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When smoke is in the air: An experimental approach to characterise fuel emissions on past humans dwellings☆

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ABSTRACT

Fire, since it became a feature of daily life, had a great significance for humans in the past. When reconstructing fire use and maintenance it is important to know what kinds of fuels were being used as energetic resources and how these were managed. We present the first results of a project that aims to investigate how important was the use of fire and how was the awareness or knowledge about the health effects on people. The objective is to study wellbeing (health and habitability) in prehistoric communities from Palaeolithic occupations in Iberian Península. Our research focuses on the identification of patterns that could refer to the decision making regarding the type of dwelling, as well as the size, ventilation, location of hearths and type of fuel used. Fire experiments were made in the cave Cova Manena (Tarragona, Spain) and in open air locations: Paleolítico Vivo and CAREX (Burgos, Spain) and Molí del Salt (Tarragona, Spain) archaeological site surroundings. The main fuel used was *Pinus sylvestris* in order to evaluate fuel management and combustion practices. In the experiments we have registered meteorological conditions, hearth temperatures, radiative heat and fine particles emissions using different tools. Results showed smoke emissions and hearth temperature are related to firewood state (dry, semi-decayed and decayed) and environmental conditions (rain, wind direction and speed). This has allowed us to monitor several data in order to analyse air quality as well as habitability conditions in the different dwelling scenarios regarding health and wellbeing of the prehistoric communities.

1. Introduction

Fire, since it started to be used as an everyday tool, became increasingly more important to prehistoric humans. Archaeological evidence indicates that hunter-gatherer groups had the ability to control fire as an established technology since the Middle Paleolithic (Sorensen et al., 2018; Brittingham et al., 2019; Aiello 2017; Monetti et al., 2021). The introduction of fire as a technological resource changed the lives of past human groups in many ways including cooking food, lighting, heating and at a social level too (Goldberg et al., 2017; Mentzer, 2014, and references therein). Although, much of this research has been dedicated to the identification of the earliest evidence rather than trying to understand the consequences of its use. During the last decades several researches have focused on specific issues that have provided insights in hearth function and maintenance (Théry-Parisot et al., 2010; Stahlschmidt et al., 2020). In this sense, experimentation has enabled exploration of fire hearth formation (Burguet-Coca, 2020); types of fuel used and heat transfer (March et al., 2014; Vidal-Matutano et al., 2017; Aldeias, 2017; Kedar et al., 2020; Théry-Parisot, 2001). Examining the functions of hearths used by people in the past is a key research issue that may contribute towards the identification of past behaviours involving fire and fuel uses.

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A key question when reconstructing past fire uses and maintenance is what kind of fuel was being used as an energetic resource and how this was managed. This topic has been increasingly discussed in archaeobotany and ethnographic investigations (Henry et al., 2018). Wood is often assumed as the preferred type of fuel. However, other types of materials (bones, dung, coal as well as other plant parts) are also known to have been used in some regions and environments (Miller, 1984; Smith, 1998, Rowan, 2015, among others). This may have been due to scarcity of wood, but also a technological choice or perhaps even a cultural preference, due to different burning properties or smells of fuels such as dung and peat (Braadbaart et al., 2017; Théry-Parisot et al., 2005; Allué et al., 2017a).

Light and heat are two of the more immediate benefits of fire use. Light is important for the extension of daily hours and protection, while heat is essential for warmth, cooking and resource modification. Assessing through experiments differences in the lighting properties of different types of fuels could help in shedding a light on whether light was the intended objective for making a fire or not (Hoare, 2020, 2023; Medina-Alcaide et al., 2021, Medina-Alcaide 2024). Air quality is likely to have varied according to fuel type, environmental conditions (wind, humidity and air pressure), location of the hearths and the managing way. Although the use of fire on a regular basis occurred in rockshelters, caves or indoor places with poor ventilation and outdoor hearths, most of the experiments carried out do not take into account archaeological and ethnographic data regarding the use of embers for "indoor" fires, as neither the size of hearths or the quantity of fuel. Usually, experiments tend to produce higher amounts of smoke with respect to what the evidence suggests (Vallverdú et al., 2010; Braadbaart et al., 2017; Hoare et al., 2023).

In addition, current studies show that urban life was essential for the onset of pernicious effects of fuel emissions on human health (Magnusson, 2013). Fuel emissions are characterised by small particle dispersion that are usually divided, according to air quality regulations, into two size groups. Particulate matter with diameter smaller than 10 μm is referred as PM10 and particles with diameters smaller than 2.5 μm, as PM2.5. PM10 are more likely to deposit on the surface of the larger airways of the upper region of the lungs while PM2.5 travel and deposit on the deeper parts of this organ, a fact that may induce lung inflammation and tissue damage (Mannucci et al., 2015; Zelikoff et al., 2002; Feng et al., 2016). However, research on the effects in earlier human communities such as hunter-gatherers or first agricultural communities are still scarce. One of the earliest and singular pieces of evidence of smoke inhalation based on chemical signals in teeth has been documented in early human groups at Qesem cave, Israel (Hardy et al., 2016).

Other studies have approached this question from bioanthropology, based on human skeletal remains (Davies-Barrett et al., 2019; Roberts, 2007; Merrett and Pfeiffer, 2000). In addition, studies on the relation between dimensions of caves and smoke dispersion have been done using the Computational Fluid Dynamics (CFD) code Fire Dynamics Simulator (McGrattan et al., 2017) for Palaeolithic sites (Kedar et al., 2020; Lacanette et al., 2017; Fuente-Fernández, 2022). Moreover, firewood experiments have been made to measure indoor temperatures and the intensity of the fires (Trbojevic et al., 2012; Östlund et al., 2013). Notwithstanding, there is still a knowledge gap about the incidence and effects of the use of fire on human health in prehistoric occupations (Shillito et al., 2021). Smoke and chemical compounds generated during the combustion process are known in modern contexts to have harmful effects on human health, which tend to be increased in females and children. As a consequence, people in charge of taking care of domestic hearths could have been affected by different kinds of diseases and long-term health issues (respiratory diseases, lung cancer, or infant mortality, among others) (Bede-Ojimadu and Orisakwe, 2020). Research on health related to indoor air quality and in particular, the relationship between fuel use and health in prehistory, are key and novel aspects that need to be further investigated (Naeher et al., 2007; Vilčeková et al., 2017; Stabridis & van Gameren, 2018; Singleton et al., 2017).

When thinking about fuel management within Palaeolithic communities, one of the most frequent species for firewood was *Pinus sylvestris* type in the Iberian Peninsula (Figueiral and Carcaillet, 2005; Badal et al., 2012, 2013; Allué et al., 2012, 2013, 2017a, 2017b, 2018; Vidal-Matutano, 2017; Uzquiano 2008, 2014; Uzquiano et al., 2008; Alcolea, 2017, 2018; Mas, 2018, Mas et al., 2021, among others). Understanding the use of this species in the past enables us to assess whether choices of past populations were driven by availability, preference, cultural habits, or other factors (Allué et al., 2022). The recurrent presence of *P. sylvestris* type charcoal in archaeological contexts has allowed specific anatomical and experimental studies about its anatomical cell structure and taphonomic aspects (Théry-Parisot, 2002; Allué et al., 2009; Théry-Parisot et al., 2010; Chrzavzez, 2013; Henry & Théry-Parisot, 2014; Allué & Mas, 2020, among others). In addition, understanding about the state and size of the firewood when gathered is still a line of research that needs more development, most often approached by dendrology studies (Alcolea et al. 2021). Lastly, fire experiments on heat radiation, light transmition and fuel emissions have taken place with *Pinus* sp. having one of the taxa selected (Hoare, 2020, 2023).

This work presents the initial results achieved from the research project FLAHME that questioned how important the use of fire was once it became a fixture of daily life, and which awareness or knowledge about the positive and negative health effects would people have had. Specially when making decisions about their type of dwelling, as well as the size, location and type of fuel used. In this opportunity, a series of analysis referring to temperature of hearth and fuel emissions will be presented to make a contribution in the understanding of wellbeing (health and dwelling conditions) in paleolithic communities who lived in winter scenarios and dealt with, for example, scarcity of dry firewood, windy nights and rainy seasons in the Iberia Peninsula. With this in mind, open air and indoor (a cave) fire experiments were made with *Pinus sylvestris* type of fuel considering size, condition and behaviour of the taxa during the combustion of fire hearths for specific purposes.

2. Material and methods

As experimental archaeology is a widely developed field and the selection of variables and factors depends on the decision-making of specific criteria, a certain number of challenges have been approached in the planned activities. The protocols of FLAHME project were designed based on potential dwelling types, fuel use (type, quantity and quality), duration and replicability. An updated version of the protocol can be consulted in: https://doi.org/10.34810/data1775. We based our terminology following Vandevelde et al. (2024). This study is also based on previous experience from authors of the manuscript (Burguet-Coca, 2020) and methods based on Hoare (2020) and Shillito et al., (2021) previous research. Related to this work, the methodology applied intends to answer the question about how aware were people in the past about the state and conditions of the fuel gathered for fire activities. It also considered if this represented a challenge in the choice of type of dwelling where to light the fire, whether it was open air with flat soil with the influence of the meteorological conditions or locations indoors that would be more beneficial for different types of fires (central fires for activities, small fires for sleeping, among others).

In this work, we present nine experimental fires carried out with *Pinus sylvestris* wood (Fig. 1). Experimental activities have been carried out in four locations, considering the protocols and aims of the project:

- Experimental Archaeology Center (CAREX, Atapuerca, Spain), (Continental climate with cold winters − 850 m.a.s.l.). One open air experiment.
- Paleolítico Vivo (Salgüero de Juarros, Spain), (Continental climate with cold winters − 850 m.a.s.l.). Four experiments in open air.

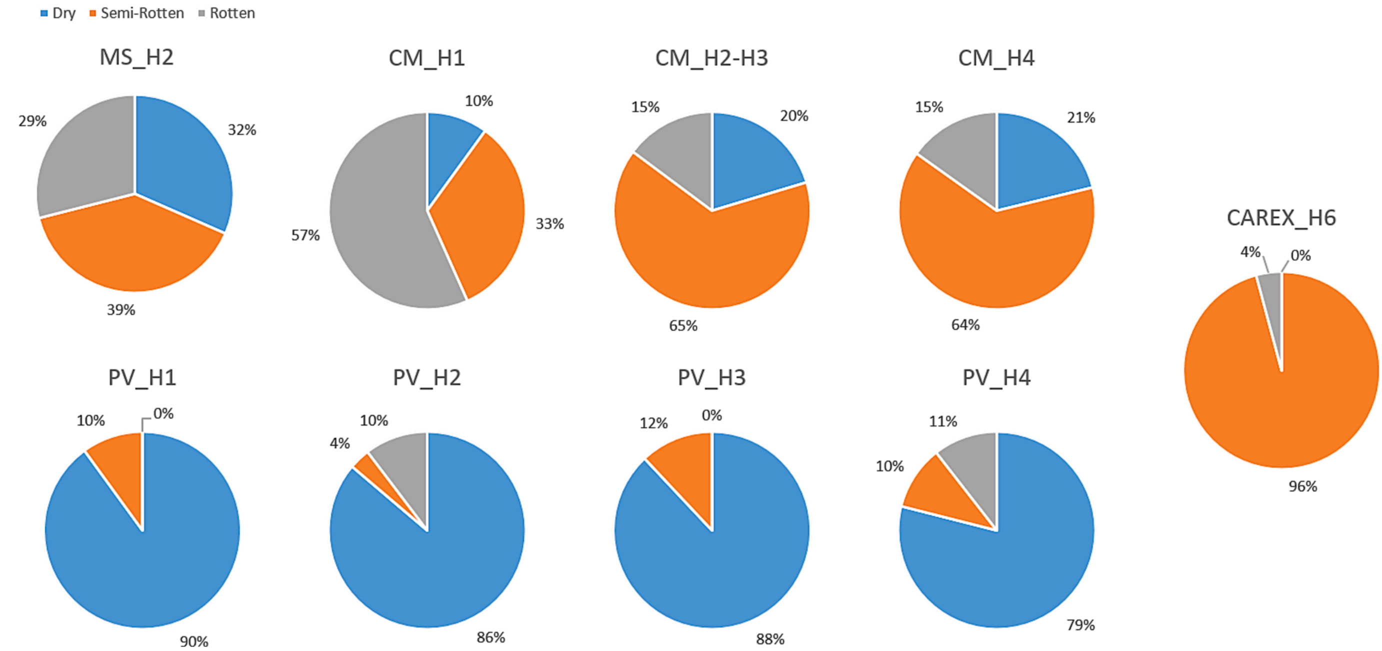

Fig. 1. *Pinus sylvestris* state of wood (MS and CM experiments with wood gathered from Prades (Tarragona); while CAREX and PV experiments from the nearby area in Arlanzón (Burgos).

- Surroundings of the Molí del Salt archaeological site (Vimbodí i Poblet, Spain), (Mediterranean climate – 496 m.a.s.l.). One open air experiment.
- Cova Manena (El Catllar, Spain), (Mediterranean climate – 50 m.a.s.l.). Four experiments inside the cave (Fig. 2).

All experiments consist in realising flat hearths on clean soil with no additional rock structure around, to reduce variables and simulate the general pattern known for palaeolithic hearths (Table 1). Sizes of hearths ranged from 40 to 50 cm of diameter. Fires were active for around 2 h and measurements such as environment, smoke emissions, and hearth temperature, were monitored from the start of the fire until the extinction of the flames. Half of the firewood was incorporated at the start of the experiment and additional fuel was supplied as needed to sustain the flames. Although this could have an influence on the fire duration, temperature reach and smoke production- as discussed by the bibliography (Théry-Parisot et al., 2010; Hoare, 2020, among others)-, the protocol aimed to explore fire use and smoke emissions, maintaining on purpose the flames to imitate a specific activity. Adding all the firewood at the beginning or at specific times will eventually reduce variables, but it would also exclude possible interpretations about smoke emissions and health conditions that were not similar to the ones in the past. Furthermore, firewood state (dry, decayed and/or wet) affects the fire, therefore needs to be evaluated considering the duration, temperature and smoke emissions.

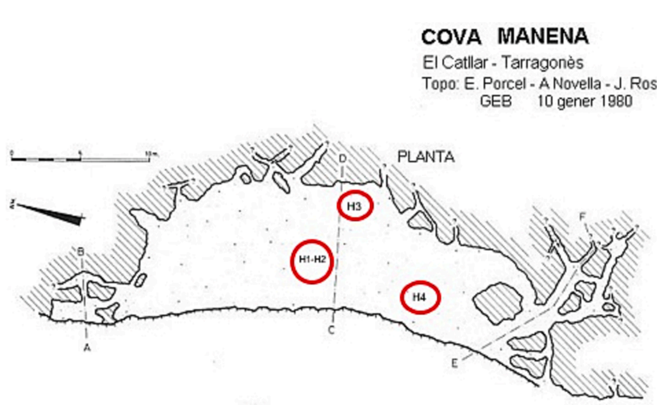

Fig. 2. Topography of Cova Manena with hearths. Modified from https://espeleoworld.com/c/cova-manena.

Firewood was gathered in the nearer area where the required species is available. For all the experiments, the fuel used were *P. sylvestris* branches different in size, state, and quantity (10 kgs per hearth). Table 1 and Fig. 1 summarise the conditions and quality of the wood gathered in each location for carrying out the experiments. Considering that the state of the charcoal in palaeolithic sites is usually preserved with a diverse degree of decay (e.g. Théry-Parisot et al., 2010, Allué, 2002, among others), we followed a random firewood gathering strategy collecting both dry and semi-decayed wood. Thin (2–4 cm) and medium (4–10 cm) branches were collected mostly from the trees and the soil.

Additionally, dry grass was used during the ignition process. In some of the experiments (PV-H3 and PV-H4) pine cones were added to evaluate the temperature rising differences and to study the remains (Garay & Berihuete Azorín 2023). Also, systematic sampling for anthracology and phytoliths of each hearth was carried out following the protocols of previous experiments (Burguet-Coca, 2020; Mas, 2018). Analysis of these remains are in progress and will not be presented in this study.

Following the protocol for experimental fires a grid was established with reference points (from 1 to 10) at 1, 2 and 3 m away from the fire in the four cardinal directions (North, East, West and South) in order to measure heat radiation and smoke emissions at different ranges. For this, we created a vector file (.shp) with the hearth basemap using QGIS software (version 3.30.1). With the air quality and heat measurements data from the experiments we created heatmaps of the thermal radiation for each experiment. Heatmaps were made with the Interpolation tool that allows to calculate the Inverse Distance Weighted (IDW), range of measurements were adjusted for each experiment and colored with Linear Interpolation with 5 continuous classes.

All experiments included a series of measurements and analyses that will enable the integration of different methods and disciplines to achieve the objectives:

- *Climatic conditions:* In order to evaluate how environmental conditions affect the duration and behaviour of the fires regarding smoke emissions and heat duration, a meteorological station (PCE-M120)

Table 1
Summary of the activities made with the experimental fires.

N° Experiment	Code-Site	Date	Taxon	Start	Duration (hs:min)	Type of Site	Max. Temp.	Average Temp.
1	CAREX_H6	13/12/2023	P. *sylvestris*	18:00	2:39	Open Air	766,3°	368°
2	MS_H2	23/10/2023	P. *sylvestris*	20:30	2:17	Open Air	729,7°	511°
3	CM_H1	14/02/2023	P. *sylvestris*	20:30	2:30	Cave	463°	–
4	CM_H2	31/10/2023	P. *sylvestris*	18:30	2:03	Cave	933,4°	619,23°
5	CM_H3	31/10/2023	P. *sylvestris*	19:50	1:42	Cave	237°	100°
6	CM_H4	7/02/2024	P. *sylvestris*	17:00	1:53	Cave	708°	477°
7	PV_H1	6/03/2023	P. *sylvestris*	23:30	1:52	Open Air	905°	383,45°
8	PV_H2	7/03/2023	P. *sylvestris*	22:00	2:01	Open Air	997,3°	420,41°
9	PV_H3	8/03/2023	P. *sylvestris*	22:10	2:06	Open Air	601,4°	328,68°
10	PV_H4	9/03/2023	P. *sylvestris*	22:23	2:35	Open Air	857,8°	528,51°

was set in place. The time, temperature, wind, rainfall and humidity conditions were recorded (Table 2).

– *Air Quality measurements*: The use of air quality monitoring stations (HandiLaz Mini II PMS with range of 0.2 μm to 10 μm) helped to measure air quality and fine particulate conditions during the experimental fires of both indoor and outdoor fire hearths according to each different dwelling scenario. The representation of the data is by particle counts considering particles matters of 0.2, 0.5, 1, 2.5, 5 and 10 μg/m^3 (e.g. Fig. 5). Spatial distribution of the concentration of particles matters were represented by PM2.5 and PM10 μg/cu.m and by the spatial distribution of the concentration of the particles (e.g. Fig. 7).
– *Temperature control of the hearth:* In order to measure each fire's temperatures achieved at the beginning, re-fuel and once extinguished, calibrated thermocouples type K were used (8 per hearth K type thermocouples with a PCE-T390).
– *Radiative heat measurement*: A grid was established (Fig. 7) to measure heat radiation with the thermocouples type K at 1 m, 2 m, and 3 m both indoor and outdoor experiments, to model heat transfer conditions on a living situation.

3. Results

Results of the experiments are summarised in Table 1. Moreover, in Fig. 3, hearth temperature, together with the temperatures reached during the experiments are shown. Radiative heat emissions are represented through heatmaps using QGIS software with mean values (Figs. 7 and 8). Smoke emissions were calculated with particles count per hearth during different moments of the experiments (Figs. 5, 6 and 7). Also, mean values of 2.5 and 10 um small particles concentrations were calculated and represented in heatmaps with the interpolation tool (Figs. 7 and 8). In these figures, colour and range of measurement have been adjusted to each experiment due to variability in daily temperatures in each region and variation in the experiments. In Burgos, average temperature of the experiments varied between 3 °C and 11 °C, while in MS and CM experiments were between 12 °C and 17 °C. Databases with the raw data of the experiment's result can be consulted at CORA repository https://doi.org/10.34810/data1879. Also, GIS projects with heat radiation and air quality analysis can be consulted at https://doi.org/10.34810/data1880.

3.1. *Paleolítico Vivo experiments*

These experiments were carried out in Paleolítico Vivo, Salgüero de Juarros, during March 2023, in order to simulate winter outdoor occupations. For this, firewood from medium and small branches of *P. sylvestris* collected in the nearby area were used. Although we gathered dry wood from trees that were not particularly decayed (Fig. 1), in many cases it was wet due to the rains that occurred during that week. The fires carried out during the night allowed us to evaluate the habitable conditions in the open air in the face of low temperatures (2 °C) and with windy and rainy conditions.

During the **PV-H1** experiment at the beginning (23:30) it was drizzling and the soil was wet. We had to set the firewood in square form so that not all of the branches touched the floor and got wet. After a minute the rain stopped and the fire could be started properly. During the rest of the experiment the wind was affecting the fire. For the first part of the experiment hearth temperature was reaching 400 °C, after one hour the temperature reached the maximum of 905 °C and then kept over 600 °C the rest of the time. Temperature measured by the weather station was between 6,5–6,8 °C and wind came from NW most of the time. However, radiative heat during the experiments shows a media temperature of 6.7–7.2 °C in the surroundings, with the exception of 2 m north of the hearth at 5.81 °C (Fig. 8). About air quality, Fig. 5 shows particle counts with a peak after one and a half hours over the north section of the hearth, also 2.5 and 10 μg/cu.m were in that zone (Fig. 8).

PV-H2 fire was lit at 22 pm. The night was windy during all the experiment (around 6–7 km/h with NW direction) and the thermocouple that measured the centre of the hearth had to be moved several times. This was interpreted as an effect of the wind that influenced one side of the hearth with the consequence that the "centre" of the hearth moved to the opposite direction as flames and the fire consumed more wood from that area. Measurement of the central part of the hearth was around 600 °C the first hour and then reached the peak of 997.3 °C. Environmental temperature was around 8 °C, but near the fire radiative heat measurements differentiate the north area of the hearth with a media of 9.97 °C at 1 m among the others. Particle counts values for the first part of the experiment gave the highest amount, simultaneously with the beginning of the hearth with 600 °C, later it remained stable for the rest of the experiment (Fig. 5). Smoke emissions concentrations of 2.5 and 10 μg/cu.m were higher in the north and east area of the hearth (Fig. 8).

In **PV-H3** and **PV-H4**, *P. sylvestris* pine cones were added at the beginning and in the middle of the experiment for the purpose of studying possible peaks of temperature and proportion of their presence among their remains (Garay and Berihuete-Azorín, 2023). PV-H3 was performed during a warmer night (9.7 °C) at 22:10 with wind from the N-NW between 6.1 and 9.7 km/h). Hearth temperature peak was at 601 °C and was sustained during the experiment. Fig. 3 shows a decay in the temperature after one hour of the experiment, caused by the change of direction of the wind and consequently it was necessary to adjust the thermocouple. Radiative heat shows that the north area of the hearth was warmer (medium 9.7 °C) and the east area the least (7.63 °C). About fuel emissions, particle counts were significantly lower than in the others experiments, however there is a peak at 2 h of the experiment (Fig. 5) at 1 m in the north area of the heart. Unlike the other experiments, the media of 2.5 and 10 μg/cu.m concentrations were higher in the north area of the hearth at 2 m (Fig. 8).

PV-H4 started at 22:23 during a night with a temperature ranging from 7.6 to 8.1 °C and wind blowing from the NNW and NE of 8.6 km/h most of the time. During this experiment, measurement of windchill was significantly lower than other cases (between 5.4–5.7 °C). Hearth temperature had a peak of 857 °C and an average of 528,51 °C (Fig. 3). Due to the change of wind direction (from NW to NE), the west area of the

Table 2
Weather measurements during the experiments.

Experiment	CAREX_H6					
Duration (hh:mm)	**0:00**	**0:30**	**1:00**	**1:30**	**2:00**	**2:30**
Outdoor Temperature (°C)	5.4	5.2	4.4	4.2	4.5	4.3
Outdoor Humidity (%)	82	85	89	88	85	86
Relative Pressure (hPa)	1010,4	1011,0	1011.0	1011.3	1011.7	1012.1
Wind Speed (km/h)	2.5	0.0	0.0	2.5	0.0	0.0
Wind Direction	N	N	N	N	N	SSE
Windchill (°C)	5.4	5.2	4.4	4.2	4.5	4.3
24 Hour Rainfall (mm)	8.40	8.40	8.40	8.40	8.40	8.40
Experiment	**MS_H2**					
Duration (hh:mm)	**0:00**	**0:30**	**1:00**	**1:30**		
Outdoor Temperature (°C)	13.9	13.0	12.5	11.7		
Outdoor Humidity (%)	75	79	82	83		
Relative Pressure (hPa)	1013.0	1013.3	1013.3	1013.4		
Wind Speed (km/h)	0.0	0.0	0.0	0.0		
Wind Direction	NNW	NNW	NNW	NNW		
Windchill (°C)	13.9	13.0	12.5	11.7		
24 Hour Rainfall (mm)	0.00	0.00	0.00	0.00		
Experiment	**CM_H1**					
Duration (hh:mm)	**0:00**	**0:30**	**1:00**	**1:30**	**2:00**	**2:30**
Outdoor Temperature (°C)	4.5	3.8	4.0	4.6	5.3	6.3
Outdoor Humidity (%)	88	87	91	90	89	87
Relative Pressure (hPa)	1012.9	1012.9	1012.9	1012.9	1012.9	1012.7
Wind Speed (km/h)	0.0	0.0	0.0	0.0	0.0	0.0
Wind Direction	ESE	ESE	ESE	ESE	ESE	ESE
Windchill (°C)	4.5	3.8	4.0	4.6	5.3	6.3
24 Hour Rainfall (mm)	0.00	0.00	0.00	0.00	0.00	0.00
Experiment	**CM_H2-H3**					
Duration (hh:mm)	**0:00**	**0:30**	**1:00**	**1:30**	**2:00**	**2:30**
Outdoor Temperature (°C)	15.7	13.3	12.7	12.3	11.8	11.3
Outdoor Humidity (%)	73	80	82	82	84	77
Relative Pressure (hPa)	1012.9	1013.0	1013.0	1013.3	1013.7	1013.0
Wind Speed (km/h)	0.0	0.0	0.0	0.0	0.0	0.0
Wind Direction	NNE	NNE	NNE	NNE	NNE	SE
Windchill (°C)	15.7	13.3	12.7	12.3	11.8	11.3
24 Hour Rainfall (mm)	0.00	0.00	0.00	0.00	0.00	0.90
Experiment	**PV_H1**					
Duration (hh:mm)	**0:00**	**0:30**	**1:00**	**1:30**	**2:00**	
Outdoor Temperature (°C)	6,5	6,9	6,8	6,7	6,8	
Outdoor Humidity (%)	91	89	90	92	92	
Relative Pressure (hPa)	1012,8	1012,3	1012,1	1012,1	1011,9	

Table 2 (*continued*)

Experiment	CAREX_H6				
Wind Speed (km/h)	0	5	0	0	3,6
Wind Direction	NW	NW	WNW	NNW	N
Windchill (°C)	6,5	6,9	6,8	6,7	6,8
24 Hour Rainfall (mm)	0	0	0	0	0
Experiment	**PV_H2**				
Duration (hh:mm)	**0:00**	**0:30**	**1:00**	**1:30**	**2:00**
Outdoor Temperature (°C)	8.1	8.0	8.0	7.9	8.0
Outdoor Humidity (%)	82	84	85	86	86
Relative Pressure (hPa)	1013.7	1013.6	1014.1	1013.7	1013.9
Wind Speed (km/h)	3.6	7.2	6.1	6.1	6.1
Wind Direction	NW	NNW	NNW	NNW	NNE
Windchill (°C)	8.1	6.8	8.0	7.9	8.0
24 Hour Rainfall (mm)	0.90	0.90	0.90	0.90	0.00
Experiment	**PV_H3**				
Duration (hh:mm)	0:00	0:30	1:00	1:30	2:00
Outdoor Temperature (°C)	9.9	10.0	9.7	9.7	9.7
Outdoor Humidity (%)	93	92	93	93	92
Relative Pressure (hPa)	1014.5	1014.8	1014.6	1014.7	1014.9
Wind Speed (km/h)	6.1	7.2	6.1	7.2	9.7
Wind Direction	NW	N	N	NW	NW
Windchill (°C)	9.9	8.9	9.7	8.6	7.1
24 Hour Rainfall (mm)	9.90	9.90	9.90	9.90	0.00
Experiment	**PV_H4**				
Duration (hh:mm)	0:00	0:30	1:00	1:30	2:00
Outdoor Temperature (°C)	8.1	7.9	7.9	7.7	7.6
Outdoor Humidity (%)	84	85	84	84	85
Relative Pressure (hPa)	1017.6	1017.9	1018.1	1018.2	1018.4
Wind Speed (km/h)	6.1	8.6	8.6	8.6	8.6
Wind Direction	NNW	NNE	NNW	NE	NE
Windchill (°C)	8.1	5.7	5.7	5.5	5.4
24 Hour Rainfall (mm)	0.00	0.00	0.00	0.00	0.00

hearth was also warmer with a media of 11.1 °C. The following morning, the ash concentration was significantly smaller than that of the other experiments and also the thermoaltered soil surface was significantly larger than the original hearth (Fig. 10). About smoke emissions, the north area, both 1 m and 2 m, were the most affected by the dispersal of the small particles (Fig. 5), also shown with the 2.5 and 10 µg/cu.m concentrations (Fig. 8).

3.2. *Cova Manena experiments*

These experiments were carried out in El Catllar, Tarragona, during February 2023, 2024 and October 2023, simulating indoors winter occupations. Firewood was gathered from the Prades mountains (Tarragona) with more proportions of semi-decayed and decayed branches (Fig. 1). The fires were made during the night to evaluate colder habitable conditions in a cave (Fig. 2).

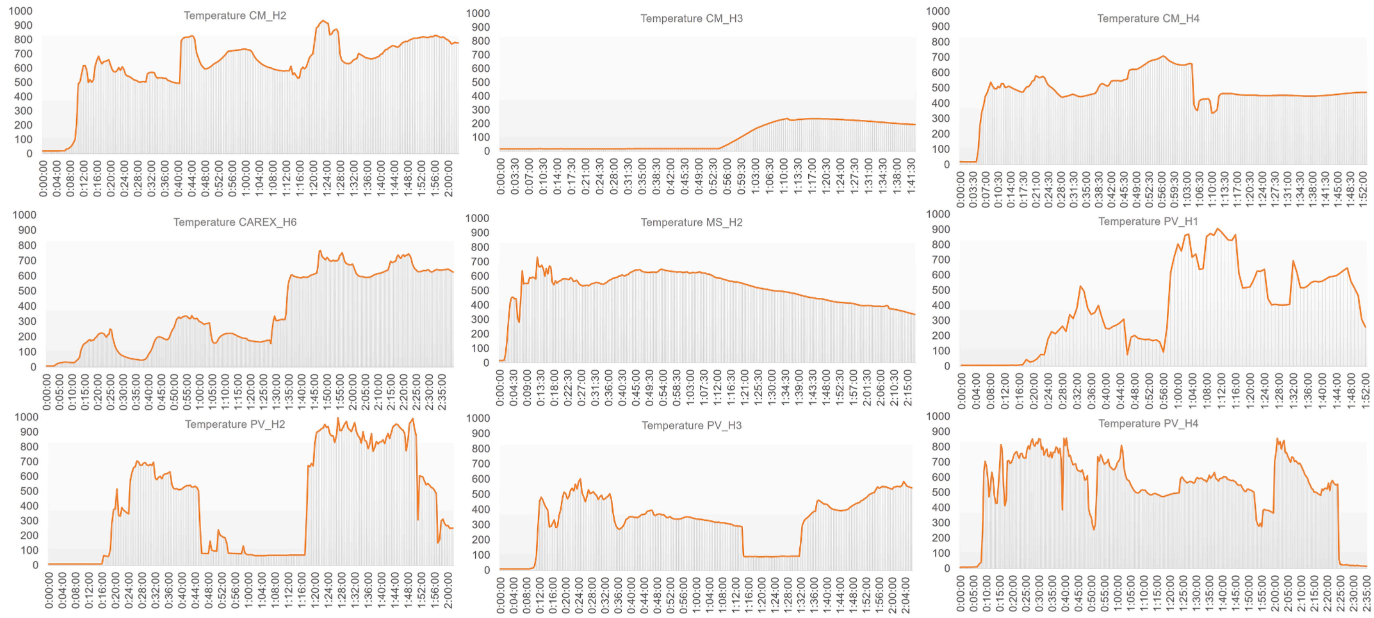

Fig. 3. Hearths central temperature during the experiments for the duration of the flames.

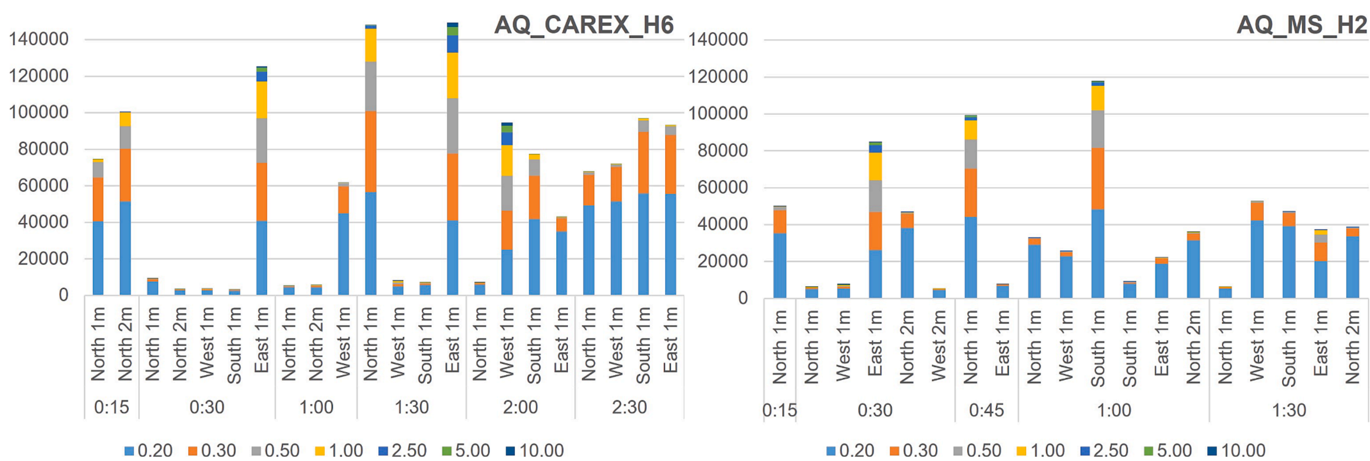

Fig. 4. Particle count measurements in CAREX and Molí del Salt experiments.

CM-H1 hearth was made in February with no wind speed registered. Temperatures were from 3.8 to 6.3 °C during the experiment. Although hearth temperature was taken, there was a problem with data saving, so no graph could be made. However, 463 °C was the peak temperature registered. On several occasions we could determine that a certain log was producing more smoke than others (Fig. 9).

CM-H2 hearth started at 18:30 with an air temperature between 11.3 and 15.7 °C. Also, no wind was registered that day. Hearth temperature rose quickly because at minute 6 temperature was already above 600 °C and the peak was 933 °C. Radiative heat (Fig. 7) shows a warmer area in the west part of the hearth, although the temperature difference with the others was less than a grade. Particle counts had a peak at the first hour of the experiment, associated with a refuel activity since embers being withdrawn for the CM-H3. Also, concentrations of 2.5 and 10 μg/cu.m were placed into the west part of the hearth. Although smoke was concentrated in the cave, there was no difficulty in breathing or loss in visibility registered (Fig. 9).

CM-H3 was planned to be a brasier, embers were obtained from CM-H2 and transfered to the new location. Temperature reached 237 °C and maintained for the following hour. Radiative heat was warmer at the west part of the hearth, however there was also the influence of CM-H2. Particle counts were higher at the beginning of CM-H3. However concentrations were different from 2.5 and 10 μg/cu.m.

CM-H4 was made in February 2024, there were unfavourable conditions with the meteorological station and no measurements were saved. Fire started at 17:00 because there was an intent of preparing another brasier but it failed due to the difficulty in transporting the embers. At the beginning temperature rose quickly because in 6 min it was already over 500 °C, although peak temperature was 708 °C. Radiative heat was also warmer in the west at 24 °C, meanwhile in other areas it only reached 16 °C. Particle counts were steady high during the experiment, although concentrations of 2.5 and 10 μg/cu.m were higher in the north area of the hearth.

3.3. *Molí del Salt experiments*

These experiments were made in the surroundings of the archaeological site Molí del Salt, Vimbodí i Poblet, Tarragona, during October 2023. Only the experiments made in open air and with *P. sylvestris* type of wood are presented here. Firewood for this experiment was also gathered in the Prades mountains (Tarragona) with a comparable distribution of decayed, semi-decayed, and dry wood (Fig. 1). This

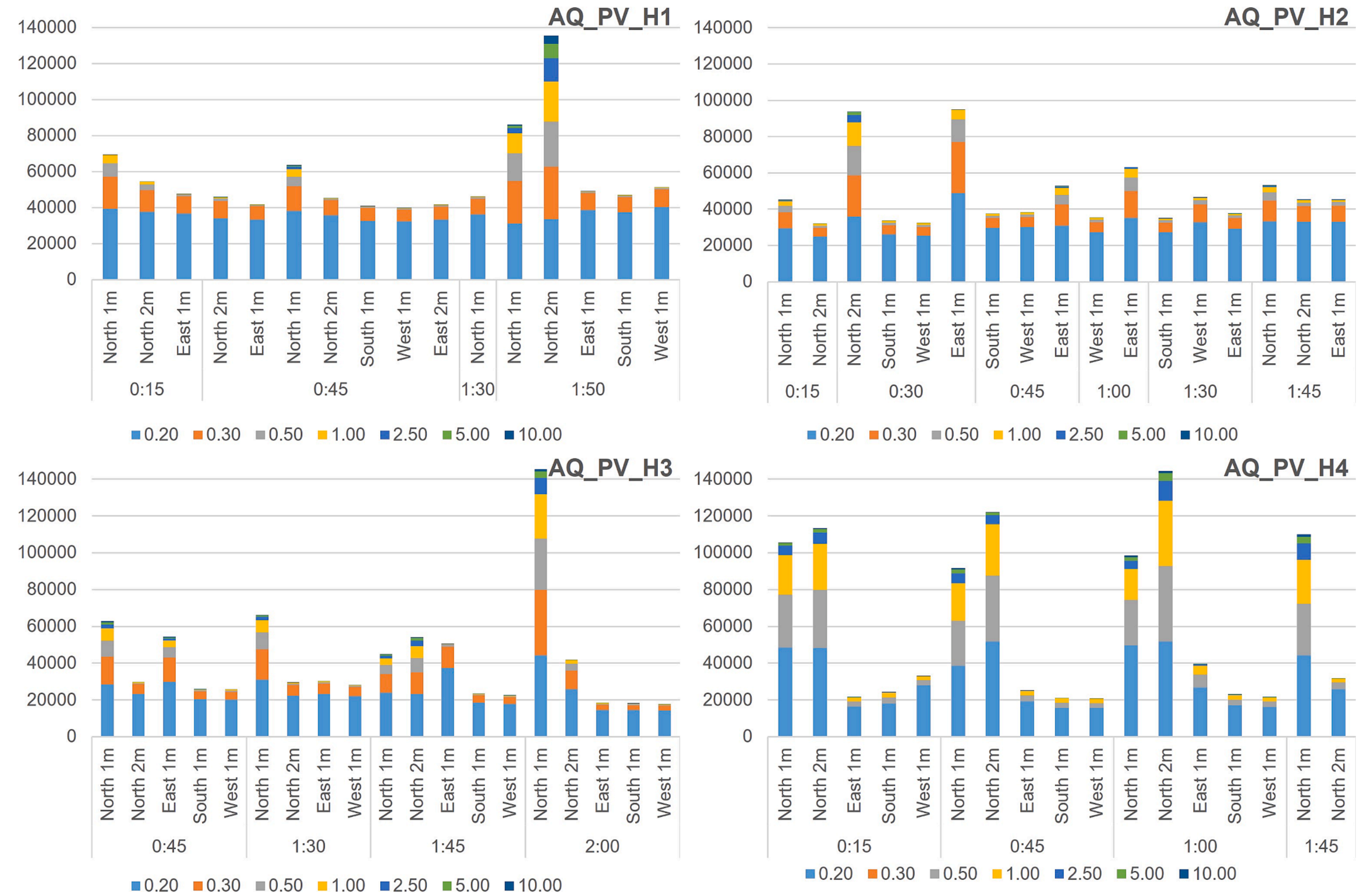

Fig. 5. Particle count measurements of Paleolitico Vivo experiments.

experiment was made during the night at 20:30 with temperatures between 11.7 and 13.9 °C. There was no wind registered during the experiment. The start of the fire was quicker than the other experiments reaching 600 °C within the first five minutes; the peak of temperature was 729.7 °C. East of the hearth was warmer (14.6 °C) than the other areas, although for less than a grade (13.6 °C) (Fig. 8). About smoke emissions, different areas of the hearth (north, east and south) were having high values of small particles at different times (Fig. 4), However, considering the concentration of 2.5 and 10 μg/cu.m, the east area was the most affected.

3.4. CAREX experiments

These experiments were made in the Experimental Archaeology Centre (CAREX, Atapuerca, Spain) in December 2023. On this occasion only the experiment at open air with *P. sylvestris* is presented. Firewood was gathered in the nearby areas and the state of the wood was generally semi-decayed (Fig. 1). The fires were made at night time to evaluate winter use of fire with low temperatures and rainy nights. During CAREX-H6, temperature was between 4.2 and 5.4 °C and the wind was slow (2.5 km/h sometimes) with a North direction. However, since it had been raining all day and it was drizzling that night, it was more difficult to start the fire. Fire started at 18:00 but it took an hour and a half to reach over 400 °C, being the peak at 766,3 °C. Radiative heat showed a difference of the media temperature being the northeast area at 3.71 °C at 2 m and the south at 6.6 °C. About 2.5 and 10 μg/cu.m, the east area of the hearth was most affected in concentration (Fig. 7).

4. Discussion

This research includes 10 experimental fires for the study of firewood behaviour according to quantity and quality of the wood and the environmental conditions. The study includes analyses of the hearth temperatures and fuel emissions. Results show that hearth temperature and fuel emissions, when making fires with *P. sylvestris* fuel type, are affected by environmental conditions (wind), location (open air vs. cave) and fuel conditions (state of the wood). The following discussion arise from the obtained results:

According to the experiments in Paleolítico Vivo, CAREX and Molí del Salt wind direction and speed can affect the by-products of the fire (heat and smoke). Temperature of the hearths was different in the six open air experiments. Overall, at some point in the experiment, each hearth reached between 600 and 800 °C, although CAREX_H6 and PV_H1 took longer. Besides environmental conditions, we believe that the state of the firewood played a crucial role in this. Also, some hearths proved to reach higher temperatures (PV_H1, PV_H2 and PV_H4).

Firewood of *P. sylvestris* in these experiments were balanced in the PV_H1, H2, H3 and H4 experiments, with mostly dry branches (Fig. 1), while CAREX_H6 and MS_H2 had more semi-decayed and decayed wood. The amount of firewood, 10 kg each heart, with thin (2–4 cm) and medium (4–10 cm) branches, as well as size of hearth were standardised among experiments (between 40 and 50 cm diameter). With this in mind, smoke emissions on the experiments of Paleolítivo Vivo showed total counts starting from 20,000 μg/m^3. In the four experiments, a range of 20,000/40,000 μg/m^3 was registered with alternating peaks over 100000 μg/m^3. These peaks were produced due to refuelling and wind effects, however, PV_H4 highlights because peaks were more frequent. CAREX_H6 and MS_H2 values were more variables than PV

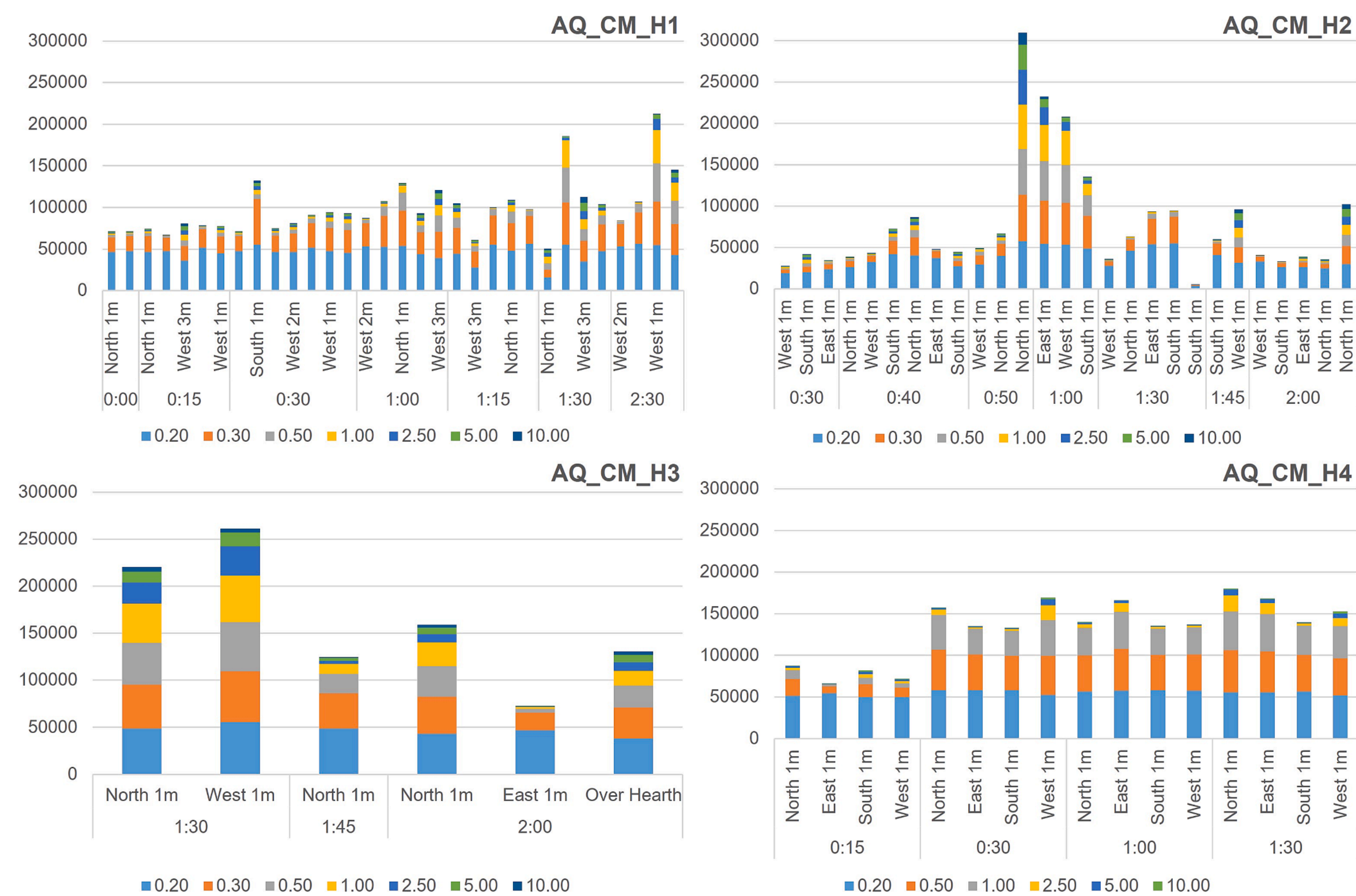

Fig. 6. Particle count measurements on Cova Manena experiments.

experiments. Baseline particle counts were below 10000 μg/m^3, with a second range that was between 40,000/60,000 μg/m^3 for CAREX_H6 and 30,000/40,000 for MS_H2. Peaks in the first one were between 80,000/100,000 μg/m^3 and for MS_H2 60,000/80,000 μg/m^3.

Regarding size of the hearth, we observed that although a fire could be started with a certain diameter, one of the main factors that affected it was refuel and wind direction and speed. About refuelling, it was always intended to be consistent in time of need, with the purpose of maintaining the flames; however this could also mean that, depending on the behaviour of the fire in relation with the wind and location, sometimes refuelling needed to be more frequent in some hearths than in others (within less than 5 min). Also, as mentioned before, wind speed and direction affected hearth behaviour directly: in the cases of stronger winds more temperatures, more combustion of the firewood was happening.

Radiative heat was also associated with wind direction, such as the case of CAREX_H6 and PV_H1, H2, H3 and H4. This means that some areas around the fire would be warmer than others, even a close distance such as 1 m. But it would also mean that smoke concentrations will be higher in those directions (Figs. 4 and 5). The only experiment where wind was not recorded was MS_H2 and there heat radiation was distributed more equivalently within the different directions (Fig. 8).

After sampling the remains and cleaning, we observed that the thermoaltered surface ended up being wider than expected. This variability was not only related to the quantity of firewood and the heat reached (March et al., 2014) but also to the effects of wind. As seen in hearth PV_H2 and H3, wind direction to NW made the surface wider in that direction. This was also proved when checking the central heart thermocouple that needed to be relocated since the "centre" of the fire had moved.

The experiments in Cova Manena showed how fires with *P. sylvestris* type of wood can vary according to the state of the firewood (decayed and semi-decayed wood), on temperature and smoke emissions. Unlike the open air experiments, environmental conditions did not affect the fires in a direct way since no wind speed was recorded by the meteorological station. Also, environment temperature was above 10 °C for CM_H2, H3 and H4, with the exception of CM_H1. In our experiments the radiative heat showed similar results to the published research (Hoare, 2023), near the fire (1 m) temperature was higher, although some areas were warmer than others. For the experiments in Cova Manena, this could be associated with the air direction inside the cave. These aspects are variable in each cave and are associated with the air circulation (Fuente-Fernández, 2022; Kedar et al., 2024).

In terms of firewood conditions, H1 had the higher amount of decayed firewood, while H2, H3 and H4 had similar proportions of decayed and semi-decayed firewood (Fig. 1). However, there are no differences regarding temperatures between the fires H2 and H4, being the first the one that reached higher temperatures (Fig. 3). Temperature of H1 fire was not properly registered, and therefore we unfortunately are not able to compare it with the others. H3 experiment was a brazier from embers lighted in H2, as a way to start testing the productions of brazier in caves for warming during night activities or sleeping. This type of hearth has been suggested, for example, in the Middle Paleolithic occupations in Abric Romaní (Vallverdú et al., 2010).

The smoke emissions of CM hearths showed some differences between H1, H2 and H4 total amount of particles (Fig. 6). During the first hour, both H1 and H2 had between 60,000 and 80,000 μg/m^3; in the case of H1 a peak was observed by the end of the experiment. This was probably due to a single branch that was struggling to stay lit and therefore produced more smoke (Fig. 9). It is interesting to consider that it would have been possible that, for this to happen in the past, people would have taken actions like adding more wood so it may burn

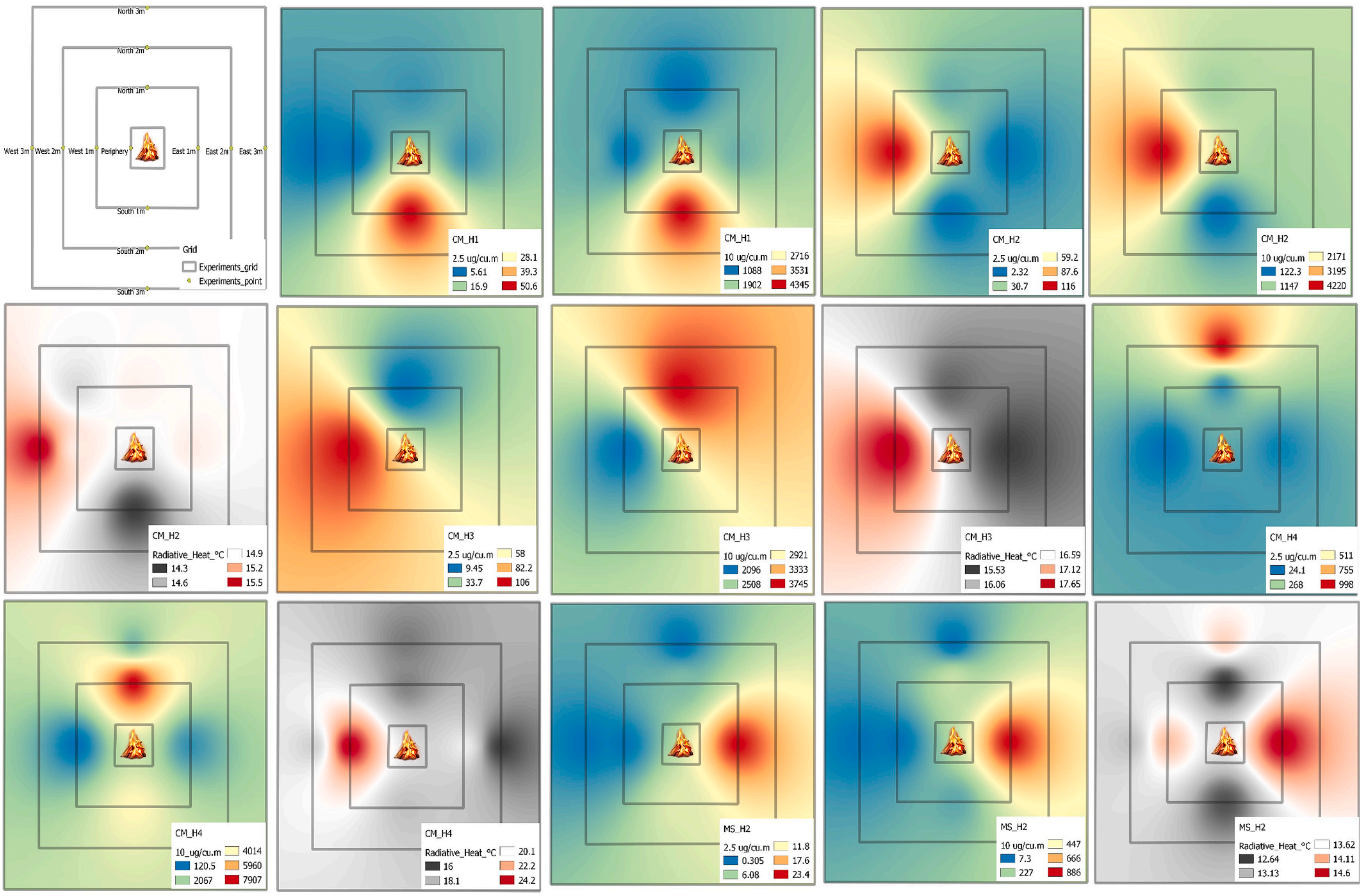

Fig. 7. Radiative heat and concentration of particles in Cova Manena and CAREX experiments. The colour varied according to each hearth.

completely or taking the fire outside so it did not produce more smoke. The study of the wooden imprints from Abric Romaní layer M has shown that spatial patterns of not completely burned wood remains, might suggest this kind of situation (Solé et al., 2013). In H2, the peak of particles above 100,000 $\mu g/m^3$ was observed with the refuelling, which would probably mean that in some cases this activity could produce more smoke than intended. Smoke concentrations were, as radiative heat, concentrated in one of the directions, generally East or South, more frequently than others.

However, H4 produced more smoke than the other cases, even having 10 kg of firewood and similar environmental conditions. Future studies about their remains would possibly indicate with more detail the type of decayed firewood, since macroscopically this was similar in proportions to H2. Moreover, H3 was a brazier and its smoke production was higher (above 150,000 $\mu g/m^3$). Although it is important to consider the influence of H2 which was burning at the same time and had already filled the cave with smoke. The importance of dimensions of caves and shelters and location of hearth has been shown as significantly important regarding airflow for Palaeolithic sites (Kedar et al., 2020; Lacanette et al., 2017). Our experiments have yielded more precise results concerning the impact of environmental conditions and wind direction on smoke from fuel emissions and its impacts on the habitability of the caves.

Firewood gathering of *P. sylvestris* was made during the days before the experiments. A random strategy was applied for collecting dead branches from different trees according to their availability. In some cases wood was gathered from the floor if they were dry enough. In most cases, preference was for branches that were cut and collected by hand and not with electric saw. Sizes (length and diameter) were measured to assure a random selection between 2 and 10 cm of diameter and to avoid large logs that will last longer in the fire.

Different states of the wood were described (Fig. 1). Although a large proportion of dry branches were gathered, especially for PV experiments, generally all experiments had semi-decayed or decayed branches. This would have affected fire temperature and smoke emissions. For example, CAREX_H6 had the majority of semi-decayed firewood and showed low temperatures (under 400 °C) during the first part of the experiment. MS_H2 experiment had a more balanced distribution of dry, semi-decayed and decayed wood and temperatures were higher at the beginning (over 700 °C), kept nearly 600 °C during the first hour and the temperature curve was slowly falling during the rest of the experiment. On the other hand, PV_H2 experiments had more dry wood and also higher temperatures (peaks over 900). Although wind speed was about 6 km/h and this therefore affected the combustion of the wood.

Archaeological research on charcoal shows a great variety among the different states of the wood that was burned for the Iberian Peninsula (Vidal-Matutano, 2017, 2018; Uzquiano et al., 2018, Allué et al., 2018; Allué & Mas, 2020). Therefore, an interpretation about the state of the firewood gatherers during the palaeolithic needs to consider the possibility that a random strategy with dry/semi-decayed and often decayed wood was chosen. With this in mind, our experiment provides more information about the different behaviours of the *P. sylvestris* type of firewood considering not only their state, but also the environmental conditions which would have influenced the burning. In addition, we have now some results to shred light into the dwelling activities and health scenarios when making this type of fires.

We cannot dismiss the possibility of other strategies or actions adopted during the combustion such as standing far away in the fire, or using some parapet structures to cover the wind. Also, small fires were generally for small groups, in cases when the number of people increased, the question remains in the case fires were bigger or people

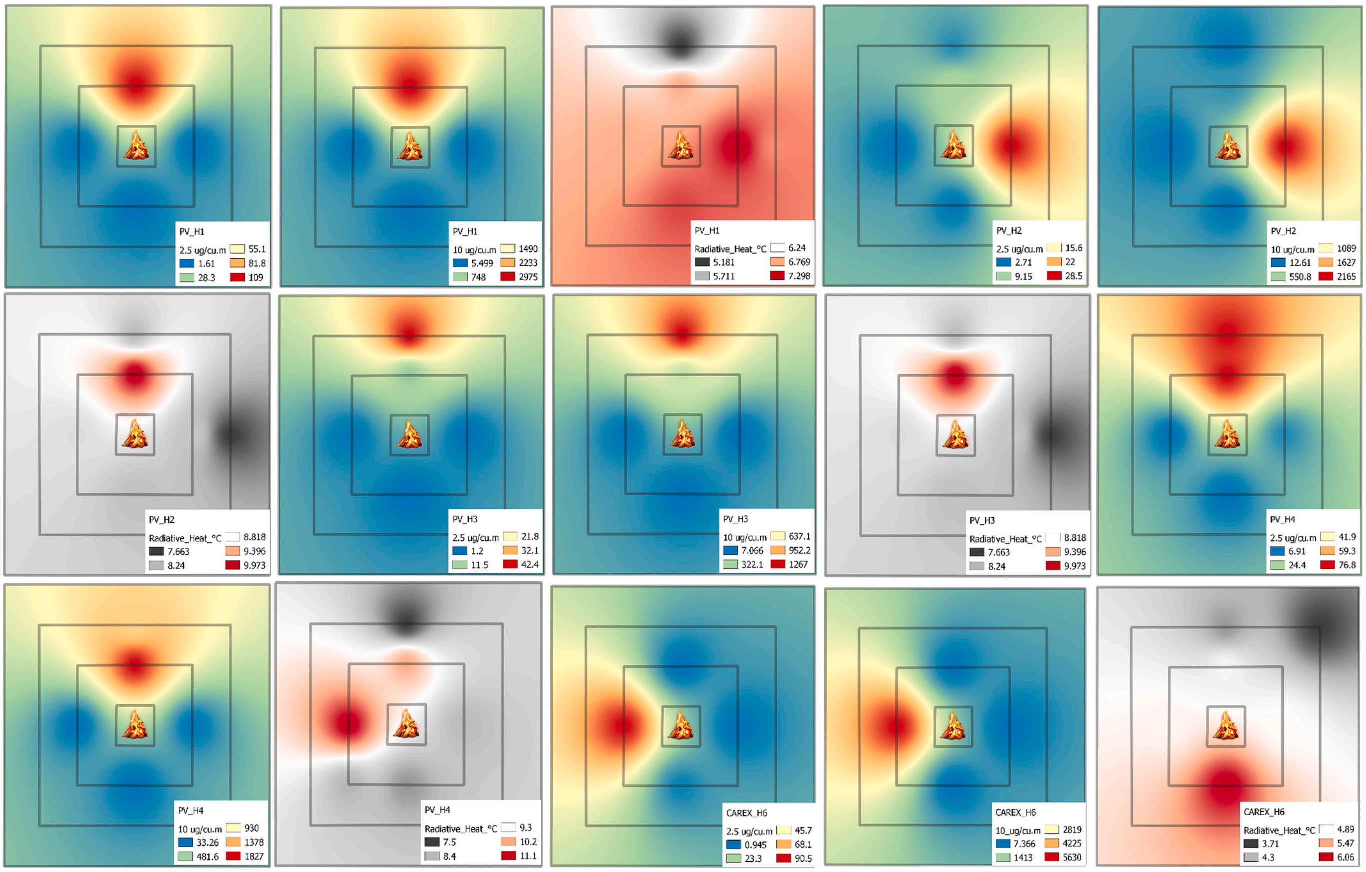

Fig. 8. Radiative heat and concentration of particles in Paleolítivo Vivo and Molí del Salt experiments. The colour varied according to each hearth.

were using other areas in response to smoke emissions.

We also have more results about people interacting within the warmth of a fire. Hoare (2020, 2023) experiments gave us a start about how people in the past were staying warm at different distances of the hearth. In this case, we also provide information when wind is affecting the flames and considering the smoke emissions while getting warm. Warmth would have been essential during winter occupations, especially in open air fires. Although it is difficult to think of lighting a fire with bad weather like rain or high speed wind, the experiments started to give us an idea of what it would be like, and what the possibilities of breathing healthy and staying warm were at the same time during these scenarios.

Hearth temperature was different in all the experiments and this was as expected considering that environment conditions and firewood state were not standardised for all cases. However, by observing the meteorological variables such as temperature, wind and rain, we now have more information about fire behaviour during these conditions and also about the habitability of the places where people lived. In the future, analysis on charcoal remains will provide information on their thermal alteration (Théry-Parisot, 2002; Allué et al., 2009; Théry-Parisot et al., 2010; Chrzavzez, 2013; Henry & Théry-Parisot, 2014; Allué & Mas, 2020, among others).

Particle counts gave us an approximation of dispersal of small particles around the hearth with refuelling activities and when environmental conditions were affecting. PM 2.5 and PM10 μg/cu.m are the most relevant to consider, while PM10 could affect the larger airways of the upper region of the lungs, PM 2.5 would travel and deposit on the deeper parts of this organ (Mannucci et al., 2015; Zelikoff et al., 2002; Feng et al., 2016).

Concentrations in the enclosed experiments of Cova Manena were varying according to firewood conditions and refuelling moments. One particular moment happened with CM_H2 peak of particles at the hour of the experiment because embers were taken away to set up brazier CM_H3. At that moment, with the remaining embers we put firewood again in order to get the fire lit. It is interesting to mention the difference between the two moments when small particle counts were over 50,000 μg/cu.m and after the refuel when it reached over 25,0000 μg/cu.m. This sets the question about refuelling strategies for fires that are extinguishing and people in the past wanted to re-light them.

On another hand, open air experiments such as PV showed that wind direction and speed affects participle dispersal. In PV_H4 while the East, West and South area of the hearth had values below 40,000 μg/cu.m, the north area of the hearth had particle counts over 100,000 μg/cu.m during all the experiment, even at 2 m. That means that not only some areas of the hearth were healthier, but also in those environmental conditions, smoke inhalation would have been harmful even at greater distances of the fire. However, considering the other experiments in open air, wind direction has been changing or there was no wind at all and small particles concentration peaks were varying in different directions over the experiments. This also gave a greater variability in smoke inhalation where the "safe zones" were also changing in time.

5. Conclusions

We have made experimental fires in open air and one cave scenario (Cova Manena) in order to measure hearth temperature, heat radiation and smoke emissions. We made 9 fire experiments (10 kg of firewood) that lasted around 2 h each with the purpose of exploring specific small fires production related to short time occupations of a site. We also made these fires during autumn and winter in order to consider short-time occupations with unstable climatic conditions. Our experiments focussed on the type and conditions of the firewood gathered, with the intent of replicating randomised and generic gathering scenarios regarding fuel management and firewood selection of past societies.

Fig. 9. Hearths experiments previous, during and post combustions pictures: A-B-C are CAREX-H6 experiments; D is Cova Manena; E-F belongs to CM-H1; H-I to CM-H2; J belongs to CM-H3; lastly K belongs to CM-H4.

With our result we can demonstrate that:

- The range between PM0.2 and PM10 concentrations were shown to be dependent on the state of the firewood of *P. sylvestris*. Considering World Health Organization guidelines for daily exposure levels to be safe at 20 μg m − 3 in a 24 h period, and the results obtained by previously published work (Shillito et al., 2021; Hoare et al.,2023; Kedar and Barkai 2019), levels in our experiments were higher in some cases. This was particularly evident since smoke emissions concentration were over areas around the hearth that were affected by the environmental conditions (e.g. wind).
- When thinking about warm and smoke regarding firewood of *P. sylvestris*, we have shown that there is an influence by the time of using wood with different states (dry, semi-decayed and decayed) in the fire. This is related to anthracological studies on charcoal where there is a great variety among the different states of the wood that were used in fire events in the past for the Palaeolithic occupation in Iberian Peninsula (Théry-Parisot, 2002; Allué et al., 2009; Théry-Parisot et al., 2010; Chrzavzez, 2013; Henry & Théry-Parisot, 2014; Allué & Mas, 2020).
- By controlling the smoke emission and heat dispersal variables in the open air experiments, we showed how wind direction and speed affects combustion directly and therefore the importance of studying these dwelling scenarios in past societies contexts.
- A new question for future experiments arose regarding the interpretation of dimensions of the thermoaltered surfaces after the fire events took place. Wind direction and speed proved to affect the development of the fire by changing the structure of the hearth (e.g. PV_H1, H2, H3 and H4). It becomes necessary to consider these processes by the time of interpreting experimental and past fire events.
- The experiments in Cova Manena showed how fires with *P. sylvestris* can vary according to the state of firewood (semi-decayed and decayed) on temperature and smoke emissions. Cave dimensions and air circulation affects smoke emissions and temperature radiation in each particular case. Experiments and simulations with FDS were

Fig. 10. Hearths experiments previous, during and post combustion pictures: A-B-C belongs to MS-H2; D-E-F to PV-H1; G-H-I belongs to PV-H2; J-K-L to PV-H3; finally M–N–O belongs to PV-H4.

made exploring these aspects for palaeolithic studies (Hoare, 2023; Kedar et al., 2022; Shillito et al., 2021, among others). However, it is still necessary to apply these frame of methodologies in future research that questions about human use of fire considering the anthracological information at the time.

– Taking into account hearth temperature, refuelling maintained the range of temperatures and did not produce specific variations in smoke emissions. With the exception of CM_H2 refuelling after taking half the embers to make CM_H3. The fall of the temperature started to occurred after the last refuelling.

Fire experiments have proved to be an essential tool to explore dwelling scenarios, human activities and processes that occurred during the use of fire, and afterward, their remains. Exploring how people interacted with the flames and the health consequences of their use, is a field that needs more research. Although relevant works have been done about smoke emissions, fire by products and dwelling scenarios for people in the past, it is still necessary to keep applying this methodology in questions attached to specific research questions. In our case, we started by exploring the *Pinus sylvestris* type of firewood used in fires considering Palaeolithic occupations in the Iberian Peninsula.

CRediT authorship contribution statement

A. Robledo: Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Data curation, Conceptualization. **A. Burguet-Coca:** Writing – review & editing, Methodology, Investigation, Data curation. **M. Berihuete-Azorín:** Writing – review & editing, Investigation. **S. Bianco:** Writing – review & editing, Investigation. **J. Pallarès:** Writing – review & editing, Investigation. **S. Cito:** Writing – review & editing, Investigation. **B. Garay-Palacios:** Writing – review & editing, Investigation. **E. Allué:** Writing – review & editing, Methodology, Investigation, Conceptualization.

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Data availability

Data will be made available on request.

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