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New charcoal evidence at the onset of MIS 4: First insights into fuel management and the local landscape at De Nadale cave (northeastern Italy)

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ABSTRACT

Archaeological evidence of Middle Palaeolithic sites in Europe dating to MIS 4 remains very scarce compared to those belonging to previous (MIS 5) and later (MIS 3) periods. Of the few documented, a very low number have provided anthracological data reflecting the local landscape and fuel gathering strategies during MIS 4 Neanderthal occupations. This factor especially limits our knowledge of local landscape dynamics and the climatic conditions where these human occupations occurred. In this paper we contribute to this context through charcoal data from De Nadale cave, a single-layered Mousterian site located in northeastern Italy (Berici Hills area) and dated to 70.2 + 1/− 0.9 ka BP. Anthracological data suggests the preferential use of spruce / larch (*Picea - Larix*) as firewood together with cryophilous pines (*Pinus* tp. *sylvestris*) and birch (*Betula* sp.) indicating prevailing harsh climatic conditions. Additional analysis focused on taphonomic features affecting charcoal point out to advance decay evidence prior to charring caused by fungi and insects. Although further data is needed, our results provide complementary information agreeing with the faunal spectrum, the small mammals assemblage and the nearby terrestrial pollen sequences

1. Introduction

During the development of the Upper Pleistocene (ca. 126–11.7 ka BP), continuous climatic changes with varying intensity depending on regions and periods had place (Rasmussen et al., 2014). Marine Isotope Stage 4 (MIS 4), a short stage which took place between ca. 71 and 57 ka BP, was characterised by a minimum of summer insolation on the northern latitudes producing a greater extension of polar ice caps and a descent of the sea level (Rasmussen et al., 2006; Sánchez Goñi and d'Errico, 2005). Cool conditions and a progressive increase of semi-desert plants have been detected in several marine records and pollen terrestrial data from Europe (Fletcher et al., 2010; Harrison and Sánchez Goñi, 2010; Sánchez Goñi and d'Errico, 2005; Sánchez-Goñi et al., 2013). In the specific context of the northeastern region of Italy, pollen data indicate the presence of cold climate vegetation characteristic of fully glacial conditions (Amorosi et al., 2004; Campo et al., 2020; Pini et al., 2010, 2009). Nevertheless, local environmental conditions, which vary significantly within a small territory, may not always reflect wider regional trends (Mallol et al., 2019).

When studying past human behaviour, one of the main objectives is to obtain accurate data regarding human – environment interactions and the adaptative responses to climatic changes (Banks et al., 2021). In this sense, charcoal analysis contributes to the identification of fine-scale local heterogeneities in the landscape with, obviously, a human filter i.e., the results of firewood collecting actions in a supply area (Badal and Heinz, 1991; Chabal, 1992). Considering this, anthracological remains are always recovered and analysed following its scattered and concentrated nature based on the standard anthracological methodology (Chabal, 1992, 1997). While scattered charcoal is the result of several combustion events over time, charcoal from concentrated contexts usually represents isolated combustion events. Thus, most scattered charcoal assemblages are representative of the local landscape, since they respond to successive fuel gathering activities. This archaeobotanical proxy has been applied in several Middle Palaeolithic sites offering meaningful palaeoenvironmental and palaeoeconomical data (e.g., Allué et al., 2017; Basile et al., 2014; Carrión Marco et al., 2019; Chrzavzez, 2006; Martínez-Varea et al., 2020; Théry-Parisot,

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2001; Vidal-Matutano and Pardo-Gordó, 2020). However, most of the charcoal data come from Middle Palaeolithic sites dated to MIS 3 and only few studies provide data on the local landscape developed during MIS 4 (e.g. Carrión Marco et al., 2019; Moncel et al., 2015; Ntinou and Kyparissi-Apostolika, 2016; Vidal-Matutano, 2018; Vidal-Matutano et al., 2015). The small number of MIS 4 sites that have yielded charcoal data still hinders obtaining a high resolution picture of the local climatic conditions in which these Neanderthal occupations occurred (Vidal-Matutano, 2018). In order to contribute with new charcoal data from this period, the following study presents anthracological data from De Nadale cave, a single-layered context in the Berici Hills, in north-eastern Italy. This paper focuses on the botanical identification and the taphonomic analysis of a charcoal assemblage framed at the onset of MIS 4. Our main aims by wood charcoal analysis are to provide a local picture of the landscape and the climatic conditions developed during this period and to suggest first insights into fuel selection criteria adopted by Neanderthal groups at this site.

2. Regional setting

2.1. The site

The region where De Nadale is located is dominated by three geomorphological units: the Po and the Adige alluvial plains in the south,

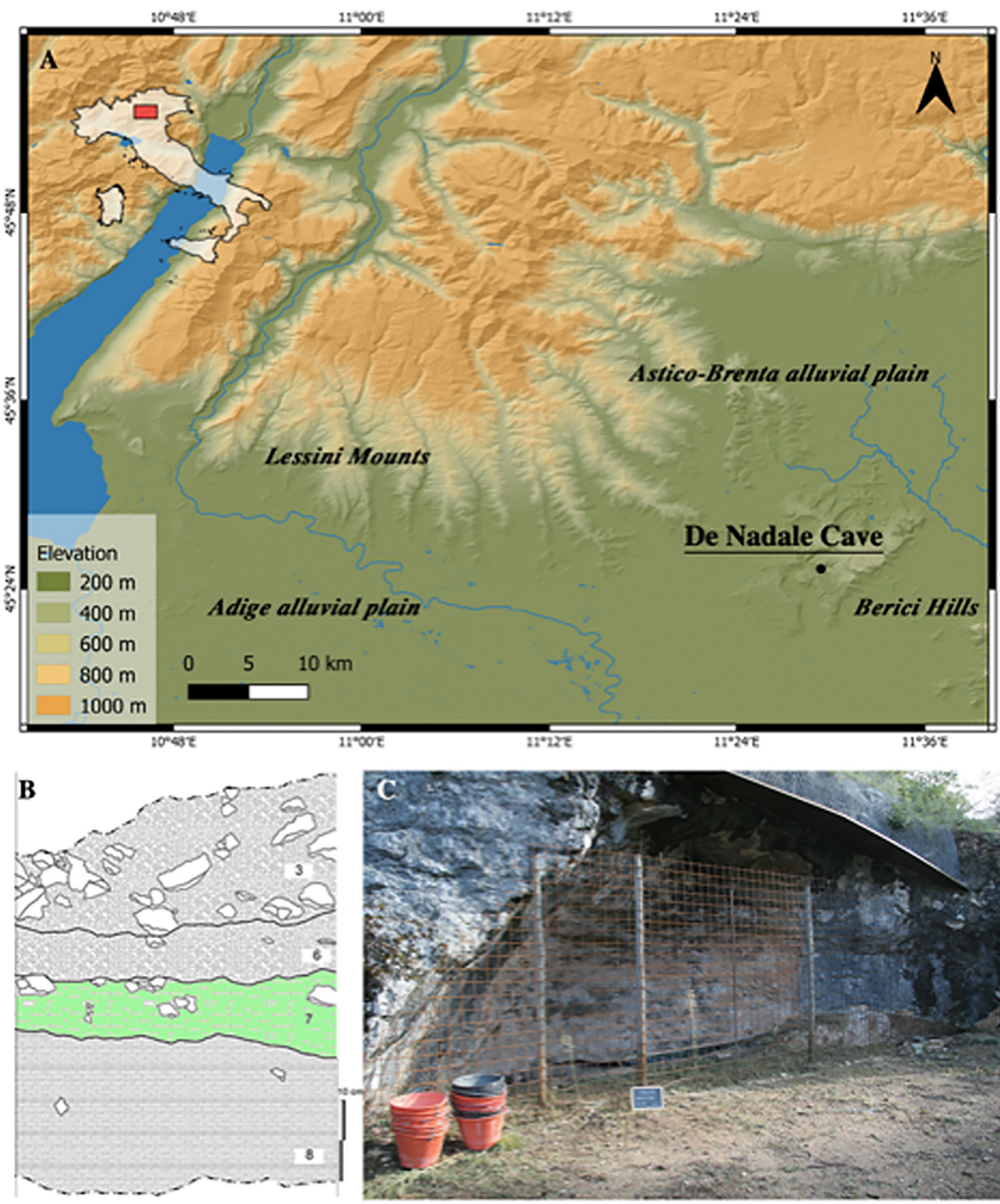

Fig. 1. A) The geographical location of De Nadale Cave in the North-east of Italy; B) the stratigraphic sequence of De Nadale Cave (dotted lines show the roof and the bedrock of the cave; Unit 7 is colored in green); C) the entrance of the site.

the pre-Alps in the north and two small sub-alpine massifs (the Berici and the Euganean Hills) in the south-east (Fig. 1). The present-day physical landscape of the Berici Hills is an ensemble of markedly different morphological zones. Above De Nadale cave, at an average elevation of 250 m, the karst plateau forms a gentle honeycomb with sinkholes and various depressions (including ponors and limestone pavements) succeeding one another, delineating an extremely uneven topography with peaks and block karst affected by surface dissolution. West of De Nadale, the plateau is dissected by the Liona Valley, a depressed system with pocket-valleys, swampy environments and steep slopes all around. To the east, the Pozzolo ancient karst surface is a wide trench cutting through the plateau in a NW-SE direction at an elevation of 150 m, ending at both the SE and NW (Sauro, 2002).

The Berici Hills area produced an important amount of Palaeolithic evidence, both as open-air sites and as caves and shelters (Leonardi and Broglio, 1961; Bertola and Peresani, 2000; Peresani, 2001, 2015) used by Neanderthal foragers as part of a settlement system extended to the Euganean Hills, the Alpine foreland and the southern slope of the Alps (e.g., Peresani, 2012, 2013).

De Nadale cave is a small cavity at 80 m a.s.l., above the narrow and swampy Calto valley. It was first reported in 2006 and extensively excavated since 2014. The field campaigns, carried out from 2014 to 2017 and still ongoing, exposed a short stratigraphic sequence composed of eight different stratigraphic units (SU), including one single anthropic layer (SU7) embedded between Pleistocene sterile sediments (SU6 and SU8) (Jéquier et al., 2015).

SU7 extends on almost entirely the cavity. It yielded a lithic assemblage attributed to the Quina Mousterian (Jéquier et al., 2015; Livraghi et al., 2021) dated to 70.2 + 1/−0.9 ka BP by U/Th (Jéquier et al., 2015). The anthropic layer yielded thousands of fragmented bones, charcoals and a Neanderthal deciduous tooth (Arnaud et al., 2016). The frequentation at De Nadale is framed in a landscape dominated by open woodland formations and dry meadows at the very beginning of MIS 4 (López-García et al., 2018), a period still quite unknown in the north of Italy.

2.2. Biogeographical context and current vegetation

The current bioclimatic conditions are subhumid mesotemperate (mean annual precipitation between 500 and 900 mm and mean annual temperature between 10 and 15 °C) (Pesaresi et al., 2014) (Fig. 2). Nowadays, thermophilous and mesophilous flora predominates in the area (*Pistacia terebinthus, Amelanchier ovalis, Cotynus coggygria, Prunus mahaleb, Fraxinus ornus, Quercus pubescens, Quercus petraea, Acer campestre*). Besides this, the region is also characterised by the presence of *Ostrya carpinifolia, Carpinus betulus* and *Tilia platyphyllos* (Blasi and Biondi, 2017; Tasinazzo, 2001).

3. Materials and methods

The anthracological material included in this study was recovered during the 2014 and 2017 archaeological field seasons by water-screening the sediments using a 2 mm mesh screen. Along with this sampling method, some charcoal fragments visible during field work were hand-picked and recorded three-dimensionally. While most of the material comes from the scattered charcoal assemblage of Unit 7 (i.e., charcoal as a result of several combustion events and its spread across human living surfaces), a few fragments were recovered from concentrations 7SI and 7SII.

Each charcoal fragment was manually fractured for the observation of transverse, tangential and radial sections. Taxonomic identification was performed using a Nikon Labophot-2 bright/dark field incident light microscope with 50–500× magnification at the University of Las Palmas de Gran Canaria, Spain. Comparisons were carried out by consulting specialised wood anatomy atlases (Jacquiot, 1955; Jacquiot et al., 1973; Schweingrüber, 1990, 1976) and a reference collection of modern wood taxa. Photography and the detailed observation of the anatomical and the taphonomic features were conducted using a Zeiss EVO 15 scanning electron microscope (SEM) through prior metal coating at the University of La Laguna's General Research Support Service (SEGAI).

Fungal degradation patterns such as collapsed cell walls, cavities and deformations of the anatomical structure were observed on *Picea – Larix* and *Pinus* tp. *sylvestris* charcoal fragments. Determination of the Alteration Level (A.L.) on the transversal section of each charcoal fragment from both taxa was performed, following the protocol proposed by Henry and Théry-Parisot (2014). Thus, the characterisation of fungal decay was based on the four A.L. previously established: no alteration (A.L. 0), low alteration (A.L. 1), medium alteration (A.L. 2) and high alteration (A.L. 3). This previous study aimed at the identification of fungal decay features and focused on *Pinus sylvestris* showed that a quantitative approach allowed discriminating charcoal assemblages resulting from the combustion of sound, moderately decayed and rotten wood. Due to the lack of a reference dataset for fungal alterations of *Picea* sp. and *Larix* sp. on charred material, the determination of the A.L. on *Picea – Larix* should be interpreted with caution as all taxa do not show equal responses towards fungal attacks (Henry and Théry-Parisot, 2014). However, considering the reduced anthracological assemblage from the Nadale Cave, our objective is not aimed at correlating the microscopic alteration features observed on the charcoal with a macroscopic state of the wood (healthy, dead, rotten) but to observe preliminary general trends in Neanderthal fuel acquisition criteria from Unit 7 of the site. In addition, wood-damage (bore holes, tunnelling) caused by insects was also recorded.

4. Results

4.1. Botanical identification

A total of 158 charcoal fragments have been recovered from Unit 7 of De Nadale Cave. Within the analysed sample, one fragment was identified from the structure 7SI while the structure 7SII yielded a total of 17 fragments. Most of the material was obtained from the scattered context (n = 140) (Table 1). *Picea – Larix* (spruce – larch, Fig. 3 a–b) and *Pinus* type *sylvestris* (Fig. 3 d–e) are the most abundant taxa within the scattered assemblage, representing more than 70% of the total. Taking into account the anatomy of the wood, the distinction between spruce and larch is barely feasible since both genera share many anatomical elements (Schweingrüber, 1990). Although a more pronounced transition from the spring-wood to summer-wood has been associated with *Larix* (Basile et al., 2014), this feature is hardly distinguishable in charred wood. However, most of the *Picea – Larix* charcoal remains presented biseriate pits in radial tracheids (Fig. 3 c), which is characteristic of *Larix* (Marguerie et al., 2000; Schweingrüber, 1990). Thus, De Nadale cave remains are likely to be larch although both species could also be present. Regarding *Pinus* tp. *sylvestris*, this taxonomic category includes several cryophilous pine species that may have been present in the area: *Pinus cembra* (swiss stone pine), *Pinus mugo* (mugo pine), *Pinus uncinata* (mountain pine) or *P. sylvestris* (scots pine). Considering that the discrimination of these species based on the anatomy of wood is hardly feasible (Schweingrüber, 1990, 1976), the "approximate" nomenclature of *Pinus* tp. *sylvestris* is used. Among the deciduous taxa identified, almost 9% of the assemblage corresponds to *Betula* sp. (birch, Fig. 3 f–g) together with low values (<1%) of *Cornus* sp. (dogwood, Fig. 3 h). At least, two different undetermined angiosperms were recorded, although their advanced state of degradation prevented their botanical identification (Fig. 3 i–l). Despite the fact that 7SI and 7SII provided reduced anthracological assemblages, concentrated charcoal from these structures followed the previous observed trends, i.e. the predominance of conifers (spruce – larch and cryophilous pines) and a low proportion of angiosperms (*Betula* sp. and undetermined angiosperms).

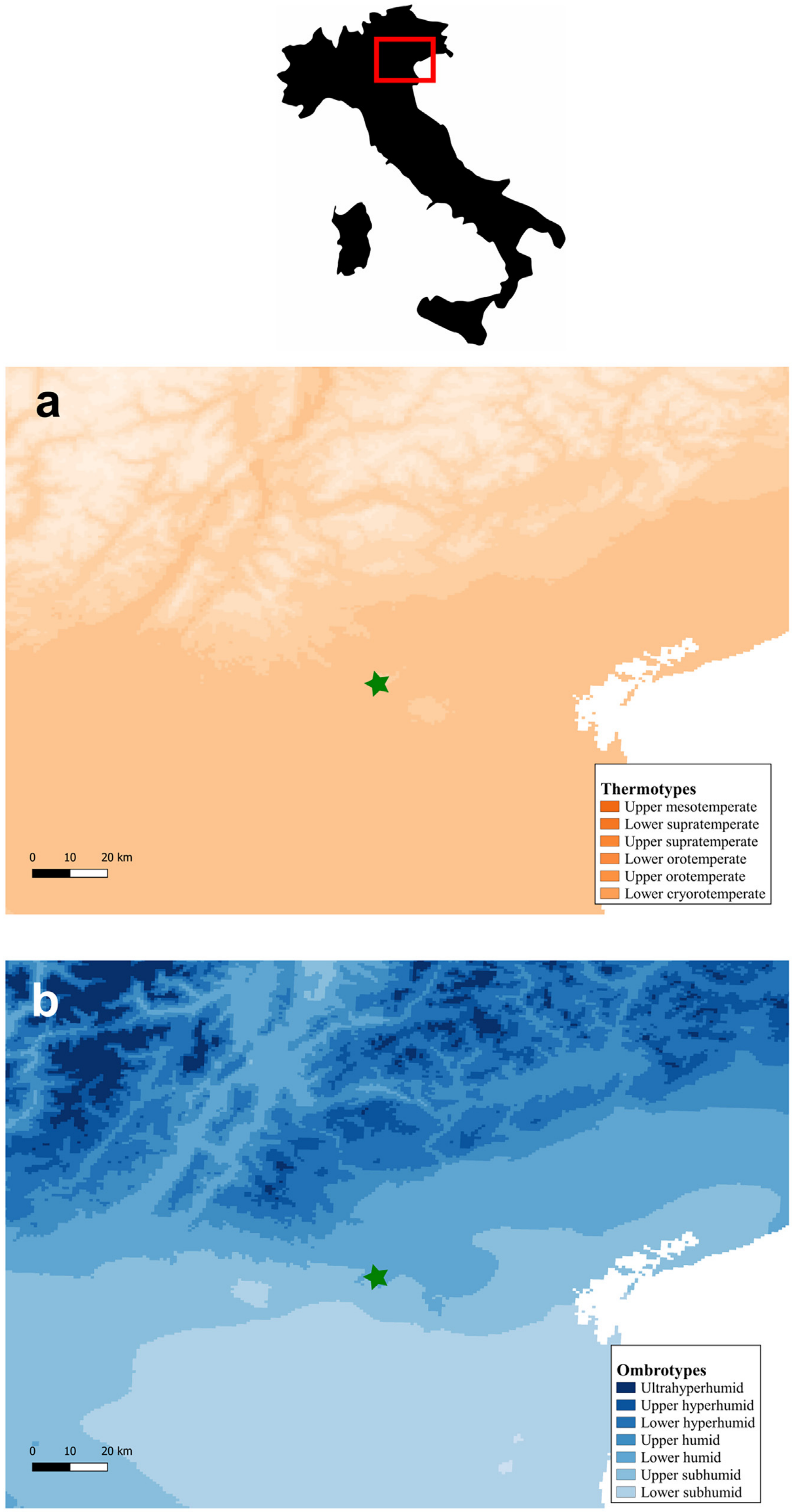

Fig. 2. Current bioclimatic conditions in the study area: thermotypes (a) and ombrotypes (b). The green star indicates the location of De Nadale cave. Maps drawn from the raster data published by Pesaresi et al. (2014).

Table 1
Anthracological data from Unit 7 of De Nadale cave.

Unit	7				
Charcoal context	Scattered		7SI	7SII	
Taxa	n	%	n	n	%
Conifers	12	8.57		2	11.76
Betula sp.	12	8.57		1	5.88
cf *Betula* sp.	1	0.71			
Cornus sp.	1	0.71			
Picea/Larix	73	52.14	1	5	29.41
cf *Picea/Larix*	1	0.71			
Pinus tp. *sylvestris*	33	23.57		7	41.18
cf *Pinus* tp. *sylvestris*	1	0.71			
Undetermined angiosperm 1	3	2.14		1	5.88
Undetermined angiosperm 2	3	2.14		1	5.88
Total remains	140		1	17	
Total taxa	4		1	3	

4.2. Taphonomic remarks

Microscopic observation of charcoal allowed the identification of different microanatomical features affecting wood structure. Vitrification (the homogenisation of anatomical elements altering some of the criteria used in the taxonomical identification) was rarely observed in a few fragments. This phenomenon affected only the 6.4% of the total and was mostly identified among *Betula* sp. fragments (Fig. 4 c).

Fungal decay features were abundant in both angiosperms and conifers. Considering that the protocol proposed by Henry and Théry-Parisot (2014) has only been applied on conifers so far, the A.L. was only determined in *P. sylvestris* and *Picea – Larix* charcoal fragments. Comparing the intensity of fungal decay features of both taxa, unaltered charcoals are mostly documented on *Picea – Larix* (94.5%), while low intensities of alteration (A.L. 1, Fig. 4 d) predominate in *Pinus* tp. *sylvestris* fragments (63.2%). High degradation (A.L. 2 and 3, Fig. 4 e–i) is completely absent in *Picea – Larix*, while it reaches 13.0% in *Pinus* tp. *sylvestris* (Fig. 5).

Wood-damage caused by insects affected 43% of the assemblage, mostly on conifers rather than angiosperms. Wood-destroying features were generally documented in the earlywood of *Picea-Larix* (Fig. 4 a–b) and *Pinus* tp. *sylvestris* charcoal fragments, although in the latter the damaged wood tissue also evidenced fungal alteration features characteristic of A.L. 2 (Fig. 4 e, g).

5. Discussion

5.1. Climate and local plant landscape at De Nadale cave

The anthracological assemblage from Unit 7 of De Nadale cave is characterised by the strong presence of spruce – larch woodland and cryophilous pine forests. The predominance of these plant formations, representing more than 70% of the total, indicates the important role that montane and alpine flora played in this region during MIS 4. These medium-high mountain plant formations would have been accompanied by the presence of birch and dogwood as recorded in the anthracological record.

The plant record is indicative of a local landscape characterised by predominantly supratemperate-orotemperate humid–hyperhumid conditions (MAT of 3–10 °C and MAP between 900 and 1400 mm). These climatic parameters contrast with current climatic conditions in the region (subhumid mesotemperate), pointing out to cooler and a more humid climate at the onset of MIS 4 period. Most of the taxa recorded through charcoal analysis are not currently present at De Nadale cave's altitude. Nowadays, larch – spruce woodland (*Larix decidua, Picea abies, Picea excelsa*) and cryophilous pine forests (*P. sylvestris, P. mugo, P. cembra*) can be found above 1000 m a.s.l. on the montane and subalpine forests of Italy (Blasi and Biondi, 2017; Ozenda, 1982; Pesaresi et al., 2014) (Fig. 6). *L. decidua* is a pioneer species very well adapted to the alpine climate and steep slopes. It's a very cold-tolerant species reaching altitudes between 1000 and 2300 m a.s.l. in the Alps and in other Central European mountains (Carpathians, Sudetes). At high altitudes in the Alps, larch forms the upper tree limit although it can also be found in mixed stands with other alpine tree species such as the swiss stone pine (*P. cembra*), the green alder (*Alnus viridis*) and the dwarf mountain pine (*P. mugo*). At lower elevations, larch is also frequent and it appears mixed with Norway spruce (*P. abies*), silver fir (*Abies alba*), silver birch (*Betula pendula*) and downy birch (*Betula pubescens*) (Da Ronch et al., 2016; Wagner et al., 2015). *P. abies* is a widespread species in the subalpine areas of the Alps growing up to above 2000 m a.s.l. (Meloni et al., 2007). It is shade-tolerant, preferring deep soils with enough fresh moisture. It can be found in pure stands but also with *L. decidua*, creating mixed larch/spruce forests typical of the alpine slopes, and also with *P. cembra* between 1800 and 2100 m a.s.l. (Caudullo et al., 2016). *B. pendula* and *B. pubescens* occur in northern Europe and are light-demanding species preferring open spaces (Beck et al., 2016). Regarding cryophilous pines, *P. sylvestris* is a widely distributed pine species across Eurasia which frequently grows in single stands although it can also be developed together with broadleaves species such as deciduous oaks (*Q. petraea, Quercus robur*) or *B. pendula* and other conifers like *P. abies, L. decidua* or *A. alba* (Houston Durrant et al., 2016). Other potential pine species, such as *P. mugo* or *P. cembra*, are especially abundant in the alpine and subalpine area of the Alps and the Carpathians between 1100 and 2600 m a.s.l. (Caudullo and De Rigo, 2016). Considering this, charcoal results from Unit 7 of De Nadale cave suggest the presence of montane and subalpine flora during MIS 4 at much lower altitudes (< 100 m a.s.l.) than currently (see Fig. 6). Larch woods would be present on the Berici Hills plateau at the elevation of 400–440 m a.s.l.) growing in mixed stands with pine and birch forests at lower elevations and in the Calto valley. The vegetation in the nearby Lessini Mounts, a montain range reaching 2000 m a.s.l., would be characterised by alpine grasslands at this period.

Unfortunately, there are no anthracological data from sites in the North of Italy that yielded deposits dated or clearly ascribable to the MIS 4. Available data comes from Fumane cave's layers framed in MIS 3 (Western Lessini mountains, 350 m a.s.l.), where charcoal analysis revealed the predominance of larch forests associated with mesophilous trees (*P. abies, B. pendula*) that spread in valley bottoms (Basile et al., 2014; Chrzavzez, 2006; Peresani et al., 2011). These data suggest that the Venetian Prealps were ecologically characterised by the presence of alpine and subalpine flora throughout the Palaeolithic period, although the elevation at which larch forests would have developed and the position of the treeline could have varied significantly between MIS 4 and MIS 2.

Charcoal data from De Nadale cave is consistent with the Italian terrestrial pollen sequences from Fimon Lake (Pini et al., 2010) and Azzano Decimo core in Friuli (Pini et al., 2009), revealing for the MIS 4 period a conifer-dominated (*P. sylvestris-mugo* and *Picea*) woodland and an abundance of broad-leaved trees (*Betula, Alnus, Tilia*) with low values of deciduous *Quercus* and beech (*Fagus*). Despite the ecological consistence of both records, larch is not present in the pollen sequences of the region for this period although it is the most commonly fuel used during Neanderthal occupations at Unit 7 from the site. Also, some taxa recorded in these pollen assemblages are completely absent in charcoal analysis (i.e., deciduous oaks). These differences could be due to the distinct spatial resolution obtained by both proxies i.e., a regional scale (pollen) vs. a local scale (wood charcoal) and, therefore, with the fact that local environmental conditions do not always reflect the regional trends (Vidal-Matutano and Pardo-Gordó, 2020). Thus, given the low values of *Quercus* in the pollen record, it is quite likely that this taxon was not very abundant in a local landscape characterised by montane and subalpine flora. Another possible explanation for the absence of *Quercus* from the charcoal record and its contrasting presence in the pollen data from Pini et al. (2010) could be the local availability

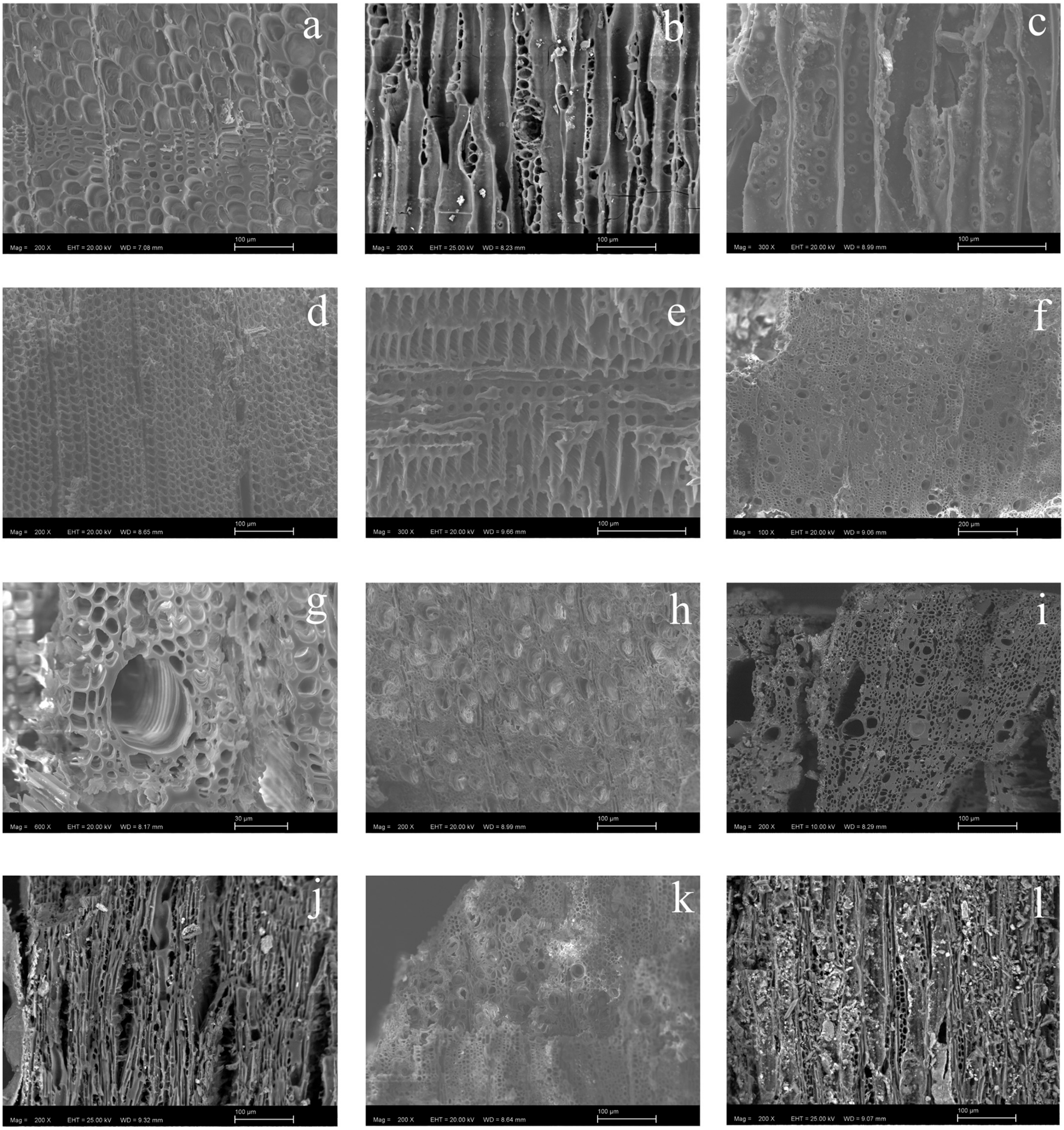

Fig. 3. SEM images of the taxa identified at De Nadale cave. a: *Picea-Larix*, transversal section (×200); b: *Picea-Larix*, tangential section (×200). Note the ray with a resin canal; c: *L. decidua*, radial section (×300). Note the biseriate pits; d: *Pinus* tp. *sylvestris*, transversal section (×200); e: *Pinus* tp. *sylvestris*, radial section (×300); f: *Betula* sp., transversal section (×100); g: *Betula* sp., transversal section (×600). Detail of a vessel with scalariform perforation plates; h: *Cornus* sp., transversal section (×200); i: Undetermined Angiosperm 1, transversal section (×200). Diffuse-porous, affected by vitrification; j: Undetermined Angiosperm 1, tangential section (×200). Rays uniseriate, bi- and 3seriate; k: Undetermined Angiosperm 2, transversal section (×200). Semi-ring porous wood; l: Undetermined Angiosperm 2, tangential section (×200). Biseriate rays.

of dead wood of the most abundant species in the record (larch-spruce and pine) during the formation of Unit 7. This resource, collected during short occupation events, could have met the group's fuel needs avoiding them from extending the firewood supply area.

Moreover, our results fit well with the study on small mammals from Unit 7 of the site evidencing the predominance of *Microtus arvalis* which is currently common in open areas and relatively drier regions of northern Italy (López-García et al., 2018). Other taxa documented, such as *Chionomys nivalis* and *Microtus agrestis*, are currently found at over 1000 m a.s.l. in the Veneto region indicating harsh climatic conditions at the time when the formation of Unit 7 took place. The palaeoclimatic reconstruction based on small mammals is also consistent with the

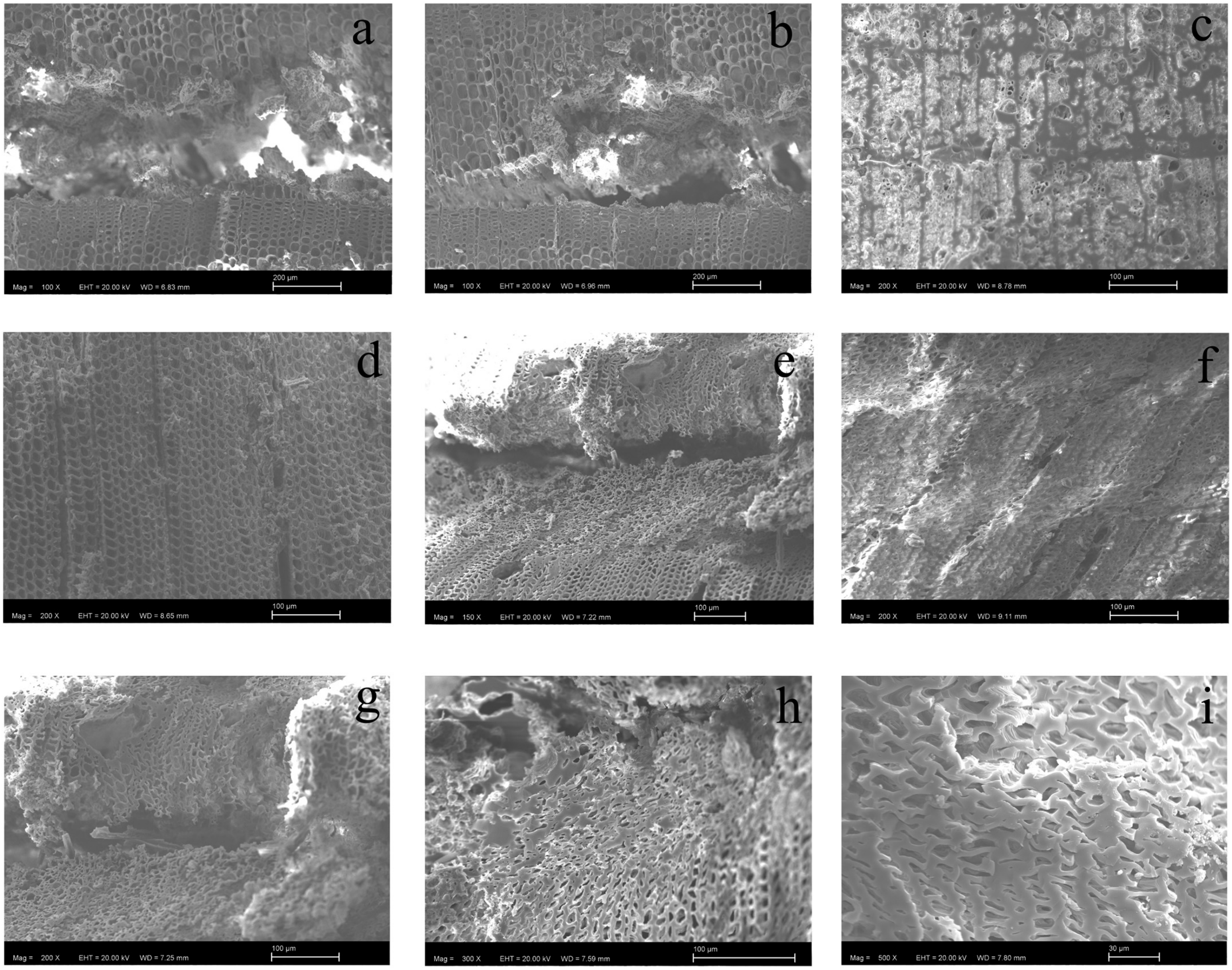

Fig. 4. SEM images of microanatomical decay features affecting wood structure. a – b: *Picea-Larix*, transversal section (×100). Transversal bore holes in the earlywood; c: *Betula* sp., transversal section (×200), vitrified tissue; d: *Pinus* tp. *sylvestris,* transversal section (×200). Cavities in cell walls (A.L. 1); e: *Pinus* tp. *sylvestris*, transversal section (×150). Cell wall deformation in earlywood and transversal bore hole (A.L. 2); f: *Pinus* tp. *sylvestris*, transversal section (×200). Deformed and vitrified earlywood cells (A.L. 2); g: *Pinus* tp. *sylvestris*, transversal section (×200). Cell wall deformation in earlywood and transversal bore hole (A.L. 2); h-i: *Pinus* tp. *sylvestris*, transversal section (×300, ×500). Deformed and collapsed cell walls (A.L. 3).

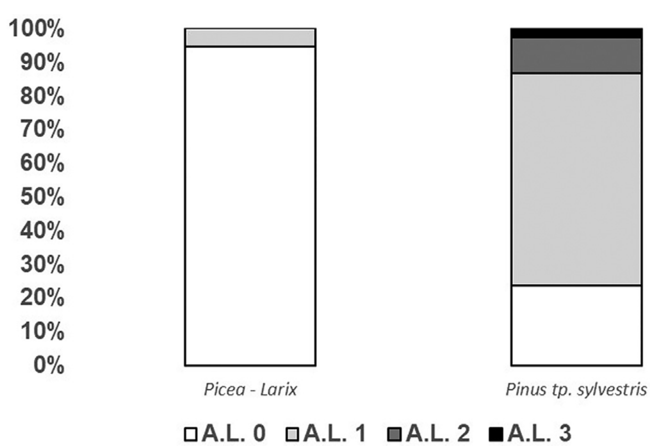

Fig. 5. Proportions of A.L. in *Picea-Larix* and *Pinus* tp. *sylvestris* charcoal fragments.

anthracological data presented here (Table 2), with the installation of a colder and a more humid climate. The faunal assemblage resulting from the zooarchaeological analysis consistently indicates ecological conditions characterised by open woodland formation and open dry meadows (Livraghi et al., 2021). Large and medium- sized ungulates – red deer (*Cervus elaphus*), giant deer (*Megaloceros giganteus*) and large bovids (*Bison priscus* and *Bos primigenius*) – dominate the faunal spectrum, both according to NISP and MNI. Smaller ungulates, such as roe deer (*Capreolus capreolus*), chamois (*Rupicapra rupicapra*), wild boar (*Sus scrofa*) and ibex (*Capra ibex*), have also been recovered although in lower quantity. Carnivore remains yielded by Unit 7 are scarce and they have been identified mainly as belonging to cave bear (*Ursus spelaeus*) and other non-identifiable bear species, with lower percentages of wolf (*Canis lupus*), fox (*Vulpes vulpes*) and badger (*Meles meles*) (Livraghi et al., 2021). In this sense, the control of the movements of grazing large herbivores at the valley bottoms due to the privileged location of De Nadale cave could have been a compelling reason for selecting the cave as a seasonal camp.

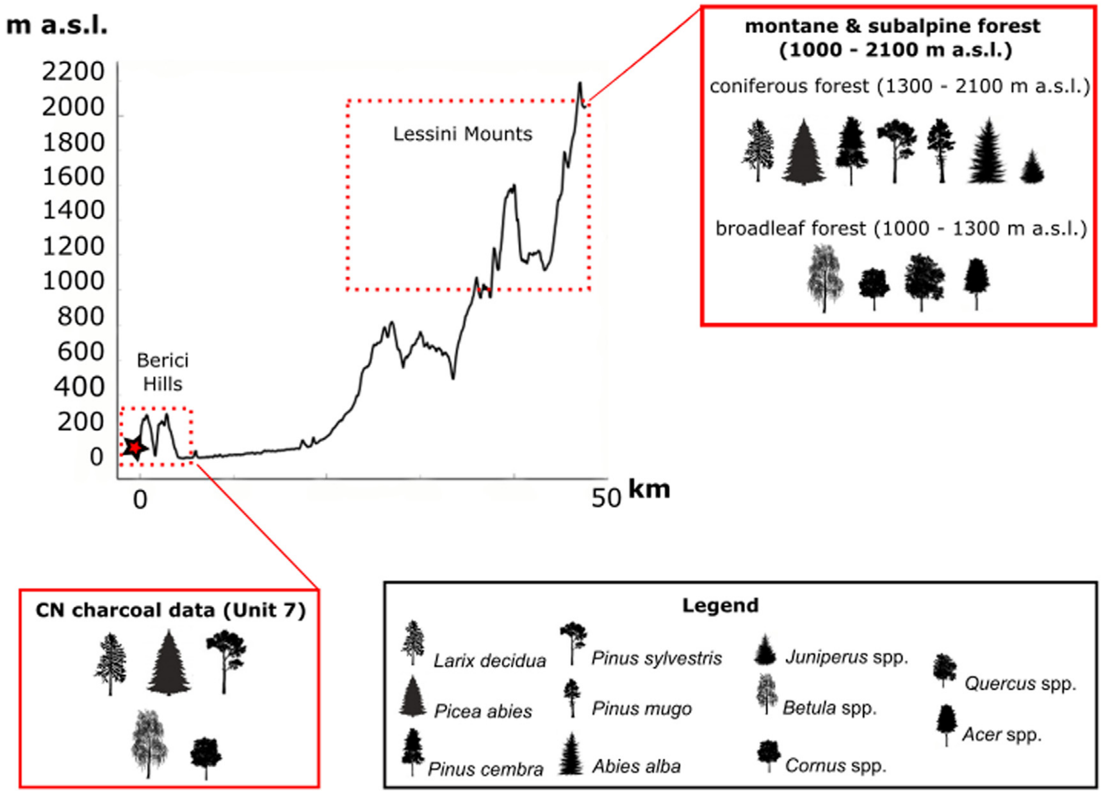

Fig. 6. Representation of the taxa identified in Unit 7 of De Nadale cave and the current distribution of montane and subalpine flora in the surroundings.

5.2. First insights into fuel acquisition criteria

At De Nadale cave, most of the conifer charcoal fragments showed decay features due to insects and fungal activity. Low intensities of alteration (A.L. 1) predominated in pine charcoal fragments with abundant cavities in cell walls observed in the transversal section. Fungal degradation was less abundant in spruce-larch, although damaged earlywood tissue was frequently recorded (see Fig. 4 a–b). A.L. 2 pine charcoal fragments presented both types of decay features (fungi and insects) localised in earlywood tracheids i.e. cell deformation and large transverse bore holes in earlywood, together with perforated cell walls in latewood (see Fig. 4 e, g–h).

Moisture and temperature are the environmental parameters with the greatest influence in the development of wood-decaying organisms (Pournou, 2020). The optimum temperature for fungi lies between 20 and 40 °C and the moisture between 40 and 80% (Blanchette, 1991; Leonowicz et al., 1999) with similar values for xylophagous insects (20–30 °C and 15–60%) (Reinprecht, 2016). However, the various cell types are not degraded equally. Wood-damage localised in earlywood is probably related with lignin distribution as latewood tracheids have lower lignin content (Donaldson, 2001). This decay feature is observed

Table 2
Palaeoeclimatic reconstruction of Unit 7 from De Nadale cave based on small mammals (López-García et al., 2018) and anthracological data; MAT, mean annual temperatura; MAP, mean annual precipitation; ΔMAT, difference between the MAT values obtained for Unit 7 and the present-day mean; ΔMAP, difference between the MAP values obtained for Unit 7 and the present-day mean.

Climatic parameters / proxy	Anthracology (this study)	Small mammals (López-García et al., 2018)
MAT (°C)	3–10	7.8
MAP (mm)	900–1400	1462
ΔMAT (°C)	− 6	−5.04
ΔMAP (mm)	+450	+560.11

among some brown-rot species preferentially degrading earlywood cells at an initial state of decay while latewood is attacked later in advanced decay (Schwarze, 2007). Regarding insects, each taxon has its own preferences based on habitat and wooden substrate, i.e. hardwood / softwood, sound / decayed wood, heartwood / sapwood, green / seasoned wood, etc. (Pournou, 2020). Insects can be "primary colonisers", digging galleries in dead wood, or "secondary colonisers" using the holes previously produced by other species. This symbiotic relationship is very common between fungi and insects due to different nutritional needs which facilitate a progressive colonisation by several wood-decaying organisms (Pournou, 2020). Indeed, due to the fact that some wood-boring species cannot digest wood unless it is fungal decayed, its damage is usually focalised on earlywood zones already degraded by previous fungal activity (Eaton and Hale, 1993). For example, termites (*Isoptera*) preferentially attack earlywood cells by tunnelling parallel to the grain and leaving undamaged the latewood tissue (Pournou, 2020). This decay-type has been frequently observed in spruce-larch and pine charcoal fragments from De Nadale cave, although the identification of the type of insects that bored through the wood remains unknown as no faecal pellets were observed. Indeed, morphological features (size, shape, texture) of faecal pellets differ from one species to another and its identification provides interesting information regarding wood condition before carbonisation (Fohrer et al., 2017; Toriti et al., 2021). Thus, the identification of microscopic decay features during charcoal analysis is a crucial step to better characterise the state of the wood (green, seasoned, decayed) used and the selection criteria that played a role in the past (i.e., gathering / cutting practices) (Allué et al., 2017; Chrzavzez, 2006; Henry and Boboeuf, 2016; Henry and Théry-Parisot, 2014; Martínez-Varea et al., 2020; Moskal del Hoyo et al., 2010; Théry-Parisot, 2001; Vidal-Matutano et al., 2020, 2017).

Our knowledge regarding firewood use and management among Neanderthal groups is progressively increasing, although the available data is still very scarce. A few studies discuss the existence of fuel gathering criteria and the use of alternate fuels such as the use of coal or lignite documented at Les Canalettes (Southern France, MIS 3) possibly involving specialised activities with high energy requirements (Théry-Parisot et al., 1996; Théry-Parisot and Meignen, 2000). The preferential use of dead wood has been suggested at several Middle Palaeolithic sites. At Fumane cave this practice was defined through the observation of wood degradation patterns and diameter stimations indicating the use of small calibres (Chrzavzez, 2006) and at La Combette (Southern France, MIS 3) the use of degraded wood was associated with specific hearth functions (i.e., meat processing) (Théry-Parisot and Texier, 2006). More recently, a quantitative analysis of microscopic decay features focused on charcoal remains from Middle Palaeolithic combustion structures of Abric del Pastor and El Salt (Southeastern Spain) was performed (Vidal-Matutano et al., 2017). This approach, following previous experimental studies (Henry and Théry-Parisot, 2014), highlighted the existence of firewood selection criteria based on dead wood gathering and also suggested smoke-related functions in one specific hearth. Similarly, other hunter-gatherer contexts have also recorded wood degradation patterns suggesting the preferential use of dead wood: Abri Pataud, Castanet (Théry-Parisot, 2002, 2001) or Abric Romaní (Allué et al., 2017).

The low number of pine charcoal fragments from Unit 7 of De Nadale cave still prevents a quantitative analysis of fungal decayed patterns and its comparison with previous experimental and archaeological assemblages (Henry and Théry-Parisot, 2014; Vidal-Matutano et al., 2017). Nevertheless, some interesting remarks can be pointed out. The results for pine degraded charcoal fragments show an overrepresentation of A.L. 1 and a much lesser presence of A.L. 2/3 charcoals. This unusual profile, not documented in experimental works (Henry and Théry-Parisot, 2014), could be related with previous studies indicating the effect of mechanical processes on charcoal considering the state of the wood before combustion (Chrzavzez et al., 2014, 2011; Théry-Parisot et al., 2010). Similar profiles were obtained in Middle Palaeolithic contexts contributing to the consideration of post-depositional processes that probably affected the higher degraded charcoals (Vidal-Matutano et al., 2017). Likewise, the overrepresentation of A.L. 1 pine charcoal fragments at De Nadale cave could reflect post-depositional processes affecting the least resistant charcoals to mechanical processes i.e., charcoals with medium/high alteration intensities (A.L. 2/3) also degraded by wood-boring insects (see Fig. 4 a–b, e, g–h and Fig. 5). These taphonomic processes could have led to the fragmentation or even the disappearance of most of the anthracological material warning us of the importance of integrating them into charcoal analyses. As suggested in other Middle Palaeolithic contexts, dead wood of the most frequent species could have accumulated in the surroundings of De Nadale cave during the formation of Unit 7. This valuable resource, easily accessible, could have been gathered by Neanderthals groups inhabiting the cave as it suits very well the hunter-gatherer way of life (short occupation events, territorial mobility, seasonal occupation). Further data is needed at De Nadale cave to analyse the statistical correspondence of these assemblages with previous studies and thus contributing to our knowledge regarding firewood collection practices.

6. Conclusions

The results presented here contribute to our better understanding of the local climatic conditions in northeastern Italy at the onset of MIS 4 and the use and management of firewood resources by Neanderthal groups. Charcoal data suggest that the climatic conditions were cooler and more humid than currently. The botanical identification of the fragments has yielded significant palaeoecological data concerning the presence of montane and subalpine flora at much lower altitudes (<100 m a.s. l.) than currently in the venetian Prealps. Spruce-larch forest would have predominated at higher elevations of Berici Hills (300–400 m a.s.l.) growing in mixed stands with pine and birch forests at lower elevations or at the bottom of the valley.

Fungal and insect decay features have been observed in conifer charcoal fragments, especially in *Pinus* tp. *sylvestris* where large transverse bore holes in earlywood degraded tracheids were documented. In spite of the low number of charcoal fragments recovered so far, the microscopic degradation features recorded could point out to the presence of dead wood in the local area and their collection by Neanderthal groups. Additionally, the effect of post-depositional processes affecting the higher degraded charcoals has been considered following previous experimental studies. Thus, the overrepresentation of A.L. 1 pine charcoal fragments compared to medium/high alteration intensities could reflect a different resistance of charcoals to mechanical processes depending on the state of the wood prior to combustion. Further research in charcoal analysis from this and other Palaeolithic sites of the region, including the recognition of decay features, will define in a more precise way selection criteria involved, hearth functions and possible changes in firewood supply areas linked to possible preferences of a specific state of wood (i.e., dead wood).

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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