinntech, Heidelberg, Germany).

3.2.4. Anthraco-typological classification

Finally, the combination of these dendro-anthracological parameters allows the classification of fragments in four anthraco-groups based on the relationship between the estimated minimum diameter and the growth rate (Dufraisse et al., 2017). Following the foresters' diameter ranking, values <7 cm were considered to represent branches, and values >7 cm were considered mature or young trunks. This is the threshold used in this work even though in the case of archaeological charcoal fragments, projected diameters <7 cm could correspond to both branches and young individuals (Picornell-Gelabert and Dufraisse, 2018). Regarding growth rate, the threshold between slow growth and fast growth in this work has been established in 1 mm based on the modern dendrological reference dataset created at the Station 1 Secorún (Figure 5). An anthraco-typological key to sort *Pinus sylvestris* tp. archaeological charcoal fragments into 4 anthraco-groups is proposed (Figure 6) following Dufraisse et al., 2017 for deciduous oak. Following these assumptions, the anthraco-group 1 corresponds theoretically to the exploitation of branches while anthraco-groups 2, 3 and 4 represent to the exploitation of trunks. The group 2 would correspond to the internal part of the trunk while groups 3 and 4 to the its peripheral part (see also Picornell-Gelabert et al., same volume).

4. Results

4.1. Taxonomic diversity

We have studied 1,480 wood charcoal fragments from 6 archaeological layers (Table 3). The presence of 7 taxa has been documented: ash (*Fraxinus* sp.), juniper (*Juniperus* sp.), Scots pine type (*Pinus sylvestris* tp.), deciduous oak (*Quercus* sp. deciduous), holm oak (*Quercus* sp. evergreen), and thorny shrubs belonging to the Rosaceae family (Rosaceae/Maloideae and *Prunus* sp.). The reported percentages of pine wood vary between 75 and 100% of the determined fragments in the different archaeological layers (Figure 7). Taken into account the total number of determined fragments in the site, the pine reaches the 91%, followed by the oak that reaches 6.7% while the rest of the taxa do not exceed the remaining 2.3%. These high levels of pine are common in anthracological deposits from rockshelters during this period.

4.2. Anatomical alterations in charcoals

This assemblage shows high levels of 4 common alterations of wood anatomy: compression wood, fungal alterations, radial cracks, and vitrification (Table 4 and Figure 8).

Cell collapse is commonly associated with decayed or rotten wood caused by fungi and xylophage insects (Moskal del Hoyo et al., 2010; Henry and Théry-Parisot, 2014; Vidal-Matutano et al., 2017) or chemical and physical changes that affect deadwood (Allué and Mas, 2020). In this record a high number of fragments shows signs of fungal degradation, affecting from 34.9 to 58.6% of charcoal fragments identified as pines. This alteration difficults the application of dendro-anthracological techniques when an important part of the surface is affected by this degradation.

Compression wood is associated to a loss of verticality in stem growth. In mountain environments, it can affect both branches and trunks growing on pronounced slopes, thus cannot be used as a discriminating factor. Reaction wood reaches from 25.2 to 69.6% of charcoal fragments identified as pines. These fragments have been avoided when possible for the application of dendro-anthracological techniques even tough correction factors minimize the influence of off-centred piths (Dufraisse et al., 2017; 2020).

The presence of radial cracks on the transversal section affects from 5.6 to 20% of charcoal fragments identified as pines. Its presence is very usual in charred wood because of the loss of volatile contents during the combustion process. Proposed as an evidence of the use of green wood, it has been demonstrated that the occurrence of radial cracks is not correlated with the moisture content, a systematic analysis of the percentage of the affected surface should be addressed in comparison with experimental works (Thèry-Parisot and Henry, 2012; Caruso-Fermé and Thèry-Parisot, 2018). Its presence do not affect in general the application of dendro-anthracological techniques.

Finally, vitrification affects from 3.2 to 24.4% of charcoal fragments identified as pines. It is the cause of the high number of fragments that could not be determined (classified as undeterminable; see table 3). Although in the current state of the research the causes of this alteration are not known (Braadbaart and Poole, 2008; McParland et al., 2010; Courty et al., 2020), it is very usual in conifers, probably associated with resin content. The presence of reaction wood, which consists of a helical thickening in the tracheid walls made of lignin, a thermoplastic material that could favour the fusion of cells in certain charcoal assemblages (Alcolea, 2017).

4.3. Minimum calibres of exploited firewood

Some wood charcoal fragments of *Pinus sylvestris* tp. have been selected for the application of dendro-anthracological tools. Trigonometric method has been applied on a total of 199 charcoal fragments. Diameter classes for each chronological period have been established on the base of minimum diameters of each fragment using pith location tool and wood diameter estimation (Table 5). The UDW has been recomposed using the Analysis Diameter model (ADmodel) (available in https://dendrac.mnhn.fr/spip.php?article237) (Dufraisse et al., 2020).

At the Esplugón site, the exploitation of small calibres predominates throughout the whole archaeological sequence. Minimum diameter classes between 4 and 7 cm predominate during the two Mesolithic phases. During the Early Neolithic this diameter class diminishes while the diameter classes between 2 and 4 cm and 7 and 10 cm gain importance. Above 10 cm of diameter few fragments have been documented (Table 5). Recomposed percentages reinforce the observed tendency.

Usually, the diameter classes <7 cm correspond to branches and/or intern part of bigger trunks, and the diameter classes >7 cm correspond to trunks (Deleuze et al., 2014). This assertion was tested and confirmed on *Pinus halepensis* (Picornell et al, same volume). However, the class between 7 and 10 cm of diameter, may be considered as a transition. In any case, it is necessary to combine these data with the growth rate of tree-rings to discriminate the parts of the exploited plants.

4.4. Growth rate

The width from 1,788 tree-rings has been measured in the 199 fragments. Up to 50 rings have been measured in some fragments of which the average value has been calculated to obtain growth rate. Results show calibrated values after applying correction factors (García-Martínez and Dufraisse, 2012).

No major differences in tree-ring width have been documented among studied periods (Figure 9). Organizing tree-ring width by diameter classes it can be observed that average values are higher in the diametric classes >10 cm. Wider tree-rings are documented in the 2 to 4 and 4 to 7 cm diameter classes but they always constitute outlier values (Figure 10).

We speak of slow growth rate for those fragments that present average tree-ring width values < 1 mm and fast growth rate for those that present values > 1 mm. The threshold has been established from the study of the modern dendrological reference dataset

Secorún. Results of dendrological analysis show clear growth width differences between trunks and branches from the same tree. These differences have been observed in each individual and are repeated in all the trees sampled in the station (Figure 5).

4.5. Anthraco-typological classification: the exploited parts of plants

Anthraco-typological classification of studied archaeological charcoals combines the estimation of the minimum calibres and the growth rate of tree-rings (Dufraisse et al., 2017). The 199 wood charcoal fragments have been classified in 4 groups (Table 6). The anthraco-type 1 has the largest number of fragments in the three studied periods, reaching almost 80% during the Early Mesolithic and 70% during the Late Mesolithic and Early Neolithic. The anthraco-types 2, 3 and 4, that theoretically correspond to different parts of the trunk, represent lower percentages, reaching 20% during the Early Mesolithic and almost 30% during the Late Mesolithic and Early Neolithic.

5. ***Human firewood management in the southern central Pre-Pyrenees during the Early-Middle Holocene***

5.1. Floristic composition of the forest: taxonomic analyses.

5.1.1. Early Mesolithic (9.4-8.5 kyr cal BP)

During the Early Mesolithic occupation in Esplugón, the *Pinus sylvestris* tp. is the most consumed wood for fuel with values reaching up to 90%. Even though extremely high values of conifers persist during the onset of the Holocene in the southern central Pyrenees in both lowland and high altitudes, pollen lake records suggest the rapid spread of mesophytes in the low montane bioclimatic belt, mainly deciduous *Quercus*, after ca. 9.5 kyr cal BP due to major environmental changes such as milder temperatures, warmer summers and an increase in water availability (Pérez-Sanz, 2014; González-Sampériz et al., 2017). These are present in the anthracological record of Esplugón in low values. Deciduous and evergreen *Quercus* hardly represent the 3% of wood charcoal fragments in layer 6 and 7% in layer 5. Shrubby taxa typical of forest edges (*Juniperus* sp., *Prunus* sp., Rosaceae) complete the list also reaching low values in the layer 6 and disappearing in layer 5.

Other Pyrenean anthracological sequences show similar results: *Pinus sylvestris* tp. prevails in low montane deposits until ca. 8.5 kyr cal BP as suggested by Forcas (Alcolea, 2015), Arba de Biel sites (Montes et al., 2016) and Artusia (García-Martínez de Lagrán, 2017) anthracological records. At the lowlands, montane pine forests are replaced by thermophilous Mediterranean pines from ca. 8.7 kyr cal BP (Alcolea et al., 2017a).

5.1.2. Late Mesolithic (8.5-7.5 kyr cal BP)

After 8.2 kyr cal BP pollen lake records suggest semi-deciduous and evergreen *Quercus* replaced mesophytes in the lowlands and low montane (González-Sampériz et al., 2017). Simultaneously, these deciduous forests replaced pinewoods also in the high montane and subalpine bioclimatic belts (Plà and Catalán, 2005; González-Sampériz et al., 2005; Pérez-Sanz et al., 2013) pointing out a relevant increase in winter temperatures and a change in the precipitation regime with a more evenly distributed rainfall (Magny et al., 2002; Morellón et al., 2009).

Pinus sylvestris tp. keep on being the most consumed wood for fuel in Esplugón during Late Mesolithic occupation in layers 4 and 3 inf. between 8.5 and 7.5 kyr cal BP. Accompanying taxa are basically the same as in the previous period and they do not reach 10 % of wood charcoal fragments. The only novelty is the presence of riparian vegetation represented by a single charcoal fragment of ash (*Fraxinus* sp.). This resilient tendency of low montane pine forests in the southern central Pyrenees is also supported by the anthracological records of Forcas (Alcolea, 2015) and Arba de Biel sites (Montes et al., 2016). On the contrary, the human use of widespread deciduous forest is well-documented in south eastern Pyrenean deposits (Zapata and Peña-Chocarro, 2005; Ruíz-Alonso and Zapata, 2017).

5.1.3. Early Neolithic (7.3-6.8 kyr cal BP)

Despite the chronological gap in the sequence suggested by radiocarbon dating (7.5-7.3 kyr cal BP) *Pinus sylvestris* tp. continues being the most consumed wood for fuel in Esplugón, reaching up to 90% of charcoal fragments in layer 3 sup. and 75% in layer 2. On the contrary, *Pinus sylvestris* tp. have completely disappeared in the eastern Pyrenean sequences at 7.3 kyr cal BP, mainly replaced by deciduous *Quercus* and yew (*Taxus baccata*) accompanied by shrubby taxa (Ruíz-Alonso and Zapata, 2017). The Neolithic deposit of Esplugón just start showing a trend towards the use of deciduous taxa in layer

2, dated in 6.8 kyr cal BP, where deciduous *Quercus* reaches almost 20% of charcoal fragments accompanied by all the aforementioned taxa. Resilience of montane pinewoods at the Esplugón site is supported by other wood charcoal analysis in southern central Pyrenees from the low montane (Heinz y Vernet, 1995; Alcolea, 2015; Alcolea et al., 2017b; Montes et al., 2016) to the subalpine bioclimatic belt (Obea et al., 2011; Obea, 2014) at least until 6 kyr cal BP. The limited presence of other taxa in the anthracological record could be related to the character of pine forests with low shrubby undergrowth (Allué et al., 2018).

5.2. Structure of the forest: dendro-anthracological techniques.

5.2.1. The parts of exploited plants.

Wood charcoal analysis worth as a valuable *proxy* to reconstruct the local vegetation in the vicinity of archaeological sites has been widely demonstrated (Vernet, 1997; Badal, 1992; Chabal et al., 1999). However, being a record of anthropic origin, the formation processes of these assemblages are not only influenced by plant species availability in the immediate surroundings of the settlement. They are always influenced to a greater or lesser extent by some factors as the length and type of human occupation, and the uses to which fire production is destined (Chabal et al., 1999; Théry-Parisot et al., 2010).

Pinus sylvestris tp. is the main taxon exploited for fuel along the whole archaeological sequence of Esplugón and also in other short-term human occupations in rockshelters, like Forcas (Alcolea, 2016) and Arba de Biel sites (Montes et al., 2016) suggesting that this woody taxon is the most available in the immediate vicinity of the sites. Even though the resilience of montane pine forests has been proposed in some inland regions of Mediterranean Iberia until ca. 7.7 kyr cal BP (Rubiales et al., 2010; Aranbarri et al., 2014) or even during the whole Middle Holocene (8.2-4.2 kyr cal BP) (Franco Múgica et al., 2001; 2005) due to the delayed onset of the interglacial conditions based on high continentality, water shortage and absence of well-developed soil (Carrión et al., 2010), regional pollen data in the southern central Pyrenees point to a retreat of montane pine forests from 9.5 kyr cal BP, more evident after 7.3 kyr cal BP (González-Sampériz et al., 2017). Wood charcoal analysis in Chaves site (7.6-7.0 kyr cal BP) reveals the use of a broad spectrum of woody taxa as expected in a long-term settlement where diversified human activities take place (Utrilla and Laborda, 2018). Although montane pine is the most consumed taxon it only reaches 30% of the charcoal fragments at level Ib (7.6-7.3 kyr cal BP) (Alcolea et al., 2017b).

Regarding the parts of exploited plants, nor big differences have been documented between the different moments of human occupation. The use of branches, between 70 and 80%, prevails over the use of trunks, between 20 and 30% throughout the entire archaeological sequence (Figure 11). The arrival of Neolithic does not imply a change in forest management strategies. This is consistent with the documented uses of the rockshelter. The main human activity is always the hunting of the forest wild species like roe deer (*Capreolus capreolus*), red deer (*Cervus elaphus*) and wild boar (*Sus scrofa*) (Obón et al., 2019). Domestic animals are restricted to layer 2 and neither storage structures nor stabling layers implying chages in the site function have been found (Laborda, 2019).

5.2.2. Montane pine forests exploitation as fuel.

The three native species of cryophillous montane pines growing in NE Iberia are normally grouped in the taxon *Pinus sylvestris* tp. Montane Iberian pines include *Pinus sylvestris* L., *Pinus mug*o subsp. *uncinata* (Ramond ex DC.) Domin, *Pinus nigra* subsp. *salzmannii* (Dunal) Franco. Theoretically they grow nowadays at different altitudes in NE Iberia: *Pinus nigra* between 500 and 800 masl, *Pinus sylvestris* between 800 and 1700 m a.s.l. and *Pinus uncinata* above 1800 masl (Costa et al., 2001), but usually they overlap biogeographically and can interbreed (Quézel and Médail, 2003). These trees do not show differences in wood anatomy allowing to identify each of them (Greguss, 1955; Schweingruber, 1990) so its past distribution at species level is not well-known (Roiron et al., 2013 Allué et al., 2018). Likewise, is not possible to know if in our deposits appears a single species or several. In any case, they share biogeographical parameters and the architecture of the trees.

We propose that the architecture of montane pines strongly influences its use as firewood. The architecture of the tree is characteristic of each species and allows to understand its growth strategy and occupation of the space. Montane pine trees present a monopodial structure composed of a single stem or trunk that reaches up to thirty metres. The trunk is generally straight but it can present alterations due to the ecological conditions of its growth (strong winds, the weight of the snow, the extreme dryness or being on a slope).

The primary branches grow in polycyclic crowns, formed annually at the same level around the trunk parallel to each other and displaying similar calibres. These trees are characterized by a strong apical dominance, meaning that the branches develop more slowly than the trunk (Riou-Nivert, 2001).

Montane pine forests have a pyramidal or conical shape when young, which nevertheless changes with age. The silouette of adult trees can vary depending on whether it grew isolated or in populations (Figure 12). When they grow up isolated generally green branches reach the foot of the tree. When they grow up in communities, these trees exert competition over each other at two levels: (i) in the soil, which affects their radical underground system, and (ii) in the air, which affects their radical air system, that is, the branches. In the first case, they "run away" from each other, moving as far as possible to take advantage of soil moisture, giving rise in general to open forests. In the second case, they “run away” seeking to reach a greater height to have more access to light. The growth in population provides a lateral shelter, that results in thinner branches and a reduced growth in diameter of the trunk (Riou-Nivert, 2001). In this case, the lower branches under cover usually die due to lack of light. There is very little physiological connection between branches and trunk (Shigo et al., 1987). When they are no longer functional, a resinous partition isolate them to protect the trunk from infections. The branch becomes parasitic and stops participating in the life of the tree. When the process of decomposition by microorganisms is advanced the branch falls according to the phenomenon known as natural pruning. This hypothesis is supported by the high percentages of degraded wood documented in the record (Figure 8), which are associated with the use of deadwood as fuel (Allué et al. 2009; Henry and Thèry-Parisot 2014; Vidal Matutano et al., 2017).

It has been proposed that factors like significant mobility of human groups, seasonal occupations of sites and a relatively limited tool kit would undoubtedly had an impact on firewood acquisition (Thèry-Parisot et al. 2016; 2018). The preferential collection of deadwood optimally ensures the supply during short-term occupations while green wood, which must be cut and dried over several months, is more suited to long-term occupations. Combustion properties largely depend on the phenological (dead or living, dry or green) and morphological (size and diameter) state of wood more than on the particular species (Thèry-Parisot et al. 2016; 2018). It has been proposed on some Palaeolithic sites the preferential exploitation of deadwood through the identification of anatomical wood decay features still perceptible after burning (Allué et al. 2009; Henry and Thèry-Parisot

2014; Vidal Matutano et al., 2017). The preference of *Pinus sylvestris* tp. beyond an environmental restriction has previously been proposed for some paleolithic sites with specific functions (Thèry-Parisot and Thiebault, 2005, Thèry-Parisot et al., 2018). Our hypothesis is that the selection of montane pine wood in Mesolithic-Neolithic transition Pyrenean sequences could be related to its capacity to produce a large amount of dead biomass, almost dry, easy to gather, and more or less regular in size and diameter, resulting in a certain overrepresentation of this taxon in non stable or seasonal settlements in rockshelters in the low montane southern central Pyrenees (Figure 13). Apart from small calibre branches, probably related to natural pruning of non-functional branches, the discrete presence of the largest diameter classes suggests the consumption of trunks as well (Figure 14). This does not necessarily imply that live trees were felled for firewood use. Montane pine forests tend to alternate live trees with dead trees (Costa et al., 2001), so dry trunks that remain standing for years would be easily cut down by prehistoric groups. Forest expansion attested from ca. 9.5 kyr cal BP and changes in fire regime (González-Sampériz, 2004; Gil-Romera et al., 2014) could have resulted in a higher biomass availability.

6. Conclusions and perspectives

Summing up, wood charcoal analysis at Esplugón reveals that montane pines (*Pinus sylvestris* tp.) is the most consumed firewood along the whole archaeological sequence. Although the deciduous *Quercus* appears from the base of the sequence its use as fuel is always secondary. These results match those from other studies in low montane rockshelters containing long sequences of human occupation during the Mesolithic-Neolithic in the southern central Pyrenees.

The recurrent observation of anatomical wood decay features suggests the main use of deadwood as fuel. First dendro-anthracological results suggest the large use of branches and sometime trunks along the whole archaeological sequence. Small calibre branches are more abundant in the record, probably related to natural pruning of non-functional branches. The discrete presence of the largest diametre classes points to the consumption of trunks, possibly taking advantage of the fact that *Pinus sylvestris* L. forests frequently alternate live and dry trees.

Finally, no important changes in forest management have been documented between the last hunther-gatherers and the first farmers, neither in terms of species nor of the exploited parts of plants. So, we propose the continuity on the patterns of firewood gathering as domestic fuel in similar contexts. This observation fits in with hunting of forest species as the main activity along the whole sequence.

The application of dendro-anthracological tools to Mesolithic-Neolithic contexts constitutes a pioneering study. To apply dendro-anthracological tools to different archaeological contexts and taxa in NE Iberia is important in order to understand possible different uses of wood. In the end, dendro-anthracological tools could also have applications to minimize old wood effect in archaeological contexts when no short-lived materials are available.

Authorship contribution statement

Marta Alcolea: Conceptualization, Methodology, Anthracological and dendro-anthracological data curation, Writing - original draft, Writing - review & editing, Funding acquisition, Supervision.

Alexa Dufraisse: Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Funding acquisition, Supervision.

María Royo: Modern reference dendrochronological dataset data curation.Luis A. Longares: Modern reference dendrochronological dataset data curation.

Martín de Luis: Modern reference dendrochronological dataset data curation.

Ramón Fábregas: Writing - review & editing, Funding acquisition.

Carlos Mazo: Conceptualization, Writing - review & editing, Funding acquisition.

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Economy and Competitivity (Spain) and the research group PRESAGE/CNRS UMR 7209 *Archéozoologie, Archéobotanique: Sociétés, Pratiques et Environnements* (National Museum of Natural History, France). The authors acknowledge the heads of the archaeological excavation, P. Utrilla (University of Zaragoza, PPVE Reasearch Group), A. Berdejo and A. Obón (*De la Roca al Metal* independent research Group), the access to archaeobotanical materials. The authors acknowledge M. Lemoine (MNHN) their assistance in dendro-anthracological data curation. We also would like to specially thank the guest editor, Eleni Asouti, the invitation to participate in this special issue.

Figure and table captions

Figures

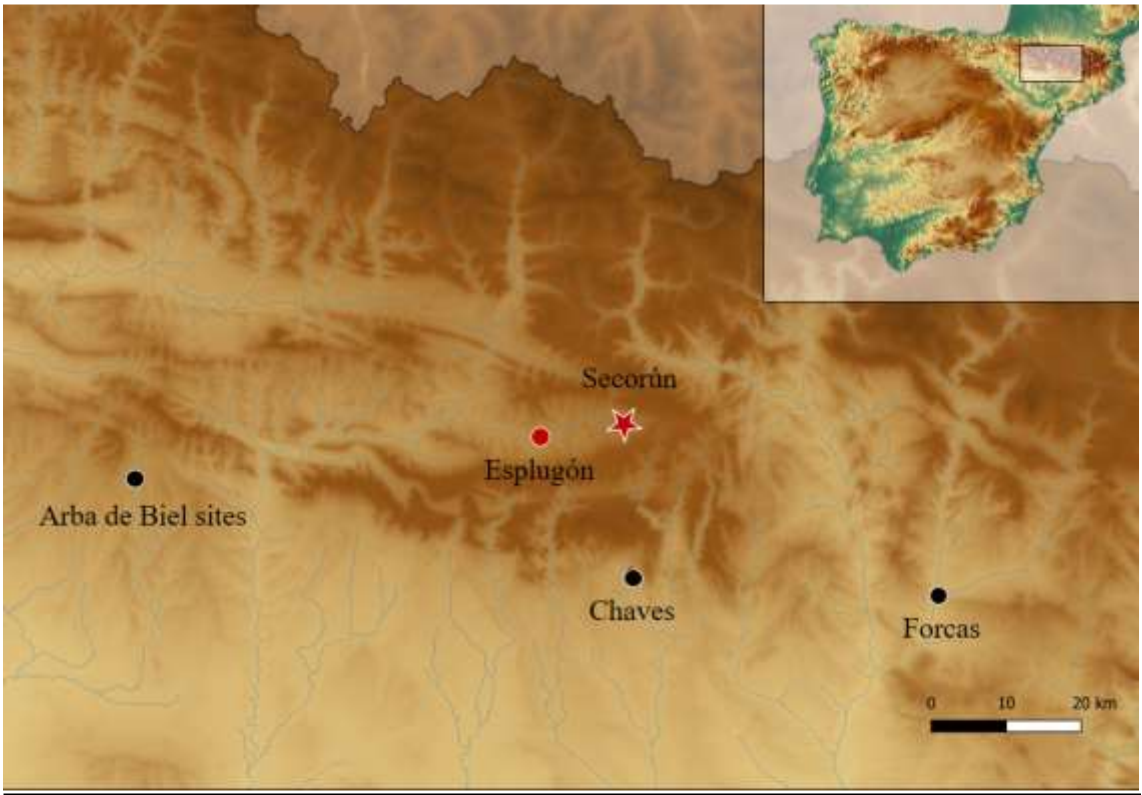

Figure 1. Location of the Esplugón site (Huesca, Spain), the Station 1 sampled for modern dendrological reference (Secorún) and the main surrounding archaeological sites mentioned in the text. Base: MDT200 IGN (Spanish Government).

Figure 2. Location of the rock-shelter in relation with their current biogeographical framework. Photographs: J.L. Peña and C. Mazo (University of Zaragoza).

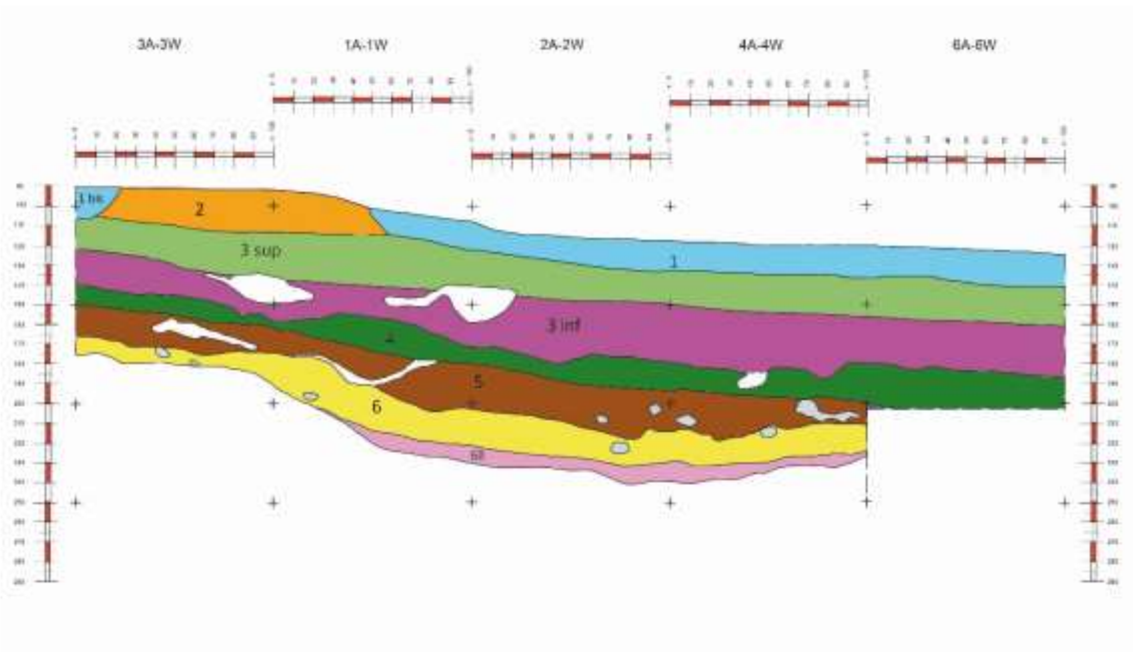

Figure 3. West-east stratigraphic profile from the Esplugón site according to Laborda, 2019.

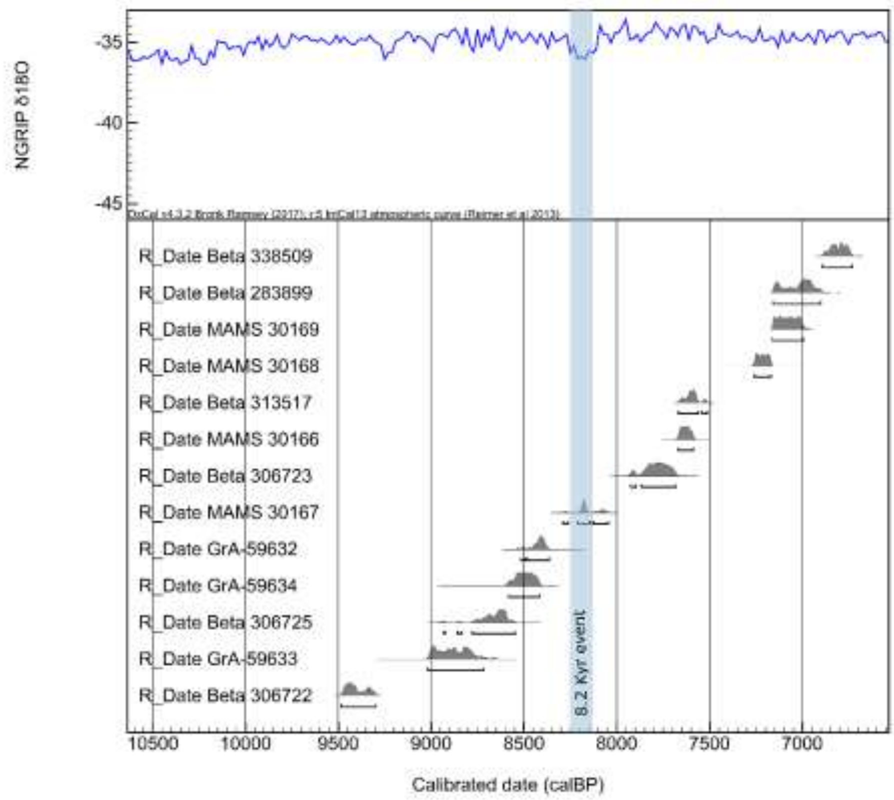

Figure 4. Plotted dates 14C-AMS cal BP from the Esplugón site and GRIP climate curve according to Obón et al., 2019.

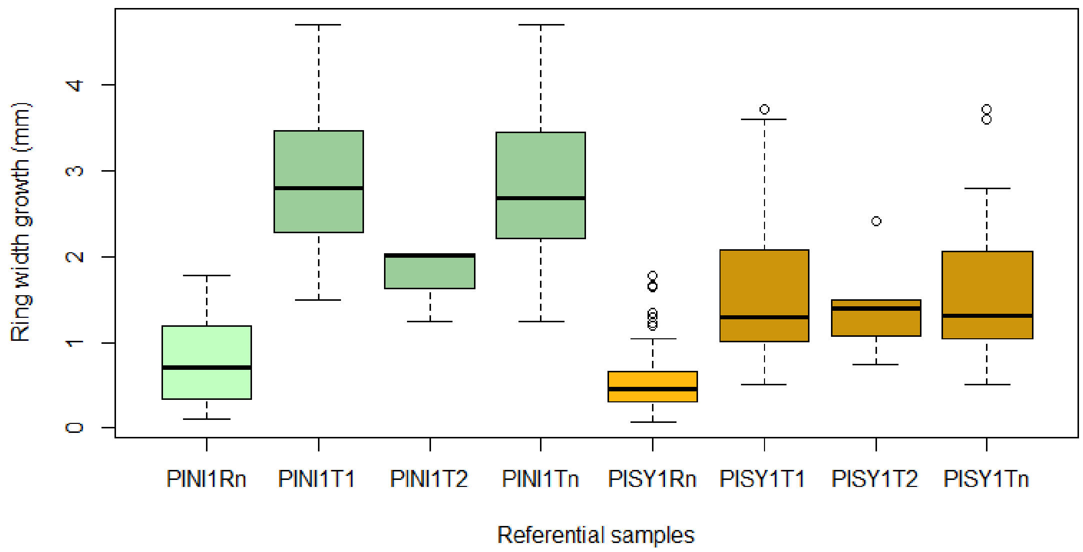

Figure 5. Boxplot showing tree-ring width analysis results in the modern dendrological reference dataset Secorún. PINI *Pinus nigra*, PISY *Pinus sylvestris*. (Rn) Total values from branches, (T1) Values from 1.30 height trunks, (T2) Values from apical trunks, (Tn) Total values from trunks.

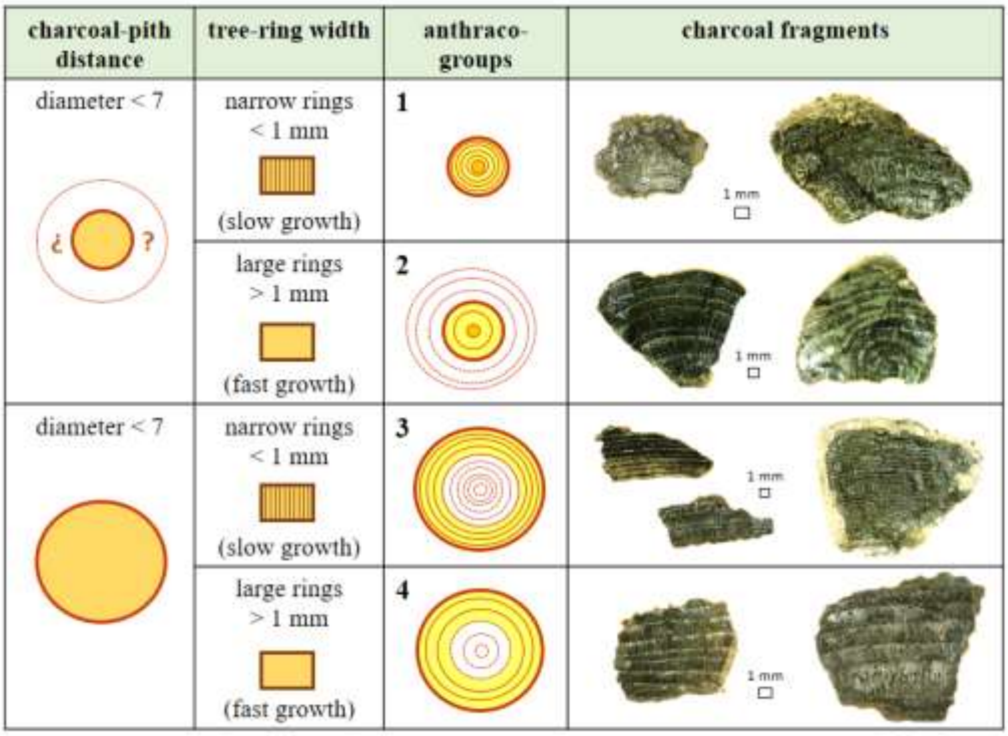

Figure 6. Anthraco-typological key to sort *Pinus sylvestris* tp. archaeological charcoal fragments into 4 anthraco-groups. Based in Dufraisse et al., 2017 for deciduous oaks.

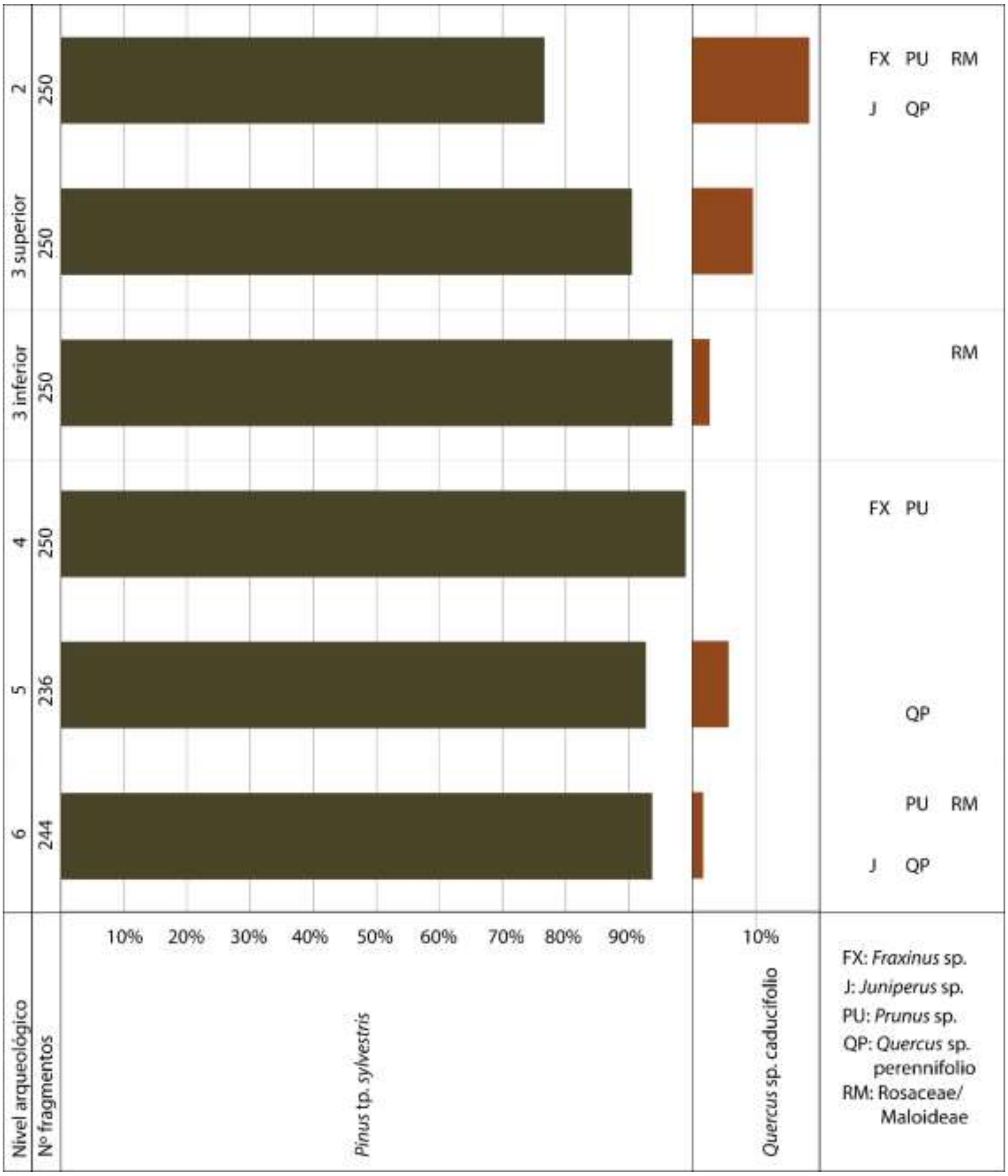

Figure 7. Anthracological diagram from the Esplugón site (Huesca, NE Iberia).

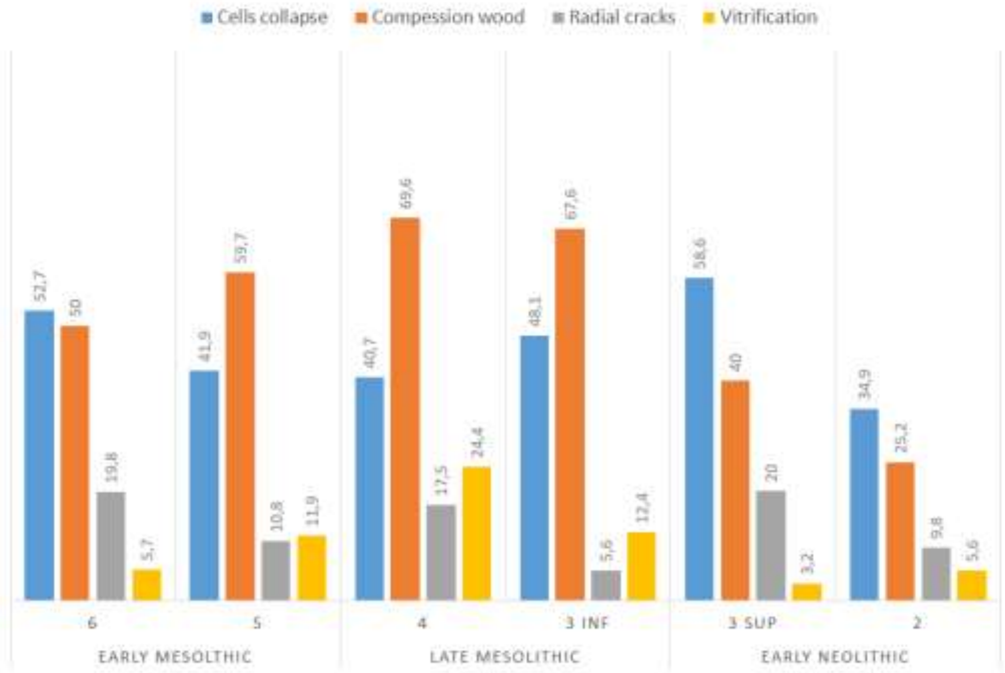

Figure 8. Anatomical alterations identified in the Esplugón charcoal assemblage by a binomial system based on presence or absence. The percentages of alteration are calculated in relation to the number of charcoal fragments identified as *Pinus sylvestris* tp. except in the case of vitrification, calculated in relation to the total number of studied fragments. (EM) Early Mesolithic, (LM) Late Mesolithic, (EN) Early Nolithic.

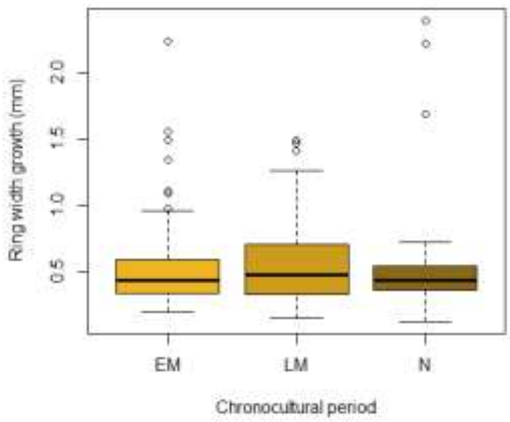

Figure 9. Boxplots showing tree-ring width analysis results in the Esplugón site. Results organized by chronological periods: (EM) Early Mesolithic, (LM) Late Mesolithic, (N) Early Neolithic.

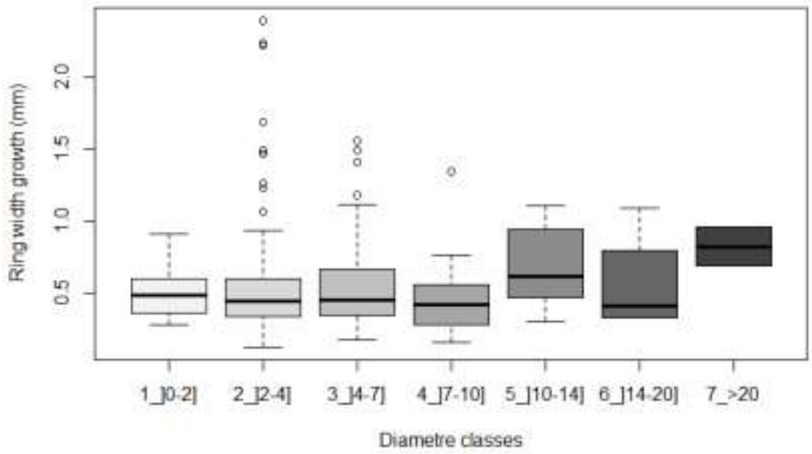

Figure 10. Boxplots showing tree-ring width analysis results in the Esplugón site. Results organized by diametre classes.

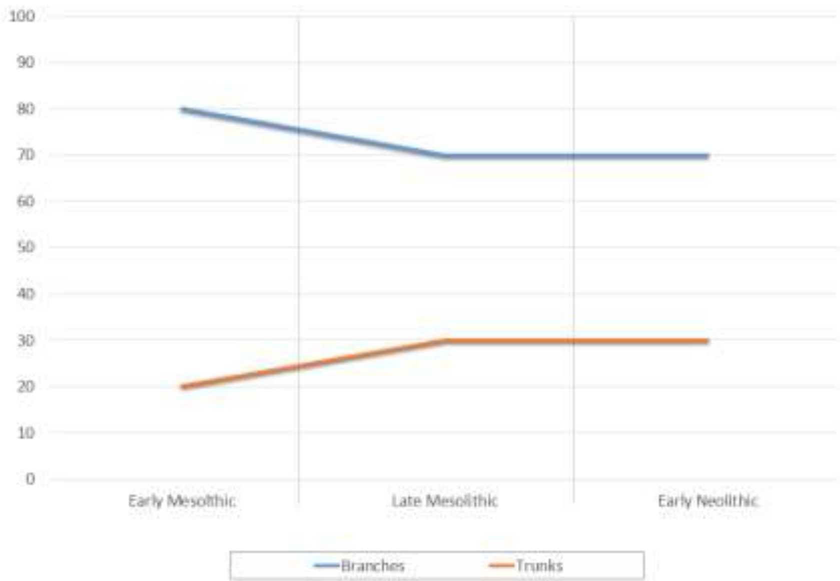

Figure 11. Evolution of the parts of plants exploited at the Esplugón site.

Figure 12. Architecture of *Pinus sylvestris* L. depending on whether it grew isolated (left) or in population (right) according to Riou-Nivert, 2001, 107.

Figure 13. Current vegetation in the surroundings of Esplugón site. A. Map based on Forest Map of Spain MFE50 MITECO, black star marks the site location. B. Deadwood accumulated in the Guarga riverbanks because of the presence of large blocks of limestone. July of 2013. C. *Pinus sylvestris* L. currently growing next to the site. Photographs: M. Alcolea.

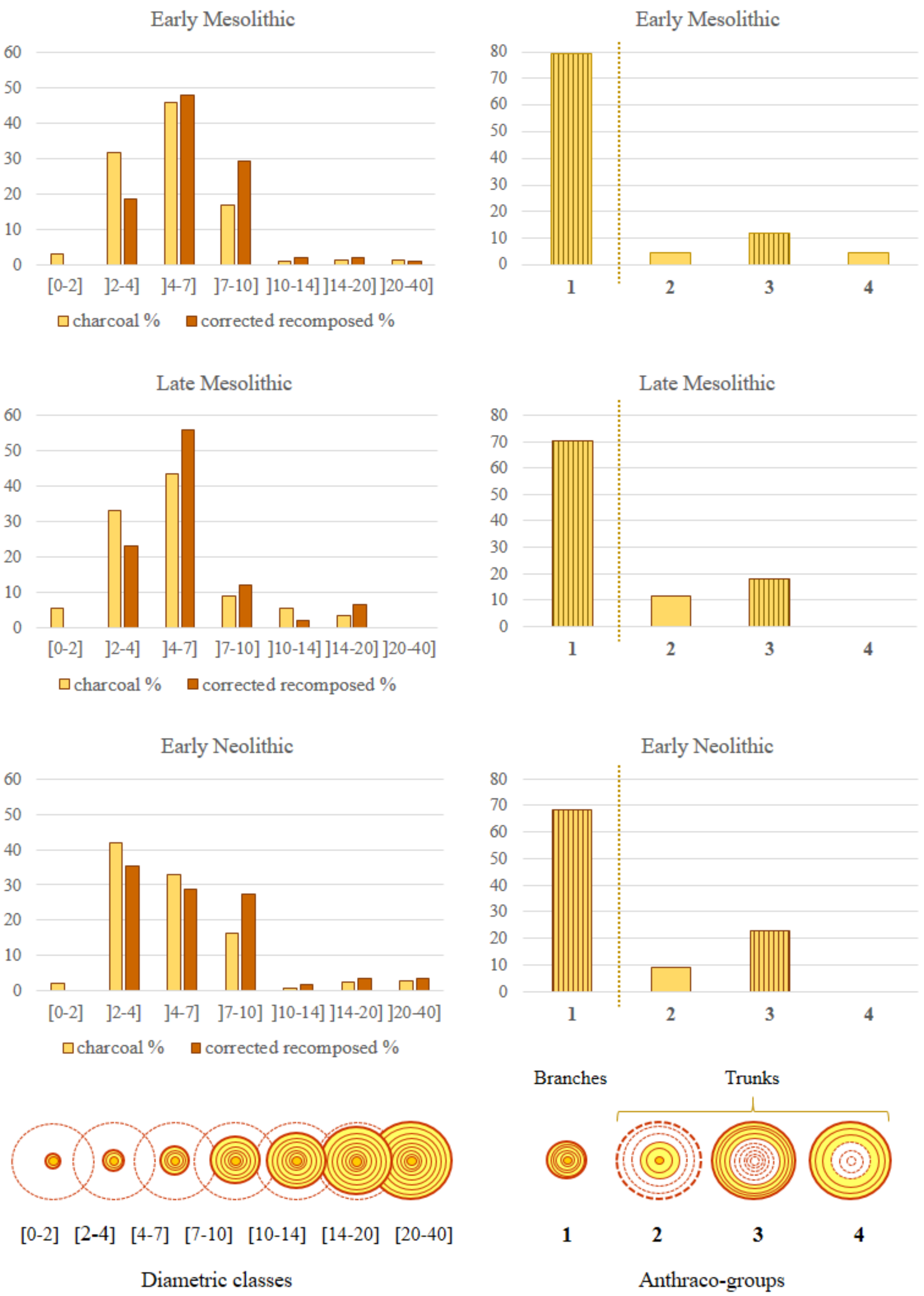

Figure 14. Diagrams summarizing the results of the application of dendro-anthracological tools to wood charcoal fragments in the Esplugón site. At left, diametric classes obtained by trigonometric method expressed in percentages by fragments and corrected recomposed percentages by ADmodel (available in https://dendrac.mnhn.fr/spip.php?article237). At right, measured fragments grouped in anthraco-groups based in anthraco-typological key showed in Figure 6. The results are grouped in chronocultural periods.

Tables

Sample type	Lab. Ref.	Date BP	Date 2s cal BP	Archaeological Layer	Phase
Bone	Beta 338509	5970±30	6893-6731	3 sup	EN
Bone	*Beta 283899*	*6120±40*	*7159-6903*	*4*	*EN*
Bone	*MAMS 30169*	*6166±23*	*7163-6997*	*6*	*EN*
Bone	MAMS 30168	6282±22	7259-7170	3 sup	LM
Bone	Beta 313517	6730±40	7668-7514	3 inf	LM
Bone	*MAMS 30166*	*6781±23*	*7670-7588*	*2*	*LM*
Bone	Beta 306723	6950±50	7926-7681	3 inf	LM
Bone	MAMS 30167	7355±23	8291-8044	4	LM
Charcoal	GrA 59632	7620±40	8519-8366	4	LM
Charcoal	*GrA 59634*	*7715±45*	*8585-8419*	*6*	*LM*
Bone	Beta 306725	7860±40	8934-8547	5	EM
Charcoal	GrA 59633	8015±45	9021-8717	5	EM
Bone	Beta 306722	8380±40	9486-9300	6	EM

Table 1. Radiocarbon dating from the Esplugón site in chronological order (OxCal v 4.3.2. IntCal13, Reimer et al., 2013; Bronk Ramsey, 2017). In italics, the dates which are not in agreement with its stratigraphic position, interpreted as intrusions due to bioturbations.

Dendro-anthracological parameter	**Morpho-anatomical criteria**	**Dendro-anthracological tools**
Growth rate	Tree-ring width	Dendrometry by image analysis software
Minimum diameter	Convergence of ligneous rays	Pith location tool and wood diameter estimation Analysis Diameter model (ADmodel)

Table 2. Table summarizing applied dendrometric techniques according to Dufraisse et al., same volume.

Layer	**6**		**5**		**4**		**3 inf**		**3 sup**		**2**	
Chronology	**EM**		**EM**		**LM**		**LM**		**EN**		**EN**	
Taxa	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
Fraxinus sp.	-	-	-	-	1	0.5	-	-	-	-	4	1.7
Juniperus sp.	3	1.3	-	-	-	-	-	-	-	-	1	0.4
Pinus sylvestris tp.	222	93.7	193	92.7	194	99	216	96.9	220	90.5	183	76.6
Prunus sp.	2	0.8	-	-	1	0.5	-	-	-	-	2	0.8
Quercus sp. deciduous	4	1.7	13	5.7	-	-	6	2.7	23	9.5	44	18.4
Quercus coccifera/ilex	3	1.3	3	1.4	-	-	-	-	-	-	2	0.8
Rosaceae/Maloideae	3	1.3	-	-	-	-	1	0.4	-	-	3	1.3
Total determinable	**237**		**208**		**196**		**223**		**243**		**239**	
Undeterminable	7	2.9	28	11.9	54	21.6	27	10.8	7	2.8	11	4.4
Total	**244**		**236**		**250**		**250**		**250**		**250**	

Table 3. Absolute and relative frequencies of the taxa identified in the Esplugón site. (EM) Early Mesolithic, (LM) Late Mesolithic, (EN) Early Neolithic.

Layer	**6**		**5**		**4**		**3 inf**		**3 sup**		**2**	
Chronology	**EM**		**EM**		**LM**		**LM**		**EN**		**EN**	
Alterations	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
Cells collapse	117	52.7	81	41.9	79	40.7	104	48.1	129	58.6	64	34.9
Compession wood	111	50	83	59.7	135	69.6	146	67.6	88	40	46	25.2
Radial cracks	44	19.8	21	10.8	34	17.5	26	5.6	44	20	18	9.8
Total *Pinus*	**222**	**100**	**193**	**100**	**194**	**100**	**216**	**100**	**220**	**100**	**183**	**100**
Vitrification	14	5.7	28	11.9	61	24.4	31	12.4	8	3.2	14	5.6
Total fragments	**244**	100	**236**	100	**250**	100	**250**	100	**250**	100	**250**	100

Table 4. Anatomical alterations identified in the Esplugón charcoal assemblage by a binomial system based on presence or absence. The percentages of alteration are calculated in relation to the number of charcoal fragments identified as *Pinus sylvestris* tp. except in the case of vitrification, calculated in relation to the total number of studied fragments. (EM) Early Mesolithic, (LM) Late Mesolithic, (EN) Early Nolithic.

Chronology	**EM**			**LM**			**EN**		
Diameter class	**n**	**%**	**AD%**	**n**	**%**	**AD%**	**n**	**%**	**AD%**
0-2 cm	3	4.5	0	7	8.0	0	2	4.5	0
2-4 cm	27	40.3	32.3	32	36.4	31.3	21	47.7	46.6
4-7 cm	26	38.8	42.4	33	37.5	47.4	11	25	20.0
7-10 cm	8	12.0	19.8	9	10.2	14.6	7	15.9	25.8
10-14 cm	1	1.5	1.8	5	5.7	2.1	1	2.8	1.8
14-20 cm	1	1.5	2.3	2	2.8	4.7	1	2.8	3.2
>20 cm	1	1.5	1.4	0	0	0	1	2.8	2.7
Total	**67**	**100**	**100**	**88**	**100**	**100**	**44**	**100**	**100**

Table 5. Diameter classes of charcoal fragments analysed by dendrometric techniques at Esplugón site. AD% = % corrected recomposed. (EM) Early Mesolithic, (LM) Late Mesolithic, (EN) Early Neolithic.

Chronology	**EM**		**LM**		**EN**	
Anthraco-type	**n**	**%**	**n**	**%**	**n**	**%**
1	53	79.1	62	70.5	31	70.5
2	3	4.5	10	11.4	3	6.8
3	8	11.9	16	18.2	10	22.7
4	3	4.5	0	0	0	0
Total	**67**	**100**	**88**	**100**	**44**	**100**

Table 6. Anthraco-groups to which charcoal fragments analysed at the Esplugón site belong according Dufraisse et al., 2017. (1) Diameter <7 and growth rate <1 mm, (2) diameter <7 and growth rate >1 mm, (3) diameter >7 and growth rate >1 mm, (4) diameter >7 and growth rate >1 mm. (EM) Early Mesolithic, (LM) Late Mesolithic, (EN) Early Neolithic.

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