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Reconstructing the heterogeneity of past woodlands in anthracology using the spatial distribution of charcoals in archaeological layers: Applied to the postglacial occupation of the Abeurador cave (Hérault) in the South of France

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ABSTRACT

Previous methodological developments in the field of anthracology have led to the definition of rigorous sampling methods in archaeological contexts, which provide highly accurate and reliable taxonomic frequency spectra as a basis for understanding past woodland vegetation. However, the fuelwood taxon frequency spectra represent a synthetic picture of forest composition in the environs of an archaeological site. Our aim in this paper is to describe the heterogeneity of woodland distribution. The Abeurador cave (Hérault) in the south of France, has previously provided an exceptionally rich palaeoecological study. We further explore the spatial frequency distributions of the charcoal taxa found in charcoal scatters from two layers dated to the Mesolithic (Preboreal). The frequencies of abundant taxa have a unimodal distribution in the sampled grid squares, close to the normal distribution. The ratio s^2/m (variance/mean) termed the 'distribution index', estimates the regularity of distribution of each taxon in the grid squares. We hypothesized that the frequency distribution of a taxon in a layer could be considered to be its statistical sampling distribution (i.e. probability distribution) in the firewood collection catchment at a given time, since the quantity of this taxon fluctuates in each firewood assemblage according to its probability of collection, relating to its distribution heterogeneity (or accessibility) in the past environment. The distribution index was then used to estimate the heterogeneity of the palaeoenvironmental distribution of each taxon and thus its random, uniform or clustered distribution. On this basis, we propose a mapped restitution of the evolution of the main woodland species in the surroundings of the Abeurador during the Early Holocene, integrated with the whole sequence dynamics.

1. Aim of the study

Methodological developments in anthracology currently provide stable and reliable datasets which are representative of past environments. This method has been shown to give complete, repeatable and consistent data, as it provides (i) a large number of woody species of all types, (ii) reproducible observations across the synchronous strata of a given site, and (iii) anthracological taxon frequency spectra with high ecological consistency (Chabal, 1997). These achievements are entirely dependent on the appropriate field sampling of charred firewood remains found in archaeological contexts and quantification methods. A broad spatial sampling of 250–400 scattered charcoals in long-term deposits, avoidance of concentrations (short-term activity) regardless

of charcoal abundance and finally recovery through sieving are necessary for the frequency spectrum of taxa to have a paleoecological representativity (Chabal, 1982, 1991, 1992, 1997; 1992; Badal Garcia, 1990, 1992; Heinz, 1990b; Théry-Parisot et al., 2010a; Kabukcu and Chabal, this issue). The burning, dispersing and crushing of charcoal resulted in the disappearance (rather than accumulation) of most of the remains into ashes or microfragments, causing a synthetic effect.

Based on these methods, the palaeoecological representativeness of the frequency spectra of taxa is now well established (Chabal, 1992, 1997; Théry-Parisot, 2001; Théry-Parisot et al., 2010a). It is generally accepted that for most activities involving the use of firewood, the species present in the environment have been used in proportion to their abundance in the local environment. The taxonomic frequency spectrum

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thus provides a synthetic picture of woodland composition in the fuel-wood catchment proximate to the site at the time of its inhabitation. The current biological characteristics and ecological preferences of extant species can then be used to interpret their past distributions, in particular their migrations in response to climate change or their dynamics related to human activities, leading to new ecological trajectories.

So far, however, in palaeoecological reconstructions, the precise distribution of the vegetation proximate to a sampling site is usually not accurately reconstructed. In anthracology, the assumptions on which the reconstruction of local woodland vegetation spatial distribution is based are often reliable because they draw on the topographical, hydrographic or geological characteristics of the present-day environment of the site, which may not have changed significantly with the passage of time. But this is only possible if the recorded species have sufficiently strong ecological preferences (e.g. soil moisture requirements) that permit positioning them accurately in space. For other species exhibiting wider ecological tolerances and requirements, there is always the risk of equifinality when interpreting their past spatial distributions (i.e. the same species could have been distributed in different types of habitats in the past compared to its present-day ecology in the same area). Moreover, the degree of heterogeneity of past landscapes, which depends on dynamic succession processes, is often unknown, thus prohibiting the spatial positioning of certain types of woodland vegetation, since: (i) the climatic and environmental conditions of a site, including soil conditions, may have changed, (ii) the species composition of past woodland communities may have differed from that of modern or historical ones due to the expansion or contraction of individual species ranges, competitive dynamics involving interspecific facilitation, tolerance or inhibition and disturbance factors, and (iii) the ecological plasticity of species has enabled them to develop in biotopes different from those in which they are currently found. Even now, it is often possible to observe that certain species may be absent from otherwise suitable habitats due to local extinctions and/or limited dispersal, while being regularly present in unsuitable habitats, if immigration from productive source areas is sufficiently large (Pulliam, 2002). In addition, in anthracology, dominant charcoal taxa such as *Juniperus*, *Quercus* or *Pinus* are often not identified to species level but only to genus or, at best, species groups. This further limits our palaeoecological understanding of the woodland communities involved and their species composition, spatial distribution and environmental fit.

In this study, we propose to address these difficulties of spatial interpretation as a whole. We provide a method to find out the degree of heterogeneity of the spatial distribution of certain taxa in the site environment at a given period of time, in order to facilitate the interpretation of their actual location in the surrounding area. We also set out to investigate whether our anthracological datasets hold information on the spatial distribution of past woodlands. In classic anthracological approaches, the mean frequencies of the charcoal taxa found in an archaeological layer are used for interpreting past woodland composition. Our working hypothesis was that any variation observed in the spatial distribution of the taxon frequency spectra, across the grid squares of a given archaeological layer, may represent fluctuations in their sampling by humans as part of day-to-day firewood collection sessions. In other words, could the spatial distribution of taxon frequencies in a layer reflect the heterogeneity of past woodlands, assuming that fluctuations in the collection of wood from each species reflect the heterogeneity of its distribution (or its accessibility) in the site environs, which in turn is reflected in fluctuations observed in the accumulation and dispersal of its charred debris in the archaeological layer? In order to test this hypothesis, we analysed the anthracological assemblages available from two successive Mesolithic strata of Abeurador cave (Hérault) in the south of France, which had previously provided an exceptionally detailed reconstruction of Mesolithic woodland composition (Heinz, 1990a, 1990b).

2. Present and past setting of the Abeurador cave

2.1. Location and archaeology

Abeurador cave is located in the south of France (560 m a.s.l.), on the southern slope of the Montagne Noire ~50 km from the current coastline of the Mediterranean, on a dry limestone plateau overlooking the plains of Aude (Fig. 1). The local topography is characterized as a hilly plateau system that rises locally to 640 m a.s.l., dissected by ravines, which slopes down to the plain 3 km to the south-east. The cave opens just under the edge of a limestone platform, incised by a large ravine: the 'Rec des Tremouls', a seasonal stream that runs ~100 m below the cave level.

The cave comprises an elongated chamber of ~90 m² accessed through a small collapsed corridor. The depth of its stratigraphy reaches 4 m in the Central sector of the cave. It was occupied between ~16,000 and 4000 cal BC, during the Upper Palaeolithic, Epipalaeolithic, Early and Middle Mesolithic and, following a stratigraphic hiatus, the Early and Middle Neolithic periods (Vaquer and Barbaza, 1987; Vaquer and Ruas, 2009). Occupation of the cave might have been seasonal and during the Palaeolithic it appears to have been sporadic. Its rich archaeological record includes evidence of a subsistence economy based on hunting, fishing and gathering, with much evidence of the exploitation of plants including legumes (Fabaceae) and fruits, from as early as the Mesolithic period (Vaquer and Ruas, 2009).

Radiocarbon age determinations for the various occupation phases were sourced from Vaquer and Ruas (2009). All dates were recalibrated with OxCal 4.3 (Table 1). Palaeoclimatic phasing for the Tardiglacial and Holocene refers to the Blytt-Sernander nomenclature established for northern Europe, updated by further studies and recent ice core stadial/interstadial chronologies (Rasmussen et al., 2014). Depending on the cited sources, we use cal BC dates in reference to archaeology, cal BP dates for climatic or palynological references and some ka BP or b2k dates.

2.2. Current climate and vegetation

Abeurador cave is situated in a rugged area, at the interface of the Upper Mesomediterranean and Supramediterranean bioclimatic zones (Fig. 2). Annual rainfall ranges from 500 to 800 mm and temperatures from -5 °C to 37 °C. Currently, the composition of the vegetation around the cave is determined by water availability and soil thickness. To the north of the site, above 600 m a.s.l. and under slightly higher rainfall, the Supramediterranean stage is marked by rather dense stands of *Quercus pubescens* mixed with *Quercus ilex*, *Acer monspessulanum*, *Acer campestre*, *Sorbus aria* and other tree/shrub species (Heinz, 1990a). *Quercus petraea* is rare and hybridizes with *Quercus pubescens*. Some of the species present in the Abeurador anthracological diagram currently only exist at higher altitudes, since they were cleared at lower altitudes after the Middle Neolithic. Currently, a low but fairly dense matorral



Fig. 1. Location of the Abeurador cave (Félines-Minervois, France) at a regional scale (IGN Geoportail relief map 2018).

Table 1

Chronological, climatic and cultural context of the Abeurador cave, Central sector. Some radiocarbon dated levels that are not present in the anthracological diagram but specify the chronology are mentioned (after Vaquer and Ruas, 2009).

Anthracological phase	Level	Anthracology	Lab. reference	AMS/Conventional	Dated material & taxon	14C BP	Age cal BC 95% (OxCal 4.3)	Age cal B.P.	Bioclimatic period	Climate	Prehistory period	Culture (lithics)
Phase 2	C2af	yes	–		–	–	–	–	Atlantic	Temperate (warm and moist)	Middle Neolithic	Classic Chassey
	C2ac	yes	–		–	–	–	–	Atlantic	Temperate (warm and moist)	Middle Neolithic	Early Chassey
	C2bc	yes	MC-2145	Convent.	charcoal	6260 ± 90	5466–5000	7416–6950	Atlantic	Temperate (warm and moist)	Early Neolithic	Epicardial
	C2bf	yes	–		–	–	–	–	Atlantic	Temperate (warm and moist)	Early Neolithic	Epicardial
Phase 1b	CX	yes	Gif-6745	AMS	charcoal	8470 ± 90	7703–7309	9653–9259	Boreal	Warming	Middle Mesolithic	Sauveterian (Montclusian)
	C3	yes	–	–	–	–	–	–	Boreal	Warming	Middle Mesolithic	Sauveterian (Montclusian)
	C4	yes	–	–	–	–	–	–	Boreal	Warming	Middle Mesolithic	Sauveterian (Montclusian)
	C5b	yes	MC-2144	Convent.	charcoal	8740 ± 90	8199–7592	10,149–9542	Early Boreal	Warming	Middle Mesolithic	Sauveterian (Montclusian)
	C6	yes	–	–	–	–	–	–	Late Preboreal	Warming	Middle Mesolithic	Sauveterian (Montclusian)
	C7	yes	–	–	–	–	–	–	Early Preboreal	Warming	Middle Mesolithic	Early Sauveterian
	C7	yes	–	–	–	–	–	–	Younger Dryas	Warming	Middle Mesolithic	Early Sauveterian
Phase 1a	F8/C8	no/yes	Gif-6746	AMS	charcoal (F8)	10,480 ± 100	10,712–10,114	12,662–12,064	Preboreal	Cold and dry	Epipalaeolithic	Late Azilian
	F8b	no	LYON-951 (OXA)	AMS	seeds (Juniperus cf. sabina)	11,090 ± 90	11,151–10,797	13,101–12,747	Late Allerød	Mild temperate (warm and moist)	Epipalaeolithic	Early Aziloid (Valorguian)
	C9	yes	–	–	–	–	–	–	Allerød ?	Mild temperate (warm and moist)	Epipalaeolithic	Ancient Aziloid, (Valorgian facies)
	C9a	no	–	–	–	–	–	–	–	–	Upper Palaeolithic	Late Magdalenian
	C10	yes	–	–	–	–	–	–	Bølling ?	Mild temperate (warm and moist)	Upper Palaeolithic	Late Magdalenian
	C10	yes	–	–	–	–	–	–	Bølling ?	Mild temperate (warm and moist)	Upper Palaeolithic	Late Magdalenian

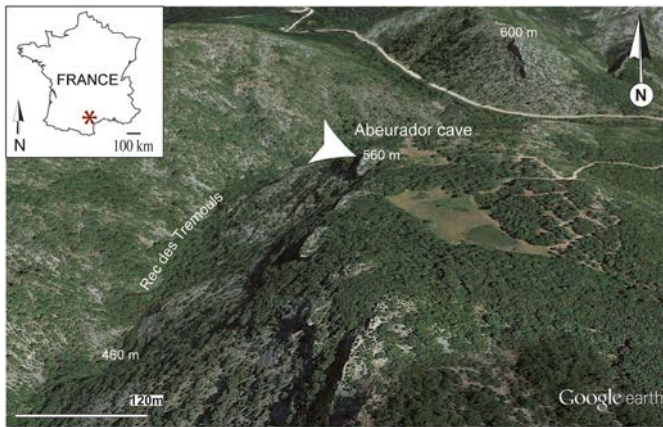


Fig. 2. The Abeurador cave in its current topographical and vegetational environment (Google Earth aerial view 2019).

dominated by holm oak covers the surroundings of the cave, the thalwegs, the ravines, the underside of the limestone ledges where run-off water flows and some of the flat areas of the plateau system where erosion is limited. *Quercus pubescens*, *Juniperus communis*, *Erica arborea*, *Calluna vulgaris*, are present on schists, with a low active lime content and better water retention. Junipers include *Juniperus communis* subsp. *communis*, *J. phoenicea* and *Juniperus oxycedrus*. On the slopes and the most eroded flat areas, low, dry scrubland includes *Juniperus oxycedrus* and other shrub species, revealing, in some places, the bare rock beneath. Water-dependent species are now found several kilometres south in the lowlands.

These rather homogeneous and dry woodlands do not represent the biogeographic potential of the region, as they reflect centuries of fire, soil erosion and over-exploitation. Despite this, most of the species of the past can be found in this diminished vegetation, with few exceptions such as *Pinus type sylvestris*.

2.3. The context of anthracological study

Abeurador cave has provided a long sequence of well-preserved charcoal material, originating from the Central sector, which has enabled the detailed application of appropriate sampling and laboratory methods (see section 1.) and the reconstruction of long diachronic vegetation histories (Heinz, 1990a, 1990b; Heinz et al., 1992; Heinz and Thiébaud, 1998). The anthracological diagram shows three main phases in the local vegetation history, from the Upper Palaeolithic through to the Middle Neolithic (Fig. 3).

Microscopic identifications of wood charcoal are often to genus level, more rarely to species (or species group within a genus). More specifically:

- Within the pines it is possible to identify *Pinus type sylvestris* i.e. either *Pinus sylvestris*, *Pinus nigra* (i.e. *P. nigra* subsp. *salzmannii*) or *Pinus mugo* ssp. (Roiron et al., 2013). *Pinus sylvestris* is the species most likely to have spread during postglacial periods, although nothing excludes the presence of other species at lower frequencies. We have assumed that only *Pinus sylvestris* was present at Abeurador.
- *Quercus* deciduous was most probably mainly *Quercus pubescens*, the current dominant deciduous oak in the Mediterranean region, but other deciduous oak species cannot be excluded, especially *Quercus petraea*.
- *Juniperus* can include several species, which, to date, cannot be differentiated on the basis of wood anatomy alone. Nevertheless, at Abeurador, thousands of carbonized remains from the seeds/fruits of *Juniperus sabina*, *J. communis* cf. subsp. *nana*, *J. communis* cf. subsp. *communis* and *J. thurifera*, were identified from the Middle

Magdalenian to the Middle Mesolithic (Heinz et al., 1992; Vaquer and Ruas, 2009) (see section 5.). At the Cova de Cendres (Spain), *J. sabina*, *J. oxycedrus*, *J. cf. communis* and *J. cf. thurifera* were also found in the Middle/Upper Magdalenian, interpreted as an open landscape in a cold continental climate (Martínez Varea and Badal García, 2018).

2.4. Climatic and anthracological phasing

2.4.1. Phase 1a

According to its radiocarbon date (Table 1), the basal layer of the sequence (C10b) dates from the Oldest Dryas, which is consistent with the microfauna indicating very harsh conditions. No charcoal data were available from C10b. According to lithics, this level dates from the Middle Magdalenian (Mistrot, 2001; Vaquer and Ruas, 2009). The anthracological diagram starts just after, in C10. According to archaeological lithics and radiocarbon dates, Phase 1 includes three levels: an Upper Palaeolithic (C10), not distinctive from a cultural point of view, and two Epipalaeolithic (C9: Ancient Aziloid; C8: Late Azilian) levels. In C10 and C9, both anthracological spectra are co-dominated by *Pinus type sylvestris*, *Juniperus* and deciduous oak forest taxa, which indicates a mild climate. In C9, the microfauna also indicates undoubtedly mild temperate conditions (Vaquer and Ruas, 2009). As C9a (with no charcoal data), which comes between C10 and C9, is attributed to the Upper Magdalenian (according to the lithics), and as C10 does not show a cold climate like C10b, C10 has also been attributed to the Upper Magdalenian. Since the transition between the Upper Magdalenian (C10, C9a) and the Epipalaeolithic (C9) dates back to ~14,000 cal BP (Langlais et al., 2012), which is very close to the transition date between the Bølling and Allerød oscillations, it must be assumed that C10 could date from the Bølling and C9 from the Allerød. According to the studies based on the Greenland Ice Core Chronology 2005 (GICC05) in the North Atlantic region (Rasmussen et al., 2014), the Bølling–Allerød chronozone (originally defined by Iversen from terrestrial records in Denmark) can be used as a synonym for DO-1 (Dansgaard–Oeschger events), i.e. as a non-archive-specific name for the generally mild climate period approx. 14.6–12.9 ka b2k.

The transient warming of the Bølling–Allerød (mild and humid), which lasted for ~1700 years, was suitable for the early establishment of a temperate forest. The presence of an oak forest attested from as early as the Upper Palaeolithic, in layers C10 and C9 (Bølling–Allerød) by the frequency of deciduous oak (20%), with *Acer campestre*, several species of Prunoideae and Mediterranean elements as *Phillyrea*, was interpreted as an indicator of local favourable microhabitats representing woodland refugium areas, in the surroundings of the Abeurador cave (Heinz and Thiébaud, 1998). The southern slopes of the site, exposed to the sun around 300 m a.s.l. and protected to the north by the relief, may have provided a beneficial microclimate.

Epipalaeolithic level (F8b) dates from the Late Allerød (without charcoal data). Layer C8, which marks the end of the Lateglacial period, is well dated to the Younger Dryas (Table 1), which in western Europe marks a period of strong climate cooling. According to Rasmussen et al. (2014), the Younger Dryas can be used as a non-archive-specific synonym for the stadial period between the Bølling–Allerød and the Holocene (approx. 12.9–11.7 ka b2k). At Abeurador, this cooling is responsible for a sharp rise in the frequencies of *Pinus type sylvestris*, which peak just before the Holocene warming, a slight decrease of *Juniperus* and a strong decline of the oak woodland taxa (*Quercus* deciduous, *Acer* and Prunoideae).

2.4.2. Phase 1b

Phase 1b starts in the Early Sauveterian, during the Mesolithic (Preboreal), at the outset of the Holocene warming, and ends in the Middle Mesolithic (Boreal). From C7 to CX, *Juniperus* is dominant, *Pinus type sylvestris* strongly declines and *Quercus* deciduous increases gradually. Temperatures at the start of the Holocene were warmer than at

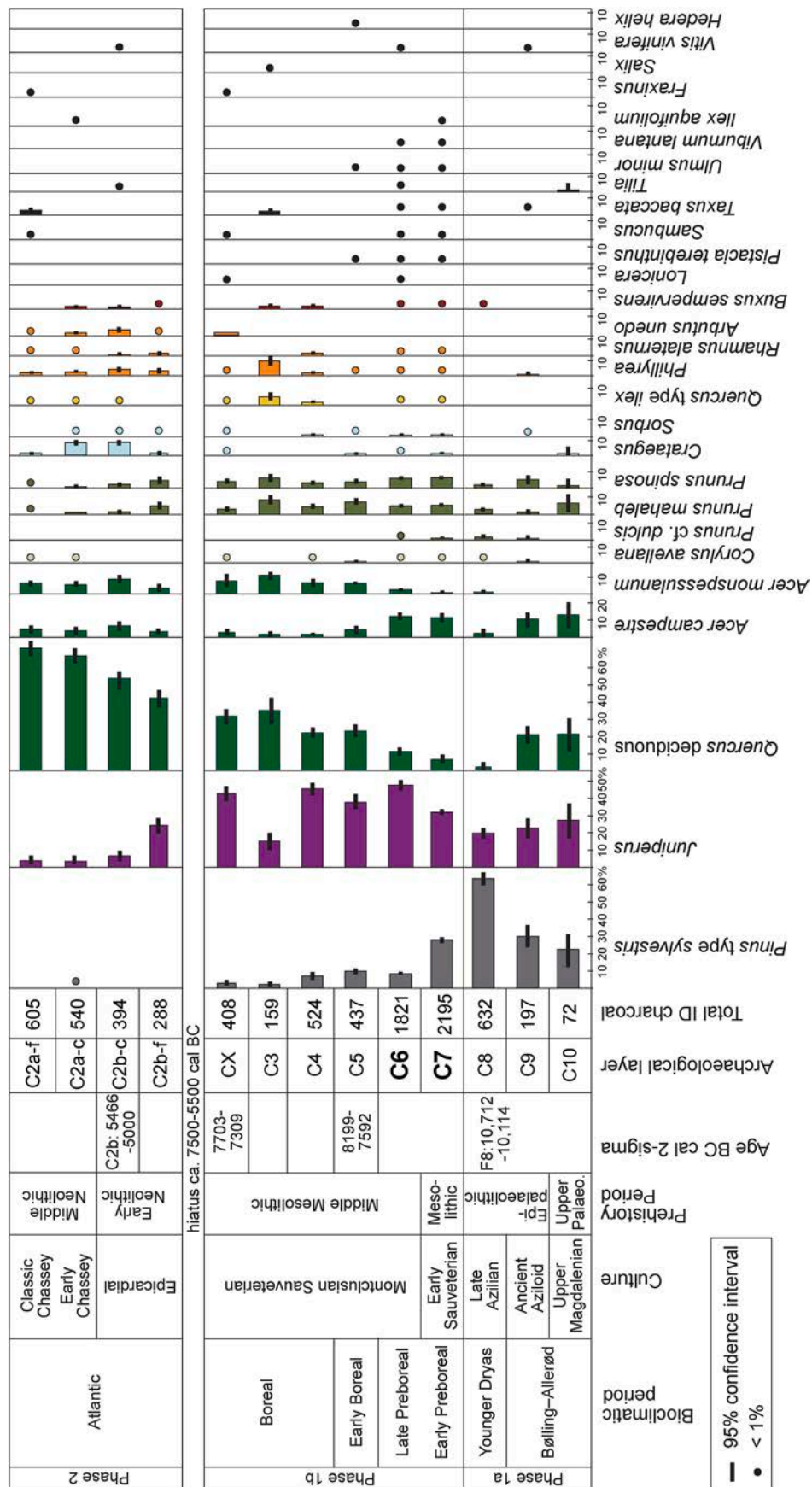


Fig. 3. Anthracological diagram of the Abeurador cave (after Heinz, 1990a, 1990b).

present, due to an increase in insolation (Petit et al., 2002). However, the scientific consensus is that there were large spatial variations worldwide in temperature increases during the Holocene and in the time it took to reach typical Holocene conditions. In Europe, according to pollen data, Mauri et al. (2015) has shown that warming intensified and reached eastern Europe and France at 8ka BP (i.e. ~8900 cal BP) peaking at ~7ka BP (i.e. towards the end of the Mesolithic). Evaluating temperature increase depends on the types of investigated proxies. According to Kaufman et al. (2020) they all indicate warming trends during the Early Holocene, some peaking as early as ~10,000 years ago (e.g. chironomids) but others (e.g. pollen) not until ~6000 years ago.

At Abeurador, temperatures possibly rose slowly throughout Phase 1b for several millennia. However, from the onset of the Early Holocene *Pinus* type *sylvestris* declined rapidly, indicating that this species could no longer sustain rising temperatures at this altitude. The slow progression of deciduous oak woodland does not necessarily reflect a correlative slow increase in temperature. Deciduous forests might have struggled to reclaim an area that had been largely deforested by the previous cold conditions and the ongoing decline of pine. The establishment of *Juniperus* shrubs probably facilitated the expansion of deciduous *Quercus* forest by sheltering acorn seedlings. Several species of juniper were very well adapted to open and dry habitats. *Prunus spinosa* and other Rosaceae, which may represent the first cold-adapted bushes (Heinz and Barbaza, 1998), and then pioneer shrubs that precede deciduous *Quercus* in an ecological succession, remain at Abeurador the constant background to the development of the oak forest until the Neolithic, but in a rather discrete manner compared to other sites occupied from the Mesolithic period (Heinz and Barbaza, 1998; Henry et al., 2013).

Throughout Europe, at the start of the Holocene, coniferous forests were replaced by deciduous forests as a result of both global warming and the ongoing northward migration of hardwood species ranges. At Abeurador, an interesting comparison can be drawn between the frequency curves of two maple species, both elements of the deciduous forest (Fig. 3). The rate of *Acer campestre* is highest, first in the oak forest during the Bølling–Allerød and later in the Early Preboreal, decreasing during the Boreal. This species adapted to a mild temperate and/or humid climate during the thermal oscillation was disadvantaged by the climate warming so long as the Holocene hardwood forest remained relatively open. It reestablishes itself, at a lower rate, in the mature and protective deciduous oak forests of the Atlantic period. *A. monspessulanum*, a more xerophilic species, was not adapted to a relative coolness and thus developed from the Boreal period only. Both *A. monspessulanum* and *A. campestre* seem to be well adapted during the Atlantic in high oak forests, alongside Mediterranean species. These observations make it possible to note that the oak forest that became established from C5 in the Early Boreal was very close to the current Supramediterranean oak groves, as we know them today under Mediterranean climate conditions. This change in forest composition could mark the advent of a climate with a more pronounced summer season during the Boreal, around 8199–7592 cal BC (Table 1). However, some Mediterranean taxa appeared earlier, first in C9 (*Phillyrea*) probably during the Bølling–Allerød, then from the Early Preboreal in C7 onwards (*Quercus* type *ilex*). *Arbutus unedo* appears from the Boreal (CX) at the end of the Middle Mesolithic, at a time of advanced global warming. It is then present continuously during phase 2/Atlantic period (Neolithic), probably favoured by its ability to resprout after cutting. At Fontbregoua in Provence (France), *Arbutus unedo* is present since the Preboreal and in a continuous curve during the Boreal and Atlantic (Thiébaud, 1997). In a general way, in France, Mediterranean species appear since the Early Preboreal, i.e. ca. 9000 BP (Henry et al., 2013). In the Iberian Peninsula, *Arbutus unedo* is found early, at different periods depending on the region, e.g. during the LGM period in charcoal from a refuge of Portuguese Extremadura, with *Olea* (Figueiral and Terral, 2002), during the Mesolithic in Portugal (Monteiro, 2013), in north-east Spain in the form of fruits (Buxo, 2008; Alcalde and Saña, 2017) and in south-east Spain in

charcoal (Uzquiano et al., 2016). According to Quézel and Médail (2003) during the Early Holocene warming around the Mediterranean basin, the thermophilic and sclerophyllous species spread from refuges, after the Supramediterranean deciduous oak species, but within these forests, progressively and asynchronously. Nevertheless, in some regions as the Ebro valley in Spain, *Arbutus unedo* is not found before the Neolithic period (Alcolea Gracia, 2017). At the Cova de les Cendres (Alicante), in southeast Spain, *Arbutus unedo* is missing in charcoal before the Neolithic (Badal and Carrión, 2001; Aranbarri et al., 2020), even if a seed of ‘cf. *Arbutus unedo*’ was found much earlier in this cave, during the Middle Magdalenian (Martínez Varea and Badal García, 2018). Like Ribeiro et al. (2019) in the case of Portugal, it can be assumed that in some regions, *Arbutus unedo* populations suffered from competition with oaks and only increased when the mature oak forest was replaced by an open forest.

2.4.3. Phase 2

Phase 2 comes after a stratigraphic hiatus and extends from the Early Neolithic to the Middle Neolithic, during the Atlantic bioclimatic period. *Quercus* deciduous becomes dominant, at the expense of *Juniperus*. A small increase of Mediterranean trees and shrubs is discreet compared to the current environment of the cave, especially *Quercus* type *ilex*. This moist and warm period is the most favourable to deciduous oak forest. The sequence ends with a Supramediterranean type forest cover. The current Mesomediterranean cover of holm oak coppice was established after the Middle Neolithic, postdating the occupation lifespan of the Abeurador cave. The persistence of the dominant Supramediterranean oak forest is very late compared to other sites in the south of France, which had been transformed under the impact of human activities from as early as the end of the Early Neolithic period (Chabal and Vaschalde, in press). By 6000 years ago, a cooling trend is recorded in climatic proxies (Kaufman et al., 2020), which is not captured by anthracological data either at Abeurador or at other Middle Neolithic sites in southern France (Krauss-Marguet, 1981; Vernet and Thiébaud, 1987; Chabal, 1997; Chabal and Vaschalde, in press; among others).

At Abeurador, three main taxa, *Pinus* type *sylvestris*, *Juniperus* and *Quercus* deciduous, are present through time, except that pine disappears at some point from the sequence. They successively colonized the environs of Abeurador cave, replacing one another, or partially in different biotopes, following the succession of climatic phases, multi-factorial shifts in soil conditions, successional dynamics and inter-specific competition. As these taxa are in turn dominant, and sometimes co-dominant, it suggests that they were well-adapted overall and have, at different points in time, marked the local landscape. Our goal is to obtain additional information on their degree of spatial dispersion, in order to better describe these dynamics.

3. Methods and material

3.1. Spatial analysis in relation to duration

Spatial analysis across a layer (and/or a defined context as a phase of occupation) is often used in archaeology for studying artefact distribution (lithics, ceramics) or archaeobiological remains such as bones, seeds and charcoals.

In this study, we were dealing with fuelwood waste debris in habitat contexts. When analysing the spatial dispersion of information, authors generally point out that primary (*in situ*) or secondary (shifted) concentrated charcoal deposits, i.e. short-term deposits, provide an understanding of one-off fuel use practices through the last firewood used in combustion features, whereas deposits accumulated in the long term are the synthesis of the many uses of wood, averaged over time, permitting palaeoenvironmental interpretation (e.g. Heinz, 1990b; Badal García, 1992; Chabal, 1992; 1997; Théry-Parisot, 2001; Asouti and Austin, 2005; Vidal-Matutano, 2016; Kabukcu, 2018).

The high spatial heterogeneity observed in concentrated charcoals,

often concretized by highly variable taxon frequencies, is generally studied to try to understand one-off human activities in relation to fire wood use, such as specific wood uses, or more generally fuel management. As they might have been moved, they may or may not follow the functional structuring of the habitat (location of hearths or activities). However, any significant heterogeneity indicates an instantaneous event (fire, activity or deposit) which would be risky to try and interpret as intentional, due to its random nature (Chabal, 1997; Kabukcu and Chabal, this issue). Since human fire-related practices are not the focus of this study, we excluded such short-term deposits from the Abeurador spatial analysis and retained only charcoal scatters accumulated in the long-term.

The aim of spatial analysis in this study was to investigate if any spatial heterogeneity observed in the distribution of scattered charcoals could be linked to the past distribution of taxa in the site environment. This approach differs from previous approaches on the topic of the spatial analysis of fuelwood remains. The residual distribution heterogeneity of scattered charcoals, recorded using a square grid, has a completely different meaning from that of concentrated deposits as it is supposed to refer to long term deposit, originating from multiple dispersal events from one or more hearths, and not from an overall movement of concentrated charcoal from a single fire. An essential practical question is to distinguish between heterogeneity due to the presence of a concentration and residual heterogeneity resulting from the long term dispersion of scattered charcoals. In addition to being very often visible during the excavation, a charcoal concentration generally reveals a significantly different frequency spectrum of taxa (from those of scattered charcoal), that enters the definition of statistical outlier (relative to an average image of the past woodlands). In this study, the record of two hearths and a shifted concentration (excluded from the dataset) illustrates such aberrant frequencies (see section 3.5). Scattered charcoal heterogeneity is always low (see section 4.), if the concentrations have indeed been excluded (which can be done *a posteriori*, thanks to spatial sampling). At this point, it can already be noted that the frequencies of abundant taxa are fairly evenly distributed in the grid squares and rare taxa are more or less randomly distributed (Heinz, 1990b; Chabal, 1991, 1992, 1997; Badal Garcia, 1992).

3.2. The working hypothesis

We address the stochastic processes that may lead to the residual heterogeneity observed in the distribution of charcoal fragments, scattered within a layer. This includes wood collection in a heterogeneous environment, firewood storage, activities involving fire, fire management, combustion, dispersal of residual waste in the living space, trampling, burial, excavation and sieving. We do not have access to most of these successive steps, but we can examine the distortion factors that may affect the frequency spectrum of taxa.

First, the physical processes such as fragmentation, combustion or post-depositional strains appear to have had a regular effect on the species in the long term and maintained their proportions, or slightly and constantly distorted them (Chabal, 1990, 1991, 1992, 1997, 2001; Chabal and Laubenheimer, 1994; Théry-Parisot, 2001; Théry-Parisot et al., 2010a, 2010b; Chrzazvez et al., 2014; Kabukcu and Chabal, this issue).

The information contained in the charcoal scatters of a layer is the addition of multiple events of fuelwood use over a given time span, maybe several months or years, in which most wood has been converted to ash. The dispersal of charcoals in each layer over time, day after day, was certainly centrifugal, from one or more hearths, reaching remote parts of the inhabited space and then accumulating throughout the layer (for a given period). Dispersing factors (e.g. trampling, sweeping) were not related to the location of the various fire-using activities and have probably impacted all taxa in the same way, as does fragmentation (Chabal, 1990; Kabukcu and Chabal, this issue). It would be hazardous to over reason on the dispersing agents and practices that we have no

knowledge about. Nevertheless, contrary to the rapid displacement of concentrated charcoal from one or more fires, which led to concentrations and outlier values, it is likely that the charcoal scattering was the result of random dispersions spread over time. This would explain why we find such fairly distributed (within a layer) and above all repeatable (between layers) taxon frequency spectra. The scattering probably followed daily fire-related activities in the form of partial or total exports of hearth content, followed by further dispersions unrelated to the fire, finally recording a residual heterogeneity in the spatial distribution of taxa frequencies, depending on the wood content of the successive fires.

Our working hypothesis is that the probability of a species having been regularly or irregularly collected in the environment, during repeated firewood collection events, may have led to heterogeneous hearth inputs, which in turn led to heterogeneous dispersal episodes of hearth fuel waste in the archaeological layer. It is quite conceivable that the probability of a species being present in a single fuelwood collection event depends on the distribution of that species in the environment. A wood species that is uniformly distributed in woodland vegetation will appear regularly in many wood collection events and, more rarely, will be absent or dominant in firewood harvests. Conversely, species characterized by highly localized distributions or limited accessibility may be underrepresented in most of the fuelwood collection harvests (regardless of local abundance) and overrepresented in a few.

However, another hypothesis must be examined. Could the heterogeneity of wood use, due to particular preferences or activities, have led to the heterogeneous hearth inputs registered? This hypothesis does not seem the most suitable, as (i) debates on the selection of species for fuel

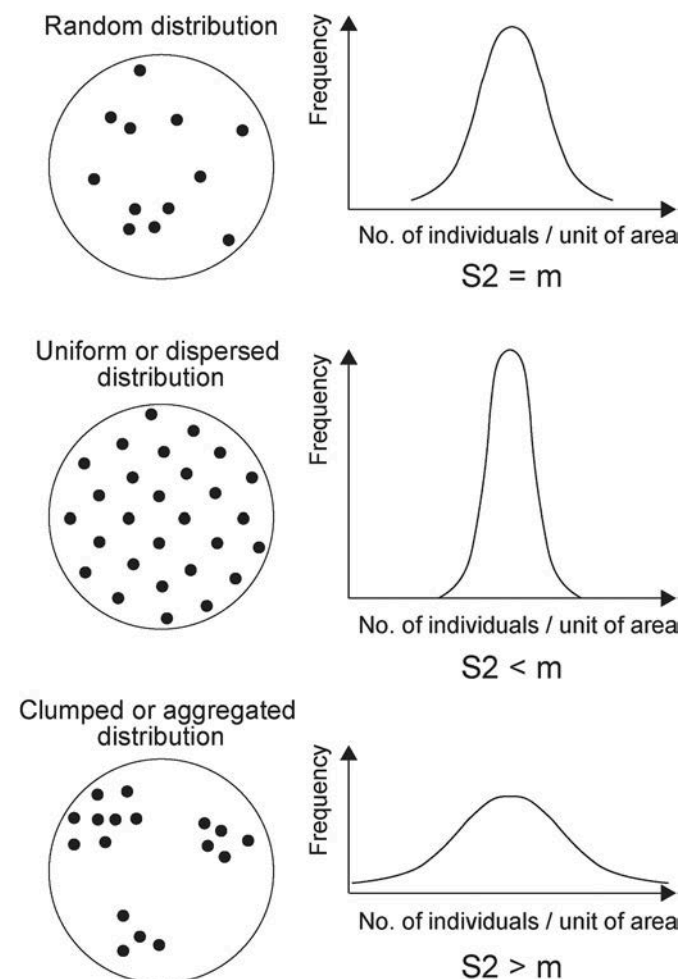


Fig. 4. Three theoretical types of distribution of living organisms in their natural environment: (a) random, (b) uniform and (c) clumped.

use, in light of wood properties and ethnographic studies, led to the conclusion that preferences for certain taxa to perform specific tasks are cultural or individual habits rather than objective species suitability (Chabal, 1997; Th  ry-Parisot, 2001; Henry, 2011; Kabukcu and Chabal, this issue), (ii) several wood uses certainly followed one another within a single day (e.g. lighting the fire, cooking, heating, lighting the cave, smoking meat, working with various materials, etc.), leading to a mixture of different successive choices and (iii) all the taxa collected and stored were probably used within a short duration, as no taxon was rejected for fire.

If an active selection of taxa did occur for any purpose, this is likely to have been during collection. It is generally acknowledged that an over-representation of rare taxa in fuelwood could only have lasted for a limited time before their disappearance and that the major taxa provided most of the fuelwood (Chabal, 1997). Some of the major taxa may have been slightly over- or under-represented relative to their abundance in the environment, due to particular behaviours, availability of dead wood according to taxa, or vegetation physiognomy, although this remains under-theorized. However, the potential distortion of the proportions between species were (i) regular, since they depend on regular factors as cultural habits or biological features and (ii) small, since the anthracological frequency spectrum is consistent with current forest compositions and coherent with observed forest dynamics.

Another key point is the temporality of the successive events that may have distorted the frequencies of the taxa with respect to their average frequency in the collection area. It is likely that variations in wood use (if there were any) were more frequent (e.g. several of them within a single day) than variations in wood collection (at most once a day, perhaps much less, and even rarer for more distant incursions). Consequently, the heterogeneity of wood inputs throughout successive collections is more likely to have contributed to that of the dispersed residues than successive uses.

Due to its probability of collection, the proportion of a taxon fluctuated in firewood assemblages, and then in residual charcoal in squares of the excavated site, relative to its heterogeneity of distribution (or accessibility) in the site environs during human occupation. Our working hypothesis states that the fuelwood waste regularly disposed of and entering the archaeological record in the form of charcoal scatters retained the residues of this spatial heterogeneity, which likely characterized successive firewood collection events. We thus hypothesize that the frequency distribution of each taxon in a layer (per grid square) may represent its *sampling distribution* (i.e. the probability distribution of a statistic based on a random sample) *in the past environment*.

3.3. The distribution index as an indicator of vegetation heterogeneity

In order to study the vegetation heterogeneity across the distribution of charcoals, we referred to distributional patterns used in ecological studies. According to Molles and Sher (2019), at a small scale (i.e. small distances over which there is little environmental change significant to the organism under study), individuals within populations are distributed in patterns that may be random, regular, or clumped. Individuals are sampled in sample plots to estimate the mean (m) and variance (s^2) in density of the population across the study area. The ratio s^2/m (variance/mean), named the 'distribution index', estimates the regularity of the distribution of individuals in the population across the study area (Fig. 4).

- (a) **A random distribution** ($s^2/m = 1$ or $s^2 = m$) of individuals is the least common form of distribution in nature, occurring only when the position of each individual of the species is independent of the other individuals. Individuals have an equal chance of living anywhere within an area. This distribution would imply neutral interactions between individuals, and between individuals and the local environment. On the contrary, in most environments, interactions with neighbouring individuals and other factors,

such as climate or soil conditions, generally cause organisms to be either clustered or dispersed.

- (b) **A uniform or dispersed distribution** ($s^2/m < 1$ or $s^2 < m$) implies that individuals occupy the land approximately at the same distance from each other. This distribution supposes antagonistic interactions between individuals, or local depletion of resources. The need to maximize the space between individuals arises from competition for a resource (e.g. moisture or light), or as a result of direct interactions between individuals within the population, such as root interactions. This can be seen in the regularity of spacing among bushes in arid zones (when the density of the individuals is sufficient for the phenomenon to appear).
- (c) **A clumped, aggregative or clustered distribution** ($s^2/m > 1$ or $s^2 > m$) is characterized by a tendency for individuals to group together. It is the most common type of dispersion found in nature. It involves a beneficial attraction between individuals or an attraction of individuals to a common resource (e.g. water, soil, temperature, shade). This type of distribution is found in environments characterized by unequal resources. For plants, it corresponds to populations with biotope preferences and local spreading.

For our purpose, we used the distribution index to estimate the regularity of the distribution of percentage of each taxon in the grid squares. As s^2 and m (in the sample) are supposed to estimate σ^2 and μ (in the past environment), we attempted to use them to estimate the heterogeneity of past vegetation, at least to compare population density patterns of major taxa. In order to use the mean and variance of the frequency distributions of taxa, it was necessary to verify beforehand whether taxa frequencies were distributed in the layers according to the normal law. Finally, distribution indexes were calculated for the most represented taxa, in the two layers studied, in order to understand their past location in the surroundings of the Abeurador during the Mesolithic, in the context of the whole postglacial vegetation evolution.

3.4. The size of the fuelwood supply area

The size of the firewood supply area, which charcoal can represent, depends on energy requirements and forest wood productivity. According to current rural areas, domestic energy needs are estimated to vary, from low-lying tropical regions to cold mountainous areas, between 0.5 and 2 m³/person/yr of dry wood (Rey and Hermeline, 1994). For the Mesolithic, under a cold/mild climate, we have considered the highest estimate of 2 m³/person/yr, which maximizes the supply area. Regarding forest productivity, pine forests regenerated by seed or woodlands regenerated by coppice resprouting have a relatively low productivity per hectare but a high capacity for regrowth after cutting, which lasts over time. According to Jolain (1961) current Mediterranean oak coppice produces 0.6–3 m³/ha/yr. A yield of 2 m³/ha/yr is retained by Curt and Marsteau (1997) and Jamet (2001). During the Mesolithic period, it can be assumed that pine forests, open steppe-forests or young spreading oak forests, had a productivity of at least 2 m³/ha/yr. According to these data, a community of 40 people, consuming 80 m³ of firewood per year, would satisfy these needs from a mainly forested area of 40 ha. More generally, according to extant models of woodland use, the fuelwood (and possibly farmland) needs of a modestly-sized hunter-gatherer or agro-pastoralist community can be met within a radius of a few hundred metres, though this varies according to group size, the density of woodland cover and the range of human activities in the landscape (Chabal, 1997; Bourquin-Mignot et al., 1999; Th  ry-Parisot, 2001).

In this study, modelling past woodland vegetation through the lens of fuelwood supply and availability, we considered the wider partly forested area 1 km radius around the cave, i.e. 314 ha. Assuming the lowest productivity of 2 m³/ha/year, this woodland area would produce

Table 2Number of charcoals per taxon and per square in Layer C6 of the Abeurador cave. Hearths were excluded from the study (after [Heinz, 1990a](#)).

Taxon	Abbreviated name of taxa	H10	H9	H8	H7	G10	G9	G8	G7	F9	E10	F8	Total per taxon (excluding hearths)	Hearth in H9	Hearth in F8-G8
<i>Pinus type sylvestris</i>	P.s.	17	22	42	14	13	16	10	17	5	4	1	161	16	5
<i>Juniperus</i>	Ju.	132	115	93	44	118	111	78	45	54	52	31	873	200	25
<i>Quercus deciduous</i>	Q.d.	28	9	30	7	22	21	24	11	38	4	19	213	16	100
<i>Acer campestre</i>	A.c.	46	22	21	12	17	17	27	7	22	30	6	227	11	0
<i>Acer monspessulanum</i>	A.m.	8	4	8	2	2	4	4	2	8	3	2	47	0	0
<i>Corylus avellana</i>	C.a.	1	0	2	2	0	0	2	0	0	0	2	9	0	13
Total Prunoideae (including <i>Prunus spinosa</i> , <i>Prunus mahaleb</i>)	Pru.	28	19	3	15	28	17	42	14	22	6	22	216	0	105
Total Maloideae (<i>Crataegus</i> + <i>Sorbus</i>)	Mal.	0	2	6	3	5	1	1	5	8	2	2	35	0	0
<i>Quercus type ilex</i>	Q.i.	0	0	0	0	1	0	2	0	1	0	2	6	0	0
<i>Phillyrea/Rhamnus alaternus</i>	Ph.Rh.	0	0	1	1	0	0	2	1	3	0	2	10	0	0
<i>Buxus sempervirens</i>	B.s.	0	0	0	0	2	0	0	0	2	0	1	5	0	0
<i>Lonicea</i>	Lo.	0	1	0	0	0	0	0	0	0	0	0	1	0	0
<i>Pistacia terebinthus</i>	P.t.	2	0	0	0	0	1	1	0	0	0	0	4	0	0
<i>Sambucus</i>	Sa.	0	2	0	0	0	0	0	0	0	0	0	2	0	0
<i>Taxus baccata</i>	T.b.	1	0	0	0	2	0	1	0	0	0	0	4	0	0
<i>Tilia</i>	Ti.	0	0	0	0	0	0	1	0	0	0	1	2	0	0
<i>Ulmus minor</i>	U.m.	0	0	0	0	0	1	0	0	0	0	0	1	0	0
<i>Viburnum lantana</i>	V.l.	0	0	0	0	0	1	0	0	0	0	0	1	5	0
<i>Vitis vinifera</i>	V.v.	0	0	0	0	0	0	0	0	0	0	1	1	0	0
Number of charcoals per square		266	196	206	100	210	190	195	102	163	101	92	1821	250	250

Table 3Number of charcoals per taxon and per square in Layer C7 of the Abeurador cave. A concentration of charcoals in G8 was excluded from the study (after [Heinz, 1990a](#)).

Taxon	Abbreviated name of taxa	H10	H9	H8	H7	G10	G7	F10	F9	F8	F6	E9	E6	Total per taxon (excluding G8)	Concentration in G8
<i>Pinus type sylvestris</i>	P.s.	48	122	78	52	28	47	45	50	23	52	21	26	644	52
<i>Juniperus</i>	Ju.	61	169	54	45	62	25	79	61	30	43	60	14	711	8
<i>Quercus deciduous</i>	Q.d.	4	39	11	5	5	10	7	11	14	15	18	14	154	1
<i>Acer campestre</i>	A.c.	18	35	19	18	19	13	27	32	8	18	36	14	258	1
<i>Acer monspessulanum</i>	A.m.	2	0	1	1	4	4	1	4	0	2	2	1	25	3
<i>Corylus avellana</i>	C.a.	0	2	0	0	0	0	0	1	1	3	4	1	12	0
Total Prunoideae (including <i>Prunus spinosa</i> , <i>Prunus mahaleb</i>)	Pru.	9	48	29	29	19	16	28	22	12	8	32	13	291	26
Total Maloideae (<i>Crataegus</i> + <i>Sorbus</i>)	Mal.	8	12	1	5	3	2	2	6	7	8	5	6	65	0
<i>Quercus type ilex</i>	Q.i.	0	0	0	0	1	0	0	0	0	0	0	0	1	0
<i>Phillyrea/Rhamnus alaternus</i>	Ph.Rh.	0	0	2	0	1	0	2	5	0	0	0	2	13	1
<i>Buxus sempervirens</i>	B.s.	0	0	0	0	0	0	0	1	0	0	4	0	5	0
<i>Pistacia terebinthus</i>	P.t.	0	3	0	0	0	0	0	0	0	0	0	0	3	0
<i>Sambucus</i>	Sa.	0	4	0	0	0	0	0	0	0	0	0	0	4	0
<i>Taxus baccata</i>	T.b.	0	0	0	0	0	0	0	0	1	0	0	0	1	0
<i>Ulmus minor</i>	U.m.	0	0	0	0	0	0	0	1	0	0	2	0	3	0
<i>Viburnum lantana</i>	V.l.	0	0	0	0	0	0	0	1	1	0	0	0	2	0
<i>Ilex aquifolium</i>	I.a.	0	1	0	0	0	0	0	0	0	0	0	0	1	0
Number of charcoals per square		150	435	195	155	142	117	192	195	98	149	184	91	2103	92

628 m3 of fuelwood per annum without exhausting its potential, which far exceeds the needs of a community numbering a few dozen people, apart from the fact that occupation was seasonal. In the case of Abeurador, occasional inputs (hunting, fishing) from further away have been assumed ([Vaquer and Ruas, 2009](#)), although the expectation is that distant procurement did not involve fuelwood collection. The taxon composition, as evidenced in the anthracological spectra, is highly consistent with the hilly surroundings and, conversely, includes few alluvial indicator taxa. The plain was certainly not the setting for regular wood harvesting.

3.5. Studied material at Abeurador cave

In the 1990s, charcoals were sampled at Abeurador cave using a 1 × 1 m excavation grid. Palaeoecological interpretation was based on the taxonomic frequency spectra obtained from the sum of the contents of the squares in each layer; the square distribution was then used to check the reliability of the dataset ([Heinz, 1990a](#); [Heinz et al., 1992](#); [Heinz and Thiébaud, 1998](#)). The hearth contents were sampled and studied separately ([Heinz, 1990a, 1990b](#)). In this study, we focused on the distribution of the per square taxon frequency spectra in two successive Early/Middle Mesolithic layers, corresponding to a phase of changing vegetation dynamics during the Early Holocene (Preboreal). Layer C6 totals 1821 charcoal fragments and Layer C7 2103 fragments. These two

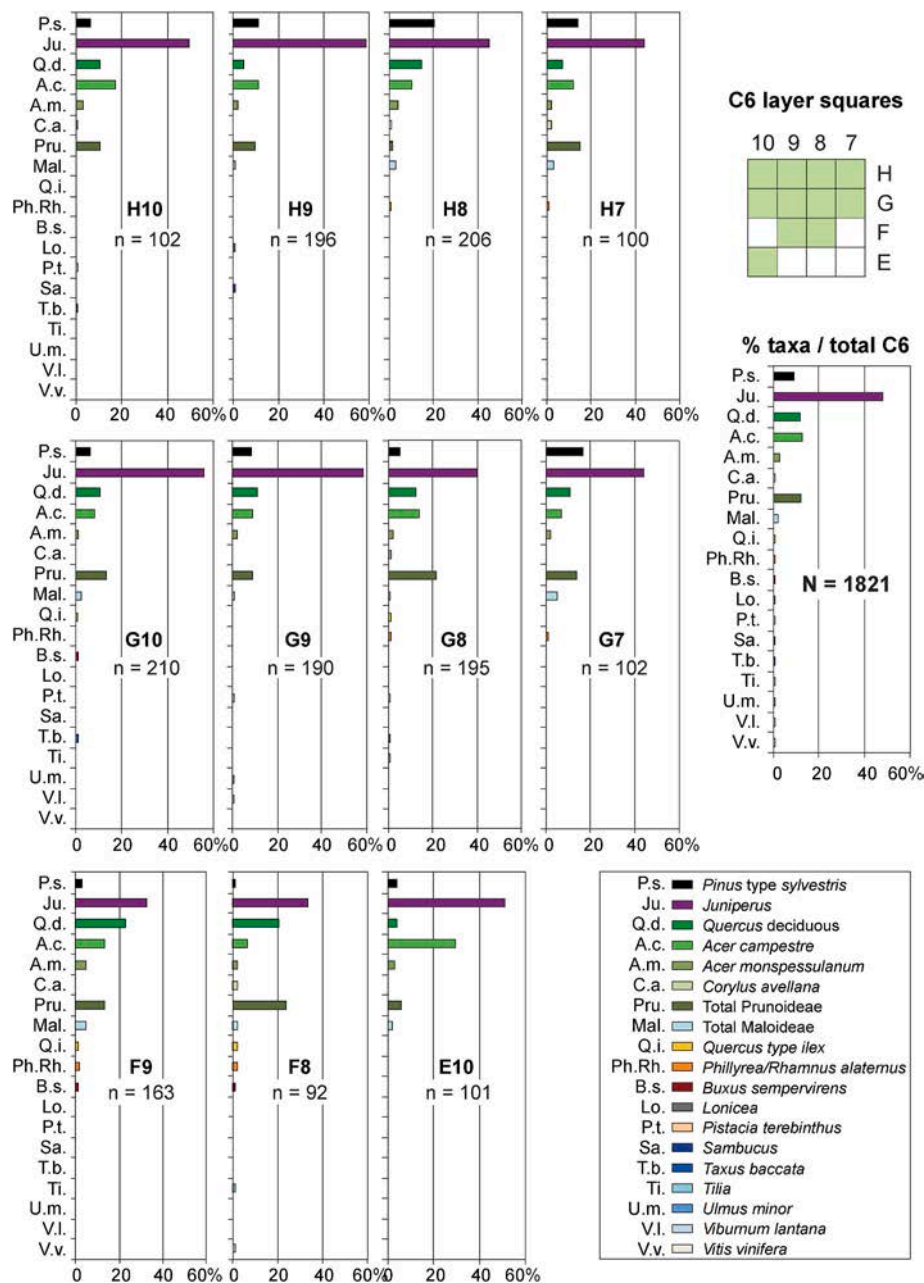


Fig. 5. Bar graphs of the relative frequency spectra of taxa per square in Layer C6.

layers were the richest on the site and the only ones that yielded a high number of charcoals per square ($n = 100\text{--}400$), permitting the application of statistical analysis using the distribution index. Two hearths in Layer C6 (Table 2) and a concentration in the square G8 of Layer C7 (Table 3), in which some taxa were clearly over-represented compared to the average spectrum, were excluded from the dataset.

4. Results

Per square taxon frequency spectra were recorded for 11 grid squares from Layer C6 and 12 from Layer C7. The absolute taxon frequencies are presented in Tables 2 and 3 and bar graphs of the relative frequency spectra of taxa per square have been plotted (Figs. 5 and 6).

At first sight, in both Layers C6 and C7, the frequency distribution of major taxa appears fairly uniform between squares. However, the relative frequencies of the most common taxa are not uniformly distributed in the squares. Global χ^2 tests on absolute frequencies show that the

square contents (taxon frequencies) are significantly different within each layer. The taxa tested were *Pinus tp. sylvestris*, *Juniperus*, *Quercus deciduous*, *Acer campestre*, total Prunoideae, and 'other taxa' (taxa with a frequency of <5 were pooled together).

Layer C6: $\chi^2 = 250$, dof = 50, $p < 0.0001$

Layer C7: $\chi^2 = 182$, dof = 55, $p < 0.0001$

In Layer C6, the taxa which contributed most to these differences were *Pinus tp. sylvestris* (26%), *Quercus deciduous* (20%) and *Juniperus* (18%). The square mainly involved in these differences was E9 (18%). In Layer C7, the species which contributed the most to these differences were *Pinus tp. sylvestris* (25%), Prunoideae (21%) and *Quercus deciduous* (17%). The square which contributed most to these differences was H8 (21%). These variations are not surprising as the χ^2 test often exaggerates differences.

According to the Shapiro-Wilk tests, the hypothesis that the relative

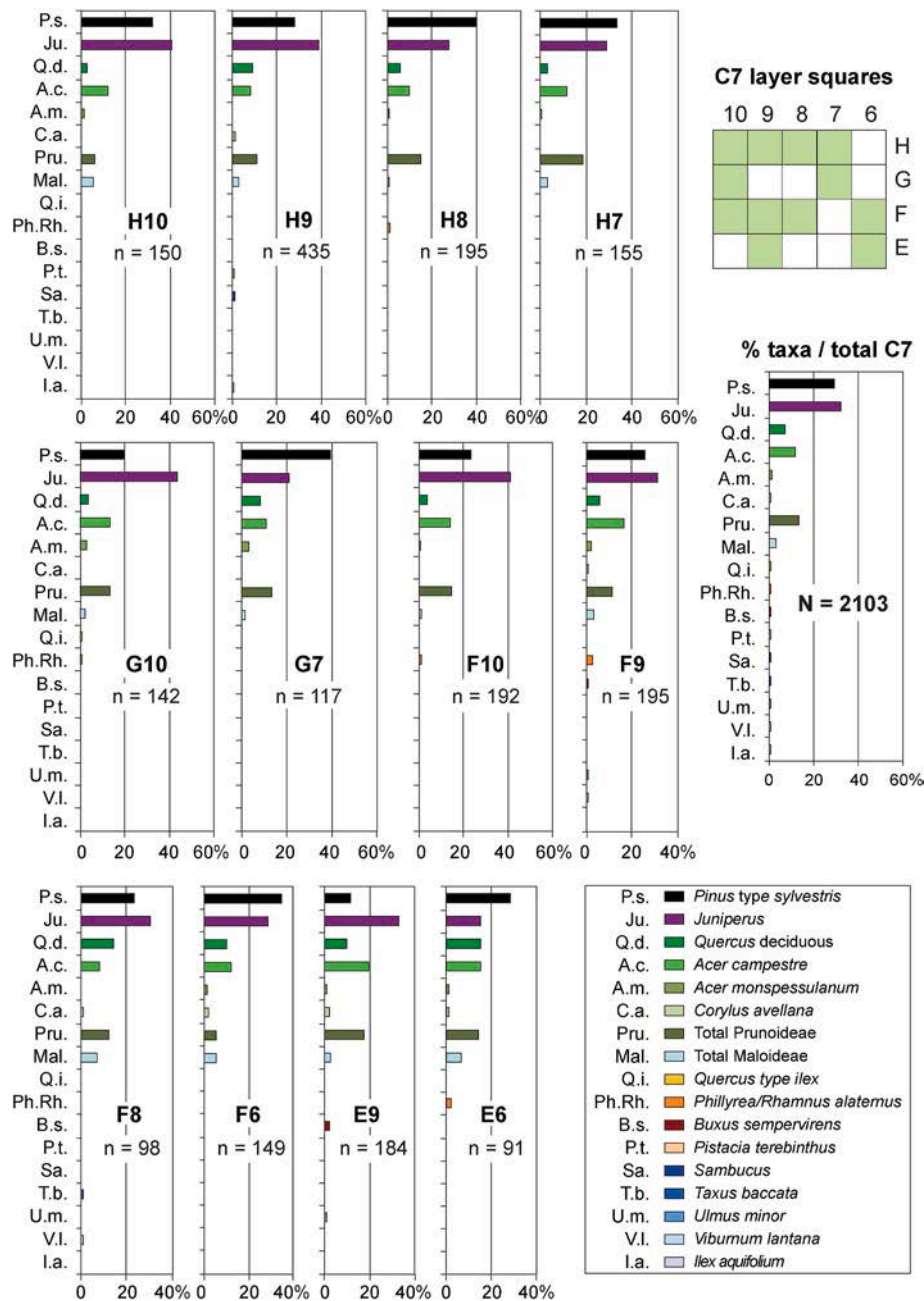


Fig. 6. Bar graphs of the relative frequency spectra of taxa per square in Layer C7.

frequencies of a taxon are normally distributed in the grid squares cannot be rejected for seven abundant taxa (Table 4). For other taxa, mixture analyses were done to exclude multimodal distributions, ruling out the hypothesis of two or several populations of data (e.g. two or several species in one genus, with different frequencies). Poorly represented taxa have a distribution that does not follow the normal law due to their low numbers. Normality was also rejected for *Acer campestre* in Layer C6, despite its rather large count, because it is overrepresented in the E10 square. If we correct the data by removing the *A. campestre* frequency in the E10 square (which does not change its total relative frequency much) normality is no longer rejected, making it possible to calculate a distribution index. However, this distribution index was not retained by the goodness-of-fit test (see below).

The fact that the seven most abundant taxa are distributed in the squares according to the normal law (with minor adjustments) confirms the huge statistical interest of the charcoal deposits and allows us to

obtain representative results from sampling a few squares (possible because the standard deviation is not too high compared to the mean). Furthermore, in accordance with our initial hypothesis, the frequency distribution of a taxon in a layer can be considered to represent its statistical sampling distribution (i.e. probability distribution) in the wood collection catchment.

The distribution averages are different from one taxon to another, since their mean frequencies in each layer are different. The distribution variances also differ, which is what we focus on here (Fig. 7). The distribution index s^2/m (variance/mean), which estimates the regularity of the taxon distribution in the grid squares, has therefore been calculated for the seven abundant taxa (Table 5). The considered mean (called m) of the relative frequencies per square of a taxon is the average of its independent relative frequencies in the squares of the layer, regardless of the total number of charcoals in each square. This mean is very close to the mean of the taxon (called $\%$, Table 4) calculated from the total

Table 4

Shapiro-Wilk normality tests in Layers C6 and C7 for the main taxa (N total: number of charcoals in the layer; N: number of charcoals per taxon; m: mean of the relative frequencies per square; %: N/N total x 100).

	Layer C7					Layer C6				
	N total = 2103					N total = 1821				
	N	%	m	Shapiro-Wilk test p-value	Normality (alpha = 0.05)	N	%	m	Shapiro-Wilk test p-value	Normality (alpha = 0.05)
<i>Pinus type sylvestris</i>	592	28.2	28.4	0.8745	+	161	8.8	8.8	0.4428	+
<i>Juniperus</i>	703	33.4	31.8	0.6258	+	873	47.9	46.8	0.4553	+
<i>Quercus deciduous</i>	153	7.3	7.6	0.1940	+	213	11.7	11.8	0.2872	+
<i>Acer campestre</i> (without E10 for C6)	257	12.2	12.6	0.8091	+	227	10.8	10.8	0.7865	+
<i>Acer monspessulanum</i>	25	1.0	1.2	0.2140	+	47	2.6	2.6	0.0995	+
Total Prunoideae	265	12.6	12.7	0.3738	+	216	11.9	12.5	0.8260	+
Total Maloideae	65	0.6	3.5	0.3922	+	35	1.9	2.2	0.3378	+
<i>Corylus avellana</i>	12	3.1		0.0047	-	9	0.5		0.0078	-
<i>Phillyrea</i> + <i>Rhamnus alaternus</i>	12	0.6		0.0017	-	10	0.5		0.0215	-

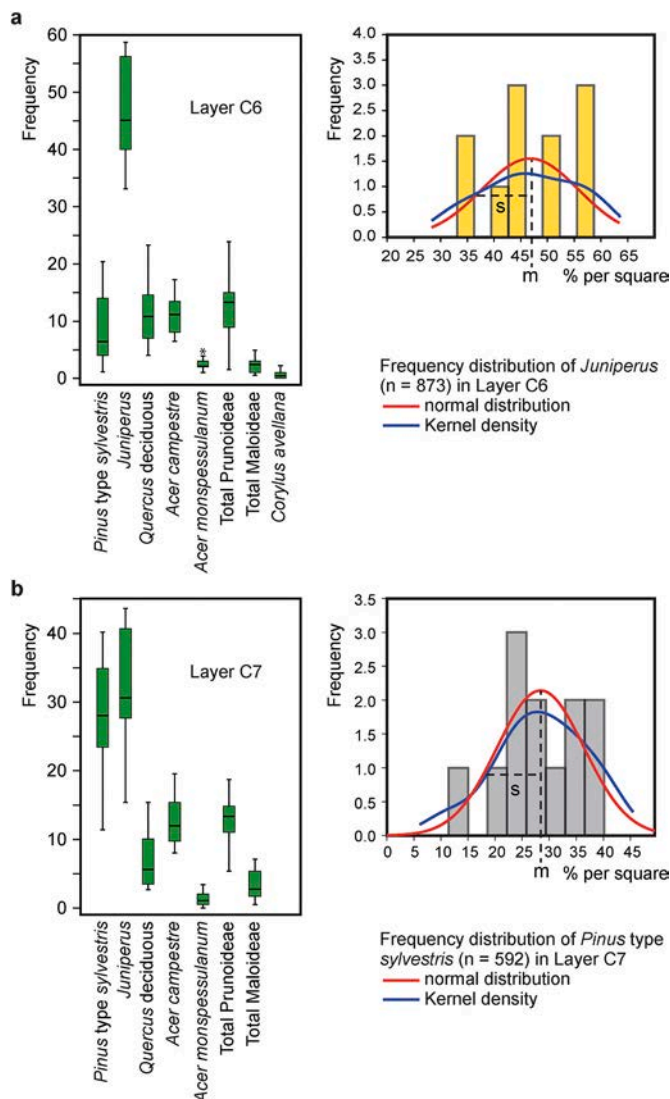


Fig. 7. On the left, box plots of the relative frequencies per square of the main taxa. On the right, a distribution histogram as an example. (a) Layer C6 and (b) Layer C7 (m: mean; s: standard deviation; the star indicates an outlier). Each taxon frequencies are normally distributed in the grid squares, although they are relatively dispersed.

number of charcoals of the taxon in the layer. The distribution indexes

range from 0.45 to 4.22.

The value of s^2/m represents an estimate, derived from a limited number of squares, of the theoretical value that would have been obtained for an infinite number of squares in a given archaeological layer. In order to test the significance of our results, our null hypothesis H_0 would be that the distribution of the frequencies of a taxon in the squares would not differ from a random distribution. In section 3.3., we mentioned that in a random distribution, the distribution index value equals 1 ($s^2/m = 1$). Our alternative hypothesis proposes that taxon frequencies are either clumped or uniformly distributed. We used a χ^2 goodness-of-fit test to determine how well the observed frequency distribution matches the expected frequency distribution (random distribution), i.e. whether the sample variance/sample mean ratio is significantly different from 1. The χ^2 values show that the main taxa *Pinus type sylvestris*, *Juniperus* and *Quercus deciduous*, and also Prunoideae in C6 level, have distributions that differ significantly from a random distribution (Table 5). We thus reject the null hypothesis H_0 . As their distribution indexes are >1 , they are characterized by clumped distributions, with variations in the degree of aggregation of individuals.

5. Discussion

5.1. Distribution indexes signification at a micro-regional scale

In this study, we assumed that taxon proportions fluctuated in each assemblage of firewood due to its probability of collection, relative to its distribution heterogeneity (or accessibility) in the environment. The distribution indexes values (Table 5), statistically validated for four major taxa in the C6 and C7 layers of the Abeurador, are supposed to represent their distribution patterns at a small scale, that of the cave surroundings during the Mesolithic. Can the distribution patterns of the main species in Layers C7 and C6 help us to better understand the dynamic successions of the woodlands around the Abeurador cave for the whole sequence?

The Abeurador environment was considered at a micro-regional scale, as the fuelwood was collected within a radius of less than 1 km (see section 3.4). The distribution indexes range from 1.75 for *Juniperus* in Layer C6 to 4.4 for *Pinus type sylvestris* in Layer C6. The validated indexes are greater than 1, indicating clumped distributions. This corresponds well to a micro-regional ecological structure made of several forest types. It is likely that species distribution in a fairly heterogeneous environment with a rugged topography leads to all dominant taxa having clumped distributions of individuals. On a finer scale, more uniform distributions might have been observed. Nevertheless, we can use these values to interpret the more or less clumped patterns according to taxa and compare their variations over time.

Table 5

Values of the 'distribution index' for seven main taxa of Layers C6 and C7, tested by a χ^2 goodness-of-fit test to a random distribution (in bold, validated data). The hypothesis of a random distribution can be excluded for the three main taxa and the Prunoideae in Layer C6, which have more or less clumped distributions (n: number of grid squares of the layer; N: number of charcoals per taxon; m: mean relative frequency per taxon; s2: variance per taxon; s2/m: distribution index; $\chi^2 = s2(n-1)/m$; significance level $p \leq 0.05$).

	Layer C7 (n = 12)						Layer C6 (n = 11)					
	N	m	s2	s2/m	χ^2 /random distribution	$p \leq 0.05$	N	m	s2	s2/m	χ^2 /random distribution	$p \leq 0.05$
<i>Pinus type sylvestris</i>	592	28.4	70.50	2.48	27.3	+	161	8.8	37.10	4.22	42.2	+
<i>Juniperus</i>	703	31.8	70.04	2.2	24.3	+	873	46.8	81.80	1.75	17.5	+
<i>Quercus deceduous</i>	153	7.6	18.39	2.41	26.6	+	213	11.8	36.01	3.06	30.6	+
<i>Acer campestre</i> (without E10 for C6)	257	12.6	11.45	0.91	10.0	–	197	10.8	11.68	1.08	10.8	–
<i>Acer monspessulanum</i>	25	1.2	1.13	0.92	10.1	–	47	2.6	1.16	0.45	4.5	–
Total Prunoideae	265	12.7	15.81	1.24	13.7	–	216	12.5	40.96	3.28	32.8	+
Total Maloideae	65	3.5	4.65	1.34	14.8	–	35	2.2	2.78	1.26	12.6	–

Table 6

Dynamics of four taxa and assumptions on their spatial distribution in the environs of the Abeurador cave in the Early Holocene, based on their frequencies and distribution indexes in Layers C7 and C6.

Taxon	Layer	%	Abundance and dynamic trend (global warming, competition and soil conditions)	Distr. index	Distribution pattern	Spatial distribution in the cave environs
<i>Pinus type sylvestris</i>	C6	9	In strong decline	4.22	Highly clumped	The pine area contracts strongly, in the ravines and at fairly high altitude
	C7	30	Quite abundant but in decline	2.48	Clumped	Still adapted and widespread, except on dry and poor soil
<i>Quercus deceduous</i>	C6	12	Spreading further in open space, seedlings need shade to grow	3.06	Very clumped	Oak expands on the plateau system as localized clusters, dependent on the protective cover of Prunoideae and junipers
	C7	7	More or less scarce, starting to spread, favoured by warming	2.41	Clumped	Located on the south-facing slopes inherited from the Younger Dryas; rather clumped
Prunoideae (including <i>Prunus spinosa</i>)	C6	12	Constant (associated with oak groves), favoured by warming, heliophilic	3.28	Very clumped (as <i>Quercus deceduous</i>)	Bushes or trees precede and protect the expansion of oaks, in the form of clusters
	C7	13		–		–
<i>Juniperus spp.</i>	C6	48	Spreading further into the newly opened spaces left by pine	1.75	Sparsely clumped or unclumped	Spreads almost everywhere, as well-spaced trees/shrubs like bushes in arid areas
	C7	32	Spreading, the most abundant and adapted taxon, favoured by warming and dry soils	2.2	Slightly clumped	Spreads in the most suitable areas; still in competition with pine

5.2. Forest dynamic trends according to anthracology

The Abeurador anthracological sequence has not recorded the early postglacial expansion of pre-steppe woody species at the end of the Last Glacial Maximum. At other sites, *Juniperus* was the pioneer, creating conditions suitable for the migration of other groups of species, such as the Rhamnaceae and the Rosaceae, both suited to cold conditions, and then finally *Pinus type sylvestris*, before the arrival of deciduous *Quercus* (Heinz and Barbaza, 1998). Under a Mediterranean mountain climate (which may represent a current analogue of the Early Holocene conditions), in a progressive succession, Scots pine is indeed capable of spreading very quickly and rapidly supplanting juniper. Scots pine is, in turn, eliminated by pubescent oak, more resistant to extreme drought events (Poyatos et al., 2008).

At Abeurador, during the Younger Dryas, under cold and dry conditions, Scots pine was dominant across the landscape and probably spread almost everywhere. The differential factor that favoured Scots pine was probably the cold, not the drought. Indeed, at the beginning of the Early Holocene (Preboreal), the rapid increase of *Juniperus* at Abeurador, highly sensitive to the rise of temperatures and extremely resistant to drought (especially *J. phænicea*), followed by *Quercus deceduous*, indicates probably a strong soil water deficit in the surroundings of the cave, due to the nature of the substratum. In C7 and C6, both warming and dry soils could explain the rapid disappearance of pine, leaving the dry, poor soils to junipers.

A similar succession has been observed at La Poujade (Millau, Aveyron) on the Causse Noir, at an altitude of 450 m (Krauss-Marguet,

1981), from the Mesolithic to the Iron Age. However, Scots pine there decreases gradually during the Preboreal and the Boreal, persisting a little until the Subboreal, in conditions undoubtedly less dry because they were more distant from Mediterranean influences. In some other areas in the south of France, palynology does not observe any expansion of *Pinus* during the Preboreal (Beaulieu et al., 1985). Such differences between sites in the representation of conifers during the Preboreal have already been noted by Henry et al. (2013).

Spatial differences in the various pathways by which species colonize are not surprising, as they depend on the contraction or expansion of their ranges and their different capacities for dispersal and maintenance in contrasting environments (Quézel and Médail, 2003). In the case of Abeurador, the differential situation for species seems due to the complex interaction between global climatic and local edaphic factors, which together determine water availability. Therefore, in the context of global warming, the main factors that governed the distribution of taxa were (i) their biotope preferences, such as temperature (altitude, exposure, topography) and soil conditions (geological substratum, topography, soil thickness, water availability), (ii) their dynamic successions involving the expansion of the range of certain species and competitive relationships with interspecific facilitation, tolerance or inhibition and (iii) the effects of climate change on all these conditions.

In the early Holocene, between the Early Mesolithic in C7 and the first level of the Middle Mesolithic in C6, variations between the major taxa indicate strong trends due to global warming. The main palaeoecological event is the strong decline of Scots pine, in favour of a vegetation more adapted to global warming, as evidenced by the quick

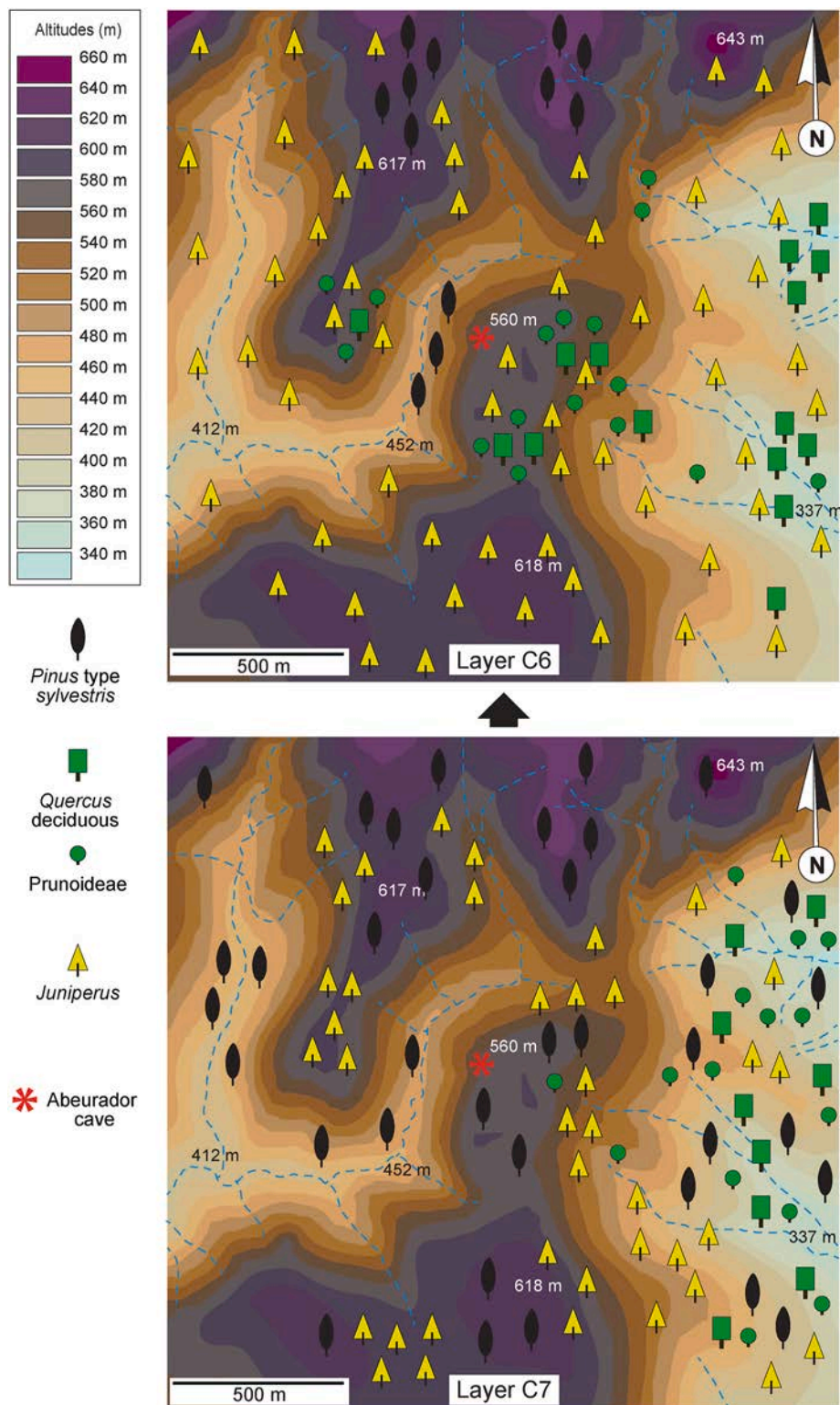


Fig. 8. Spatial evolution of postglacial vegetation around the Abeurador cave at the beginning of the Mesolithic (Preboreal), hypothesized according to anthracological frequencies and distribution indexes of the three main taxa in Layers C7 and C6 (red star: Abeurador cave; blue dotted lines: temporary streams; topographic base after IGN, 2019 www.geoportail.gouv.fr) (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article).

progression of juniper and the lesser growth of deciduous oak. According to the following levels, *Pinus type sylvestris* gradually disappears from the surroundings of the site, *Juniperus* undergoes a long phase of dominance and *Quercus deciduous* spreads gradually, to finally dominate during the Neolithic, accompanied by *Prunoideae* and

Mediterranean hardwood species. The persistence of oak populations in a refugium during the Younger Dryas permitted the rapid restart of oak forest expansion in the Early Holocene.

5.3. Spatial distribution of species based on distribution indexes

In light of these trends and the distribution patterns deduced from the distribution indexes, we propose hypotheses on the spatial evolution of the three main taxa in the Abeurador surroundings during the Early Holocene, summarized in Table 6 and including a mapped restitution (Fig. 8).

- *Pinus* type *sylvestris* had the highest distribution indexes, with an increasing index from 2.48 in C7 to 4.22 in C6. Its frequency drops in C7 and especially in C6. Its increasing distribution index probably indicates that the Scots pine area has shrunk significantly, leaving only very localized population patches in the last zones favourable for its needs. This species avoids excess temperatures and needs a relative amount of moisture (Poyatos et al., 2008). It is likely that the pine found these conditions higher up in altitude and maybe also in the shade of the deep ravines surrounding the plateau, well rooted on the lower slopes on thick colluvium soils, in relatively moist and less windy conditions. This could explain an increasingly clumped distribution pattern for this taxon in steep decline.
- *Quercus* deciduous also has a rather high distribution index: 2.41 in C7, increasing to 3.06 in C6, indicating an increasing clumped distribution when it spreads further. The Prunoideae, linked to oak in a progressive dynamic, have almost the same index (3.28) in C6 as *Quercus* deciduous (the Prunoideae index in C7 was not statistically validated). It is likely that oak forests, which expanded during this phase, remained localized clusters. At this point, it is necessary to recall the complete story of deciduous oak at this site. *Quercus* deciduous arrived very early in the environment of the site, from southern primary refugia, during the Bølling–Allerød, due to a mild and humid climate. During the Younger Dryas in C8, the deciduous oak and Prunoideae areas shrunk as a ‘secondary refugium’. Deciduous oak woodlands certainly occupied localized areas, in protected situations such as southern exposures and middle altitudes, probably sheltered under the mature conifer forests cover (pine and juniper being co-dominant in this period). It then respread slowly in the Early Holocene. In C7, we therefore assumed a distribution inherited from the previous period, extending over the suitable southern slopes. From there, the particular way in which this tree spreads involved the cover of other trees or shrubs, to protect the seedlings. In C6, when Scots pine forests shrink drastically, deciduous oak had deforested areas to conquer, with only the Prunoideae, such as *Prunus spinosa*, and junipers, as protective cover. If the deciduous oak moved, from C7 to C6, to a more clumped distribution, it is likely because during this second conquest oak woodlands colonized a mostly open environment. The oaks probably spread over the plateau in multiple small patches, from seed tree populations located in the south.
- *Juniperus* has the lowest distribution indexes, compared to the other species, decreasing from 2.2 in C7 to 1.75 in C6, suggesting an increasingly even distribution as it spread. Several species may have existed, with different ecological requirements, but all were light-demanding and adapted to drought. According to seed/fruit findings, *Juniperus communis* cf. subsp. *nana*, *J. sabina*, *J. communis* cf. subsp. *communis* and *J. thurifera*, registered from the Middle Magdalenian, remain abundant in this transition period (Vaquer and Ruas, 2009). The first two were the most abundant and the most suited during the previous cold periods (from Oldest Dryas C10b to Younger Dryas C8, alongside *Arctostaphylos uva-ursi* and *Hippophae rhamnoides*, and were interpreted as shrubby pioneer-steppe vegetation. These lasted for some time and were still abundant in C7. From C6, they sharply decreased. Despite carpology showing that *J. sabina* and *J. thurifera* were still present until the end of the Middle Mesolithic, they had probably been replaced by more thermophilous

species, such as *J. communis* subsp. *communis*, *J. phænicea* and *J. oxycedrus* (the three species present today), although the latter two were not found in charred seeds/fruits. *Juniperus thurifera* (currently rare in France), may have played a significant role, as its fruits were present notably in the Early Holocene (from C7 to C3). This small tree (up to 12 m in height, very slow-growing at altitudes ranging from 140 to 3000 m and resistant to continental climatic extremes) does not bear fruits until the age of 50 (Widmann, 1950). It may have belonged to the open Scots pine forest, as well as to the oak forest. Because of its adaptation to extremely cold winters, it is considered to be the *Juniperus* species most likely to occur in pre-steppe forests during Late glacial periods in the western Mediterranean, associated with *Pinus sylvestris*, while *J. phænicea* was better adapted to extremes of drought in southern regions (Quézel and Médail, 2003). However, *J. thurifera* cannot compete with faster-growing species, such as *Pinus sylvestris* and *Quercus pubescens*, except in high drought conditions (Widmann, 1950), or in a situation of intensive grazing (Gauquelin et al., 1999). Whatever the species, *Juniperus* has indeed been dominated by *Pinus* type *sylvestris* during the Younger Dryas and by *Quercus* deciduous during the Atlantic. It can probably be considered that brutal droughts such as those of the Oldest and Younger Dryas, even more so than cold climate, are at the origin of the successive spreads of junipers. In the Early Holocene, when junipers spread the most, probably almost all species of junipers, including all heliophilic and xerophilic, would have had the ability to colonize large areas, as transitional formations, pending the arrival of tree species. Heat-demanding juniper species probably gradually replaced cold-resistant species.

In C7, maybe still in competition with pines, junipers appear to have been more clumped than later in C6, while their frequency doubles as they spread into the newly opened spaces. *Juniperus* probably colonized more quickly than *Quercus* deciduous the open areas left free by the pine recession, especially on the flats of the plateau system, the most exposed to severe climate variations, with poor but suitable soils. In any case, it can be observed, especially in dry mountainous or Mediterranean areas, that juniper shrubs are generally well spaced, as are bushes in arid areas. The *Juniperus* distribution index in C6, a little over 1, is the closest to a uniform distribution in our data. This regularity could be due to root competition for water and nutrients. Each bush needs a large area to collect the little moisture present and tends to inhibit root regrowth in its immediate vicinity. However, this distribution pattern does not depend only on the species. Research on current desert shrub species has shown that, depending on the age of the individuals, they can first have a clumped distribution at the seedling stage (grouped around their parents), then a random distribution (when competition increases), then a uniform distribution at the old shrub stage, when competition is at its peak (Molles and Sher, 2019). Although this parallel is not sufficient to infer that the juniper populations at Abeurador grew older between C7 and C6, it is likely that they spread almost everywhere over the plateau and reached an advanced age during their long expansion period of several thousand years. Throughout the Middle Mesolithic, junipers dominated, then decreased after the Boreal because their niches were shaded out by oaks.

6. Conclusion

Using the spatial distribution of charcoals in two archaeological layers, we hypothesized that the frequency distribution of each taxon (per grid square) may represent its sampling distribution in the past environment. Distribution indexes linked to theoretical distributional patterns of vegetation were calculated, then used to propose assumptions about the spatial location of woodlands around the Abeurador cave during the Early Holocene, in accordance with the ongoing dynamics due to global climate change, local ecological particularities (edaphic drought, rugged topography) and competitive relationships of taxa. The

spatial distribution of four major taxa was mapped by hypothesis.

In this study, the method was applied to very abundant, scattered charcoal fragments (excluding concentrations), originating from fuelwood in a long-term occupied habitat context, sampled by square and using wet-sieving, according to the most rigorous anthracological methods currently available. The method requires significant sampling and analysis, but not all sites yield the abundance of material necessary to obtain more than 100 or 200 fragments per square. The very good spatial distribution of anthracological information is not specific to prehistoric habitats; however, the more structured the site (as in the case of highly organized human communities), the greater the methodological effort required to define adequate charcoal deposits.

Nowadays, anthracological datasets can provide accurate and reliable information, not only on the overall composition of past forests and their transformations over time but also on their spatial distribution in the surroundings of a site, shedding light on more specific palaeoecological issues. We believe that anthracology has reached a possible level of methodological precision that should make it a reference discipline in palaeoecology.

According to Rull (2010), *'a palaeoecologist is not simply a palaeoecologist whose data may be of interest for ecology, but an ecologist working on another time scale with different methods. Ecology and palaeoecology are only different approaches with a common objective, which is the ecological understanding of the biosphere'*. The main aims of 'ecological palaeoecology, rather than merely unravelling past climatic and environmental trends, are to reconstruct ecosystem dynamics, to understand their environmental drivers and underlying mechanisms, and to provide empirical data for testing ecological hypotheses' (Rull, 2014). Rull (2010) also recommends the refinement of quantitative methodologies to increase the objectivity of interpretations.

An anthracological approach applied to palaeoecology is indeed able to provide complete, repeatable and consistent data if it is supported by a constant methodological requirement, starting with strict field sampling rules and the analysis of sufficient quantities of material. From there, a vast field of unknowns can be opened up. Anthracological data can provide a great deal of information on past vegetation.

However, the lines of thought we propose are a very demanding approach, as archaeological charcoal can feed into equally interesting ethnographic and palaeoecological questions.

First, ethnographic issues that take place in the habitat or artisanal structures, such as fire-related behaviours and practices, need to be studied with great critical rigour of the available material and information. In particular, short-term deposits may be meaningless. Ethnographic issues that take place in the environment, such as forest management vs agropastoral practices, can find important insights through anthracology. They are only one particular aspect of palaeoecological approach and are studied according to charcoal scatters, in the same way as global changes.

Secondly, in the field of palaeoecology, well-sampled charcoals are an extraordinarily reliable and representative material. It is because, and not despite, the fact that firewood has passed through human hands, day after day, and through repeated sampling of vegetation in a relatively limited area, that wood is representative of the vegetation. And because wood has gone through an amazing synthetic stochastic process – combustion, followed by processes of dispersal and relative destruction of the remains – the information remaining in the archaeological site can be studied without too much analytical effort.

We do not pretend that no bias can exist in the datasets, but the random variations in the information are by no means a problem. Short-term deposits in hearths and other concentrated deposits are easily avoided, through sampling choices and *a posteriori* spatial analysis in layers. Sometimes poor, disturbed or very heterogeneous layers must also be studied carefully. If unavoidable biases are found in the representation of past vegetation, they probably occurred by processes of an equally stochastic nature as wood gathering or combustion processes. One can think of the particular effects of combustion on certain species

that have not yet been demonstrated (such as the possible calorific interactions between low-density and high-density woods). As we mentioned, wood collection behaviours could systematically distort the representation of certain major species, for example according to their physiognomic state, at equal biomass (e.g. high forest versus coppice, or pioneer stage vs. mature forest). Furthermore, in these latter examples, since the size of the stems determines the aeration of the fire (the main factor in ash reduction), burning small branches would leave less charcoal than burning an equal weight of large logs. These deformation factors would benefit from being modelled.

Once the sampling and analysis has been completed, present-day ecology is an essential support for interpretations of the past. The abundance of ecological literature is an obstacle and would require greater collaboration between ecologists and palaeoecologists. However, we must also be willing to go beyond what we know concerning woodland communities. We believe that current vegetation analogues are not sufficient to describe ecosystems of the past. The place of some species in ecosystems has changed because the trajectories of species in ecological successions depend on their past history in each location and because of the profound change in living conditions. We believe that anthracology, which perceives an environment of proximity, can particularly fuel these issues.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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