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There's no smoke without fire: A deep time perspective on the effects of fires on air quality, human health and habitability in the Palaeolithic and prehistory

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ABSTRACT

The use and control of fire is arguably one of the most important technological advancements of the *Homo* genus. Prehistoric populations exploit the combustion properties of fires (light, heat and smoke) for daily tasks such as food preparation, insect repellent, extension of daylight hours and modification of technology. The habitual use of fire can however lead to significant health implications through sustained exposure to smoke which can affect air quality resulting in respiratory complications. While smoke is often an important tool in hunter-gatherer activities such as smoking meats, curing hides, accessing highly prized food items' such as honey and as an insect repellent, to date, little research has been conducted on the actual levels of exposure to harmful toxins contained in smoke that Palaeolithic hunter-gatherers would have been exposed to during their daily lives. In this paper, we present a new methodological protocol for future studies wishing to examine the effects of smoke from open fires on air quality, human health and habitability in the Palaeolithic using environmental monitoring systems. We present the first systematic study of concentration levels of harmful particulate matter (PM2.5) in smoke relative to the use of other combustion properties of fires (light, smoke and radiative heat) from a wide range of fuels used in Palaeolithic fireplaces, recording different types of fires (smoking, glowing and flaming) and activity types (smoking food items, sleeping and cooking). Our empirical findings highlight significant variability in light and heat output, as well as concentrations of harmful particulate matter in smoke (PM2.5). We argue that this variation and the aim to minimise exposure to the harmful elements of smoke, likely influenced the placement of fixed fire features in habitation spaces whether open, semi-open and closed (outdoors, rock shelters, caves, huts and houses) relative to the use of combustion properties. Our results also show how human-environment interactions around fire, fuel and habitability (air quality) may have changed over time in some living structures from the Palaeolithic through to later time periods (Neolithic and Iron Age).

1. Introduction

The use and control of fire represents a major milestone in our evolution, providing many benefits such as light and heat as well as smoke to preserve food and repel insects (Bentsen, 2014; Brown et al., 2009; Gowlett, 2006; Hoare, 2019; Roebroeks and Villa, 2011; Wrangham and Carmody, 2010). Whilst the many benefits of fire are often cited and at the forefront of Palaeolithic fire research, there are also negative implications to the use of fire such as those on human health and well-being (Henry, 2017; Kedar and Barkai, 2019). Smoke from the use of open fires in internal spaces with limited air circulation (e.g., living structures, caves and rockshelters) represents a major problem in terms of its negative impact on human health (Hardy et al., 2012, 2016; Shillito et al., 2022; Kedar and Barkai, 2019). Smoke is an irritant and can cause serious health issues ranging from eye irritation to more serious lung and respiratory problems (Smith et al., 2000). Smoke produced from wood burning in open fires comprises 200 chemical materials some of which are carcinogenic and noxious (Mannucci et al., 2015; Kedar and Barkai, 2019). The impact on human health of exposure to smoke can be severe over time depending on levels of exposure, especially to the more dangerous particles that can enter the lungs and bloodstream. The inhalation of these particles depends on the size particles above 10 µm remain in the nose and upper respiratory tract and those less than 2.5 µm enter the lungs and blood stream (Kedar and Barkai, 2019). Given the smaller population sizes in the Palaeolithic, relative to later time periods, chronic illnesses relating to smoke inhala-

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tion could have proven disastrous in terms of survival (Hardy et al., 2012; 2016). Direct evidence of smoke inhalation from campfires in caves in the Palaeolithic comes from the chemical signals in teeth and human dental calculus at both Qesem Cave, Israel and El Sidron Cave, Spain dated to 400,000 and 49,000 thousand years ago respectively (Hardy et al., 2012; 2016). Whilst smoke can often be an unintentional by product of fire in inhabited spaces, its management from fuel emissions may have been an essential consideration with regards to human health and wellbeing for Palaeolithic populations, especially with regards to its immediate effects to the lungs and eye irritation (Fig. 1).

1.1. Previous research smoke, fire and human health

Although there is a high likelihood that open fire using populations of prehistoric hunter-gatherers may have been exposed to potentially dangerous levels of PM2.5 in smoke (i.e., fine, inhalable particulate matter less than 2.5 μm in size produced as a by-product of combustion) in confined habitation structures, only a very limited range of studies have addressed the implications of severe exposure to smoke in the context of Palaeolithic research (Kedar and Barkai, 2019; Kedar et al., 2022; Ferrier et al., 2014, 2017; Lancanette et al., 2017). Studies by Kedar and Barkai (2019) and Kedar et al. (2022) rely on simulated patterns of smoke dispersal in caves and rockshelters using indoor air circulation models. Research indicates that occupation areas were organised to minimise levels of smoke exposure in Lazaret cave and in rockshelters such as Abric Romani, relative to the remains of fireplaces, putting smoke exposure levels potentially in line with World Health Organisation (WHO) guidelines for safe levels (currently defined as 20–25 $\mu g/m^3$ per 24-hour period). However, these studies are currently limited in interpretive power due to empirical data deriving from open wood flaming fires which do not capture the potential effects of PM2.5 in smoke from the range of likely fuels used by Palaeolithic populations. Additionally, no study to date has addressed variability in smoke levels based on different types of fires (e.g., smouldering, flaming or smoking fires) or relative to the types of activities' such as fires for warmth, light, cooking and smoking. Although, Gentles and Smithson (1986) conducted an experiential study comparing smoke levels from flaming and glowing fires in an enclosed space. Furthermore, we lack an understanding of the behaviour of smoke relative to fireplace position in other structures such as huts which are also commonly used as living structures in the Palaeolithic and by contemporary hunter-gatherers (e.g., McCauley et al., 2020).

1.2. Fuel selectivity and hunter-gatherer tasks

The types of fuel preserved in Palaeolithic fireplaces have been shown to vary (e.g., different wood species, fresh bone, grasses and sedges, animal dung) (Théry-Parisot, 2002; Miller and Sievers, 2012; Yravedra and Uzquiano, 2013; Yravedra et al., 2016; Esteban et al., 2018; Braadbaart et al., 2020). Despite this variation, little research has so far been conducted on the combustion properties of these fuels outside of light and radiative heat and heating duration for wood and fresh bone (Hoare, 2020; Ferrier et al., 2017; Medina-Alcaide et al., 2021; Costamagno et al., 2005; Mentzer, 2009; Théry-Parisot and Costamagno, 2005; Théry-Parisot et al., 2005; Hoare, 2020; Henry and Théry-Parisot, 2014; Théry-Parisot et al., 2010). Ethnoarchaeological studies further demonstrate that hunter-gatherers utilise the different combustible properties of fire according to task, e.g., high (flaming) and low temperature (smouldering) fires (Mallol and Henry, 2017). Smouldering or glowing fires can be used at night for warmth, to preserve fire for the next day and also for some cooking activities where even heat distribution and a consistent temperature is important (Braadbaart et al., 2012). Rotten woods (wood that has been subject to fungal decay) are used to create flameless smoking fires to smoke meats, repel insects and to access high prized food items such as honey. Flaming fires are used for light and warmth as well as some cooking tasks, such as roasting and boiling, where high heat is necessary. Furthermore, ethnographic and historical accounts of fuel use, in addition to providing heat, often involve multiple cooking tasks being carried out in tandem, for example, cooking meats and plants using high heat, as well as roasting food items within embers of smouldering fires, and cooking in pits under fires (Akintan et al., 2018). Thus, it is not unusual to see in the archaeological record a range of fuel types, with different heating, lux, and smoke properties being used in mixtures (Delhon, 2018; Kabukcu et al., 2021).

We currently lack any data quantifying variation in the concentration of PM2.5 in smoke from the different types of fuels, fires and activities used in the Palaeolithic to explore the potential impact on air quality. Our project aims to fill this knowledge gap by investigating the potential impact of fuel choice on human health in inhabited spaces (open, semi-open and closed) and by further examining the use and exploitation of combustion properties of fires relative to fireplace location and activities.

2. Experimental design and methods

In this study we develop an innovative approach to examine health and wellbeing in inhabited spaces amongst Palaeolithic populations for whom fire use is central to their daily lives. We combine the methods of Hoare (2020) and Skov et al (2000) to examine potential levels of exposure to harmful PM2.5 in smoke by humans whilst using other combustion properties of fires (light, smoke and radiative heat) for necessary activities. We examine how levels of exposure to PM2.5 may vary according to the type of fuel, fire, activity and then by habitation setting, (open-air, semi-open or closed) by combining our data with previous studies (Kedar and Barkai, 2019; Kedar et al., 2022; Shillito et al., 2022; Skov et al., 2000; Ryhl-Svendsen et al., 2010).

The experiments took place at the University of Liverpool outdoor pyrotechnology facility the Experimental Archaeology Research and Teaching Hub (EARTH) in March 2020 and October 2021 inside a specially constructed 4 × 4 m shelter built for the project. The shelter was built using traditional materials hazel poles for the outer structure, willow to bind the poles and dried grasses to cover the shelter. Five tests comprising sixteen experiments were conducted in total and the fuels

Fig. 1. Images of the construction of the prehistoric shelter used for the experiments and experimental fireplace position.

used for each experiment are listed in Table 1. The fuel types used for the experiments were selected from those found to commonly occur at a range of European and African Lower, Middle and Upper Palaeolithic sites. Each individual experiment consisted of 5 kg of fuel in total. The fire was started using 2 kg of the fuel with a further 1 kg added every 15 mins for 45 mins. For the fresh bone fires, a further 1.5 kg of silver birch was used to ignite the bone, as the combustion temperature is much higher than that of wood, and bone fires cannot be started without at least a 15 % ratio of wood to begin the combustion process (Théry-Parisot et al., 2005). As wood burns faster than fresh bone as a fuel, its addition would not have had any effect on prolonging the duration of the fire but could have influenced the initial outgoing radiative heat and light as silver birch is known to have higher lux and radiative heat properties than fresh bone, (Hoare, 2020). Two different experiments were conducted using fresh bone as a fuel. The first involved the use of a selection of deer bones, including scapula, ribs, femur and vertebrae, without the epiphyses and the second, used only epiphyses from femurs. The moisture contents of the wood fuels were measured using a Valiant FIR421 moisture meter for each log. The total was then averaged by the number of logs used in each of the experiments. The experimental fires had a basal configuration of 50 cm in diameter. One k-type thermocouple was used to measure the temperature of the fires in relation to the duration of heating and was placed in the centre of the fire. A second was used to measure the temperature of the smoke column at a above the fire. The experiments were conducted using 50 cm diameter deposits. All lux, radiative heat and smoke PM2.5 concentration levels were examined in relation to the duration of flame and fire at distances of 10 and 100 cm from the fire from two fixed station points Air Quality Meter 1 (AQM1) and Air Quality Meter 2 (AQM2) (see Fig. 2.) The aim of these experiments was twofold. We wanted to measure, as close as possible, the maximum levels of PM2.5 in the smoke that humans could have been exposed to in the past from the different fuels, fires and activities, and not just at sitting distances from the fire. We set station AQM1 at 10 cm which was as close to the fire as possible, and AQM2 at 100 cm, which is the more realistic distance that people would have sat around a fire. Measurements were taken every 5 min (lux and radiative heat) and every minute (smoke PM2.5) at 55 cm height to represent someone sitting by the fire. Background measurements of lux, ambient temperature and PM2.5 levels were taken prior to the start of each experiment. Outgoing radiative heat was captured on two 15 × 15 cm pieces of black card which is known to absorb outgoing heat using an Omega OS758-Ls non-contact infrared thermometer (e.g., Hoare, 2020), and lux measurements were taken using an ISO-TECH ILM-01 handheld lux metre. The concentration of PM2.5 levels in the smoke for each experiment were measured using two air quality monitor stations, the TSI DustTrak 8533 DRX - Desktop Dust Monitor which measures particulate and aerosol contaminants, such as dust, smoke, fumes and mists. The TSI DustTrak simultaneously measures size-segregated mass fraction concentrations corresponding to PM1, PM2.5, PM10, Respirable and Total PM size fractions. With a concentration range of 0.001 to 150 mg/m^3 the DustTrak™ DRX 8533 is suitable for a number of dust and aerosol applications, including indoor air quality investigations and outdoor environmental monitoring.

Table 1
List of fuels and measurements taken for each of the experiments comprising Test 1 to Test 5. Measurements for air quality (PM2.5), light (Lux) and radiative heat (°C) were taken simultaneously for Test 1 to Test 4. For the rotten wood experiment in Test 4, only PM2.5 concentrations were measured. For the air quality measurements, an extra test (Test 5) was conducted outdoors using only animal dung and silver birch as fuels.

Test 1: Background measurements	Test 2: Combustion properties of single fuel flaming fires (N8)	Test 3: Combustion properties of mixed fuels (increase light to lower light fuels (N2)	Test 4: Glowing and smoking fires (smoking, sleeping and cooking fires) (N3)	Test 5: Combustion properties of outdoor single fuel flaming fires, PM2.5 only (N2)
Background PM2.5	Fresh bone, fresh bone epiphyses, animal dung, silver birch, oak, pine, grass, reed	Fresh bone and pine, pine and grass	Pine, oak and rotten wood	Animal dung, silver birch

The experiments took place inside a windproof shelter and outdoors. For the outdoor experiments, windspeed and ambient temperature were measured every 10 mins using a Kestrel 2000 anemometer to control for the effects of external variables. The same amount, deposit size and arrangement of fuel (pyramidal stacking) was used between the experiment types. The time taken to record the lux and radiative

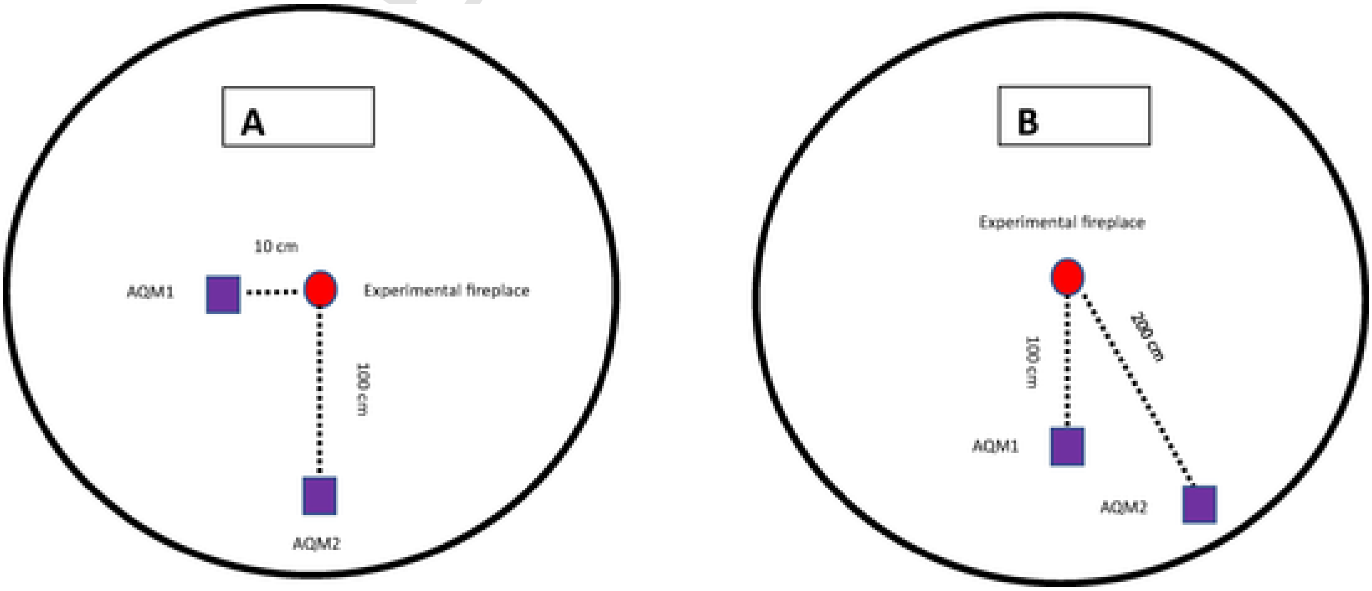

Fig. 2. a and b. Schematic diagrams showing the position of station points Air Quality Meter 1 (AQM1) and Air Quality Meter 2 (AQM2) in relation to the experimental fireplaces, which were positioned in **A,** directly under the smoke hole in the centre of the shelter (Test 1 to 4 and **B,** outdoors Test 5. The lux and radiative heat measurements were also taken from the same points as the AQM meters.

heat measurements from the two station points AQM1 and AQM2 was approximately 100 s. The same sequence of measurements was followed for each experiment, lux and radiative heat at 10 and 100 cm inside the shelter. For the outdoor experiments, AQM1 and AQM2 were positioned at 100 and 200 cm respectively and only PM2.5 measurements were taken. Fig. 2. shows the schematic diagrams for the layout of the indoor and outdoor experiments and Table 1 provides the detail for each experiment.

2.1. Combustion properties of fuel and fire and the thermal transfer of energy

The combustion of fuel from fires results in the production of heat, light and smoke. Radiant heat from fire is transferred to the surrounding environment through electromagnetic waves and can be emitted from both the flaming and glowing phases of a fire along with the embers (e.g., hot surfaces). The amount of radiant heat transferred into the environment is dependent on three factors, temperature of the fire, size and height of the flames and surface emissivity (Williams, 1982; Hoare, 2020). Flux of radiant heat is expressed by the formula $q = \varepsilon\sigma T4$, where ε is the flame emissivity, σ is the Stefan-Boltzmann constant (5.67×10^{-11} kW/m^2 K4), T is the flame radiation temperature (K) and E is the flame emissive power (kW/m^2). Heat is also transferred to the surrounding environment via convection or air currents.

Light is however only transferred through radiation which can take several forms, with only visible light being visible to the human eye. Other forms of light in the infrared range are not visible to the human eye. In terms of the combustible properties of fuels, wood density and the chemical composition, e.g., resinous woods or bone calcium, influence the luminosity properties (Hoare, 2020; Théry-Parisot and Thiebault, 2005). Medina-Alcaide et al (2021) review conditions influencing human perception of light in dark spaces which include physical aspects of the human visual system and light colour. They also record a colour threshold for human vision being a minimum of 3 lux.

Smoke emitted from fires comprises a combination of particulate matter and gasses. The production of the particulate matter phases, or soot, is the results of pyrolysis of burning materials, especially incomplete combustion. The larger diameter particles, e.g., >250 µm, tend to disperse quickly, whilst smaller particles, including those most damaging to human health <2.5 µm, remain in the air and smoke. The smoke column of any fire is hotter than the surrounding ambient temperature, therefore disperses upwards in a room or living structure and tends to disperse upwards more quickly in colder weather (Kedar and Barkai, 2019).

3. Results

The results of our experiments are summarised in Tables 2 to 4. and depicted as time series graphs in Figs. 3 to 6. The PM2.5 and lux measurements and radiative heat temperatures were calculated in terms of their average values for the course of the experiment and peak values. In each case, peak values were determined to occur between the point of the highest recorded two measurements and the point where the higher measurement began to drop substantially. Peak values are highlighted in yellow in the SI material.

3.1. Results PM2.5

3.1.1. Test 1: Background levels of PM2.5 inside the shelter

In Test 1 the background properties inside the shelter were recorded for a total of 60 min for both the air quality monitor stations. The values ranged from 6 to 14 µg/m^3 for AQM1 and from 8 to 15 µg/m^3 for

Table 2

Combustion and burning properties of fuel types plus pm2.5 µg/g concentration levels. It was not possible to measure the moisture content or lux and radiative heat for some fuels e.g., fresh bone and glowing oak and pine or rottenwood. The absence of these measurements is indicated in the respective column by a cross (x). The corresponding data for each of the experiments conducted in tests 1 to 5 are marked as T1 to T5 in the first column.

Fuel type	Species	Weight fuel Kg	Moisture content	Duration Fire (mins)	Duration Flame (mins)	PM2.5 AV 10 cm	PM2.5 Peak and duration 10 cm	PM2.5 AV 100 cm	PM2.5 Peak and duration 100 cm
Fresh bone (T2)	deer	5 + 1.5 Kg wood	x	130	100	24,220	86,727 6 mins	496	2407 13 mins
Fresh bone epiphyses (T2)	deer	5 + 1.5 Kg wood	x	140	115	21,935	83,477 7 mins	553	2751 17 mins
Animal dung (T2)	Cow	5	18	145	120	87,253	144,243 45 mins	2300	6382 10 mins
Hard wood (T2)	Silver Birch	5	21	95	70	9154	40,705 6 mins	13	27 3 mins
Hard wood (T2)	Oak	5	20	104	85	10,758	41,302 5 mins	14	41 3 mins
Hard wood (T3)	Oak glowing fire	5	x	101	x	409	2105 15 mins	17	55 16 mins
Soft wood (T2)	Pine	5	20	91	70	9327	39,034 8 mins	14	36 4 mins
Soft wood (T3)	Pine glowing fire	5	x	101	x	540	2911 15 mins	19	39 14 mins
Grass (T2)	Grass	5	Dry	65	35	19,537	60,807 4 mins	14	46 3 mins
Reeds (T2)		5	Dry	55	35	18,561	57,942 5 mins	16	51 4 mins
Mixed bone and wood (T4)	Deer and pine	5	18	131	110	29,271	78,942 7 mins	175	1440 7 mins
Mixed wood and grass (T4)	pine and grass	5	19	95	75	18,235	44,228 3 mins	22	176 3 mins
Rotten wood (T3)		5	20	69	x	21,649	43,964 10 mins	13,616	32,264 14 mins
						PM2.5 AV 100 cm	**PM2.5 Peak and duration 100 cm**	**PM2.5 AV 200 cm**	**PM2.5 Peak and duration 200 cm**
Outdoor (T5)	Animal dung	5	19	137	103	22	65 6 mins	9.8	x
Outdoor (T5)	Silver birch	5	20	98	76	9.8	25 6 mins	8.3	x

Table 3
Combustion and burning properties of fuel types plus light measurements (lux). It was not possible to measure the moisture content or lux and radiative heat for some fuels e.g., fresh bone and glowing oak and pine or rottenwood. The absence of these measurements is indicated in the respective column by a cross (x). The corresponding data for each of the experiments conducted in tests 1 to 5 are marked as T1 to T5 in the first column.

Fuel. type	Species	Weight fuel Kg	Moisture content	Duration Fire (mins)	Duration Flame (mins)	Lux Av 10 cm	Lux Peak and duration 10 cm	Lux Av 100 cm	Lux Peak and duration 100 cm
Fresh bone (T2)	deer	5 + 1.5 Kg wood	x	135	100	15.7	23.1 75 mins	11	16.9 75 mins
Fresh bone epiphyses (T2)	deer	5 + 1.5 Kg wood	x	140	115	24.6	33.9 85 mins	16.9	23.6 80 mins
Animal dung (T2)	Cow	5	18	145	120	9.8	13.7 45 mins	7.5	11.8 35 mins
Hard wood (T2)	Silver Birch	5	21	95	70	27.4	49.5 35 mins	21	40.8 35 mins
Hard wood (T2)	Oak	5	20	104	85	16	21.7 55 mins	10.4	15.5 45 mins
Hard wood (T3)	Oak glowing fire	5	x	101	x	4.4	x	1.5	x
Soft wood (T2)	Pine	5	20	104	85	26.1	42.2 30 mins	18.2	33.1 30 mins
Soft wood (T3)	Pine glowing fire	5	x	101	x	4.2	x	1	x
Grass (T2)	Grass	5	Dry	65	35	21.7	43.2 20 mins	16.2	33 20 mins
Reeds (T2)	Reeds	5	Dry	55	35	24.4	46.2 15 mins	17.1	34 15 mins
Mixed bone and wood (T4)	Deer and pine	5	18	131	110	27.5	37.9 75 mins	18.7	26 75 mins
Mixed wood and grass (T4)	Pine and grass	5	19	90	75	26.6	47 10 mins	19.5	39 10 mins

Table 4
Combustion and burning properties of fuel types plus radiative heat (RH) output (temperature °C). It was not possible to measure the moisture content or lux and radiative heat for some fuels e.g., fresh bone and glowing oak and pine or rottenwood. The absence of these measurements is indicated in the respective column by a cross (x). The corresponding data for each of the experiments conducted in tests 1 to 5 are marked as T1 to T5 in the first column.

Fuel type	Species	Weight fuel Kg	Moisture content	Duration Fire (mins)	Duration Flame (mins)	RH AV 10 cm	RH Peak and duration 10 cm	RH Av 100 cm	RH Peak and duration 100 cm
Fresh bone (T2)	deer	5 + 1.5 Kg wood	x	135	100	20.5	24.3 75 mins	17.3	20.2 75 mins
Fresh bone epiphyses (T2)	deer	5 + 1.5 Kg wood	x	140	115	21	24 0.8 75 mins	17.6	20.4 75 mins
Animal dung (T2)	Cow	5	18	145	120	17.1	18.5 85 mins	14	15 85 mins
Hard wood (T2)	Silver Birch	5	21	95	70	33.4	43.2 30 mins	26.2	35.5 30 mins
Hard wood (T2)	Oak	5	20	104	85	27.7	30.2 60 mins	23.2	25.8 60 mins
Hard wood (T3)	Oak glowing fire	5	x	101	x	19.5	x	x	x
Soft wood (T2)	Pine	5	20	104	85	27.8	32 45 mins	21.9	25.8 45 mins
Soft wood (T3)	Pine glowing fire	5	x	101	x	19.8	x	x	x
Grass (T2)	Grass	5	Dry	65	35	25.4	35.5 15 mins	20.2	26.6 10 mins
Reeds (T2)	Reeds	5	26	55	35	24.7	34 10 mins	20.2	25 15 mins
Mixed bone and wood (T4)	Deer and pine	5	18	131	110	22.6	26 80 mins	17.3	19 80 mins
Mixed wood and grass (T4)	Pine and grass	5	19	90	75	28.5	34 15 mins	22.5	27 15 mins

AQM2. The background levels were low throughout the test with no peaks or major changes recorded inside the shelter.

3.1.2. Test 2: PM2.5 levels from single fuel type flaming fires

The durations of each of these experiments varied according to the combustion properties of each fuel type (Hoare, 2020). The same amount of some fuels, such as fresh bone, fresh bone epiphyses and animal dung are known to burn for much longer than that of woods and grasses (Hoare, 2020; Théry-Parisot and Costamagno, 2005; Théry-Parisot et al., 2005), whilst individual species of wood such as oak are known to burn for longer than pine due to their density and cellular/chemical structure and composition (Hoare, 2020).

The PM2.5 levels for the different fuel types in this test and for both air quality monitors are listed in Table 2., and shown as time series data in Fig. 3.

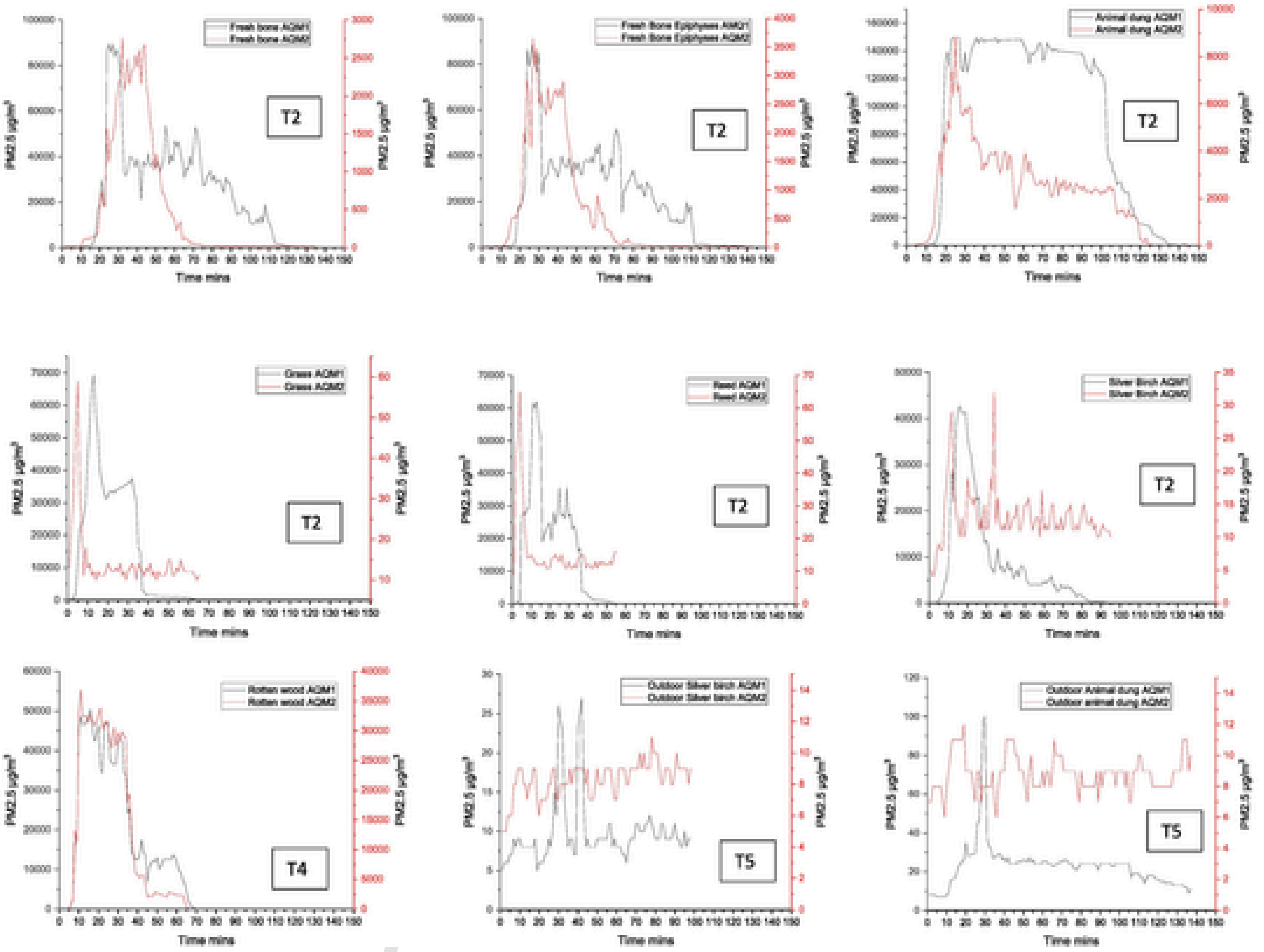

Fig. 3. Time series graphs showing concentration levels of pm 2.5 µg/g for the different types of fuels used in the experiments. The corresponding data in the graphs for each of the experiments conducted in tests 1 to 5 are marked as T1 to T5.

Average PM2.5 values for animal dung were 87,253 and 2300 µg/m³ for stations AQM1 and AQM2 over the course of the experiment, which was 145 min. Peak PM2.5 values for manure lasted for 45 and 10 mins with values of 144,243 and 6382 µg/m³ for AQM1 and AQM2 respectively.

The fresh bone experiment lasted for 130 min, and average PM2.5 levels were 24,220 and 496 µg/m³ for stations AQM1 and AQM2. Peak values lasted for 6 and 13 min and were 86,727 and 2407 µg/m³ for AQM1 and AQM2. The fresh bone epiphyses experiment lasted for 140 min, with average PM2.5 levels of 21,935 and 553 µg/m³ for AQM1 and AQM2. Peak PM2.5 levels lasted for 7 and 17 min and were 83,477 and 2751 µg/m³ respectively, for AQM1 and AQM2.

The silver birch fire lasted for 95 min, with average PM2.5 levels of 9154 and 13 µg/m³ for AQM1 and AQM2. Peak values for AQM1 and AQM2 were 40,705 and 27 µg/m³, which lasted for 6 and 3 min. The oak fire experiment lasted for 85 min, with average PM2.5 levels of 10,758 and 14 µg/m³ for AQM1 and AQM2. Peak PM2.5 levels lasted for 5 and 3 min, and were 41,302 and 41 µg/m³ for AQM1 and AQM2. The pine fire lasted for 91 min, with average values of 9327 and 14 µg/m³ for AQM1 and AQM2. Peak values lasted for 5 and 3 min and were 43,340 and 36 µg/m³ for AQM1 and AQM2.

The grass fire lasted for 65 min, with average PM2.5 values of 18,055 and 14 µg/m³ for AQM1 and AQM2. Peak values were 60,807 and 46 µg/m³ for AQM1 and AQM2 and lasted for 4 and 3 min respectively. The reed fire experiment lasted for 55 min, with average PM2.5 levels of 18,561 and 16 µg/m³ for AQM1 and AQM2. Peak PM2.5 levels were 57,942 and 51 µg/m³ for AQM1 and AQM2 lasting for 5 and 4 mins respectively.

3.1.3. *Test 3: PM2.5 levels from mixed fuel fires*

The mixed bone and wood fire lasted for 131 min, with average PM2.5 levels of 29,271 and 175 µg/m³ for AQM1 and AQM2. Peak values were 78,942 and 1440 µg/m³ for AQM1 and AQM2, lasting for 7 min. The mixed wood and grass fire experiment lasted for 95 min, with average PM2.5 levels of 18,235 and 22 µg/m³ for AQM1 and AQM2. Peak values of PM2.5 were 44,228 and 176 µg/m³, which lasted for 3 min each for AQM1 and AQM2.

3.1.4. *Test 4: PM2.5 levels from glowing fires and smoking fires*

The smoking fire experiment (rotten wood) lasted for 69 min and yielded average values of 21,649 and 13616 µg/m³ for AQM1 and AQM2. Peak values of PM2.5 for AQM1 and AQM2 were 43,964 and 32264 µg/m³ which lasted for 10 and 14 min respectively.

The glowing fire experiment (oak), including four refuelling episodes to maintain the fire, lasted for 101 min, with average values of 409 and 17 µg/m³ for PM2.5 levels for AQM1 and AQM2. Peak PM2.5 levels were obtained across the four refuelling episodes of 2105 and 55 µg/m³ for AQM1 and AQM2, which lasted for 14 and 16 min in total. The glowing pine fire lasted for 101 min, with average PM2.5 levels for AQM1 and AQM2 of 540 and 19 µg/m³. Peak values across the four

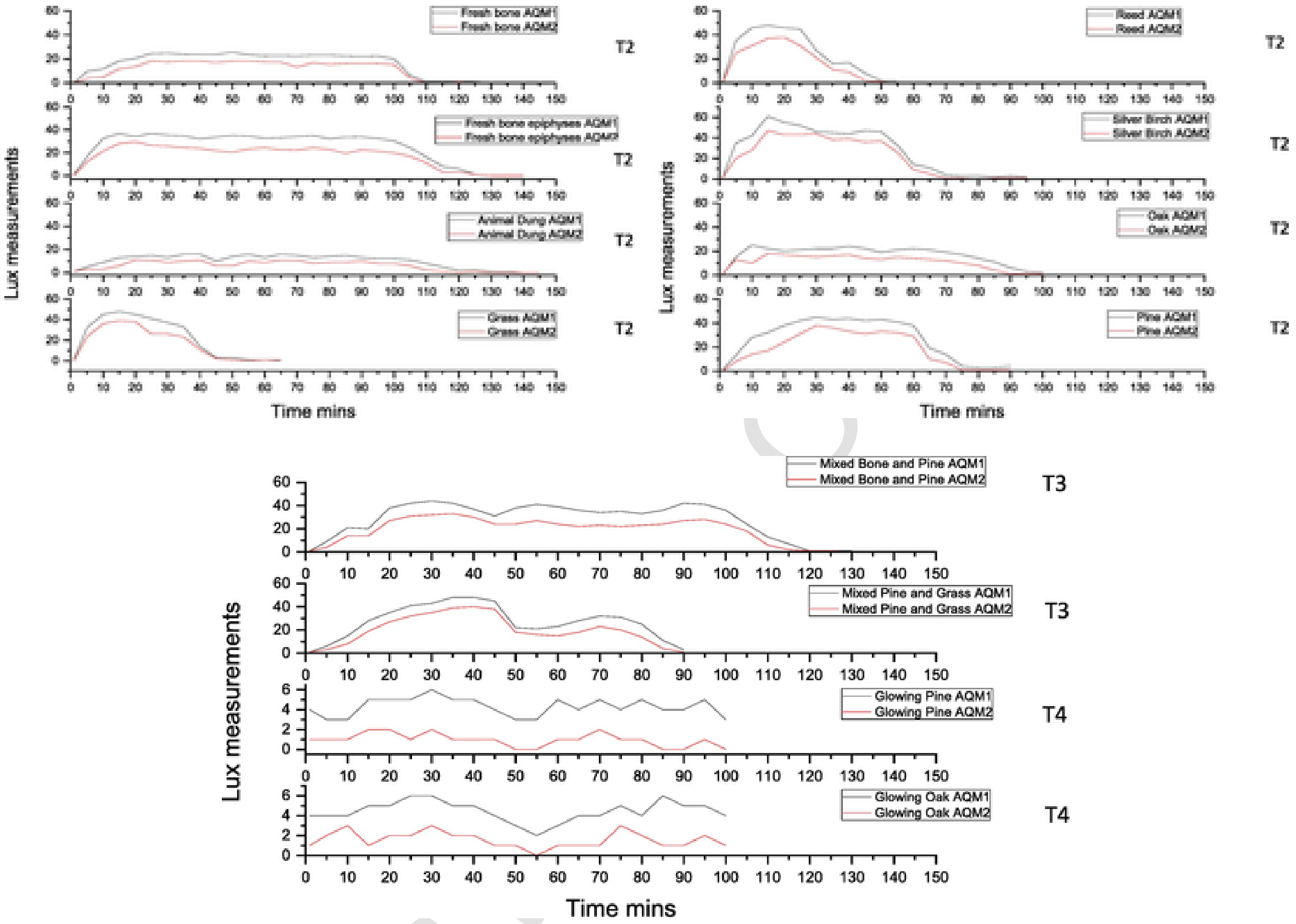

Fig. 4. Time series graphs showing light measurements (lux) for the different types of fuels used in the experiments. The corresponding data in the graphs for each of the experiments conducted in tests 1 to 5 are marked as T1 to T5.

refuelling episodes were 2911 and 39 μg/m³ for AQM1 and AQM2 and lasted for 15 and 14 min in total.

3.1.5. Test 5: Outdoor experiments PM2.5 animal dung and wood (cow and silver birch)

The concentration of PM2.5 was measured at station AQM2 which was situated at distances of 100 and 200 cm respectively, from the fire. The difference in the position of the stations from the other experiments was due to having already quantified the likely maximum PM2.5 for each fuel type. In this experiment we wanted to further examine the levels at greater distance from the fire.

The silver birch fire lasted for 98 min with average PM2.5 levels of 9.8 and 8.3 μg/m³ at stations AQM1 and AQM2. Levels of PM2.5 were only elevated above background levels at AQM1 for two periods of 3 min with levels of 25. The animal dung fire lasted for 137 min with average PM2.5 levels of 22.8 and 9.8 μg/m³ at AQM1 and AQM2 respectively. Peak values of 65 μg/m³ lasted for 6 min at AQM1 only.

3.2. Results light properties

Lux measurements were taken inside the shelter every 5 min for the duration of all the experiments. The doorway was covered over to ensure there was no interference from natural light on the lux measurements. The lux metre was taken at 55 cm metre height intervals to represent the height of someone sitting around the fire and from the same position as the AQM stations. The lux metre was pointed at a 45-degree angle toward the fire so there was no influence of natural light from the smoke hole at the top of the shelter. The lux levels for the different fuel types in this test and for both air quality monitor stations are listed in Table 3 and shown as time series data in Fig. 4.

3.2.1. Test 2: Lux values from single fuel type flaming fires

Lux values for the fresh bone experiments averaged 15.7 and 11 for stations AQM1 and AQM2 over the course of the experiment. Peak values lasted for 75 min and were 23.1 and 16.9 for AQM1 and AQM2. The fresh bone epiphyses experiment yielded average lux values of 24.6 and 16.9 for the duration of the experiment for the AQM1 and AQM2 stations, and peak values of 33.9 and 23.6 for 85 and 80 min respectively.

Lux values for the animal dung experiment were 10 and 7.5 for stations AQM1 and AQM2 over the course of the experiment, whilst peak values, which lasted for 45 mins, were 13.7 and 11.8 for AQM 1 and AQM2.

For the wood fire experiments (silver birch), average lux values were 27.4 and 21 for stations AQM1 and AQM2 over the course of the experiment, and peak values were 49.5 and 40.8 for the same stations respectively, lasting for 35 min. For the oak fire, lux values were 16 and 10.4 for the full experiment for AQM1 and AQM2, and peak values were 21.7 and 15.5 for the same positions which lasted for 55 and 45 mins respectively. For the pine fire experiment, lux values were 26.1 and 18.2 over the course of the experiment, whilst peak values, which lasted for 30 min, were 42.2 and 33.1 for AQM1 and AQM2 stations.

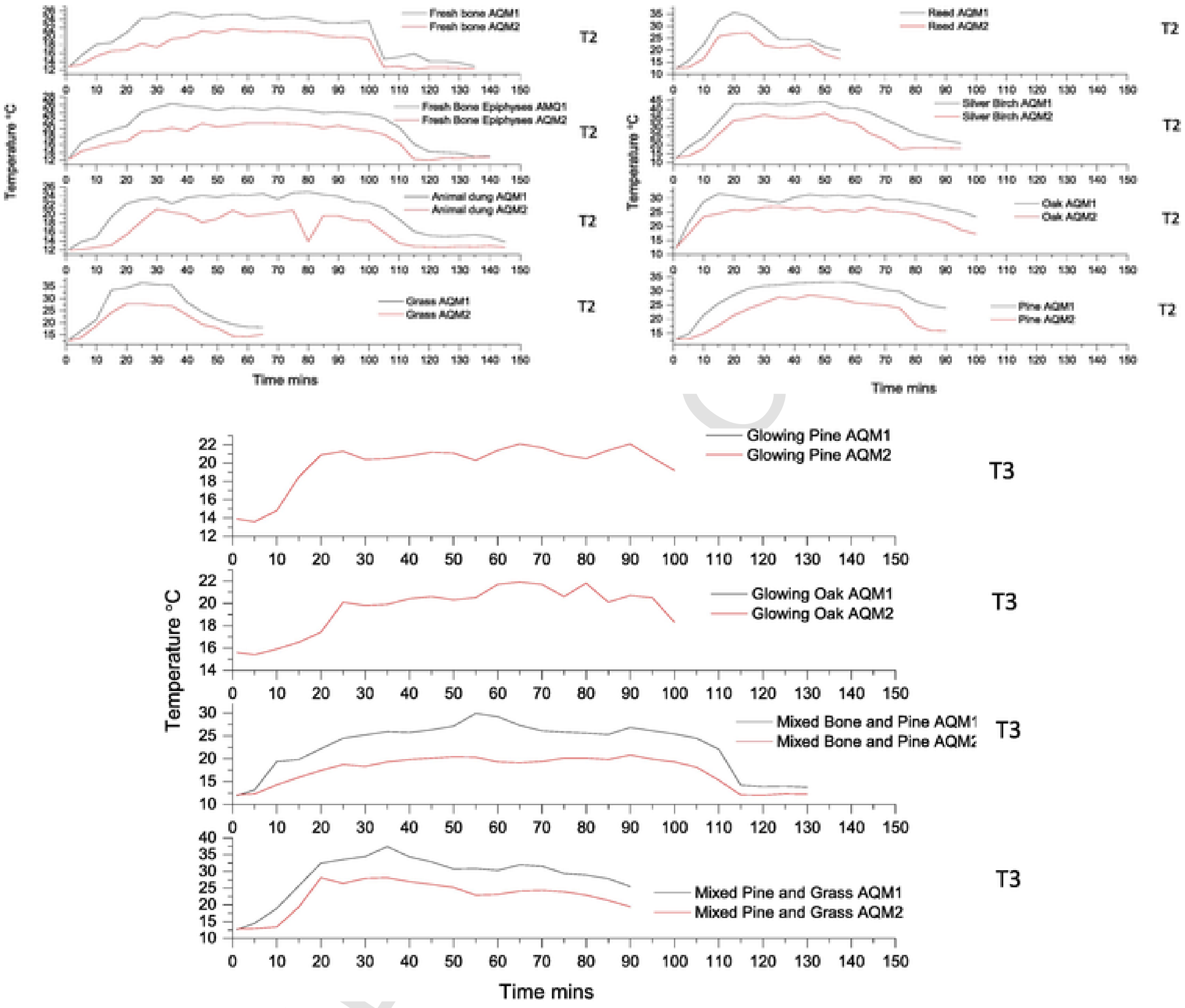

Fig. 5. Time series graphs showing radiative heat output in temperature (T °C) for the different types of fuels used in the experiments. The corresponding data in the graphs for each of the experiments conducted in tests 1 to 5 are marked as T1 to T5.

Average lux values for the grass fire experiment were 21.7 and 16.2, whilst peak values respectively lasting 20 mins were 43.2 and 33 for AQM1 and AQM2 stations. Lux values for the reed fire were 24.4 and 17.1 for the full experiment whilst peak values which lasted for 15 mins were 46.2 and 34 for the AQM1 and AQM2 stations.

3.2.2. *Test 3: Lux measurements from mixed fuel fires*

Average lux values for the mixed bone and pine fire were 27.5 and 18.7 for AQM1 and AQM2 stations for the duration of the experiment. Two refuelling episodes were conducted to examine how the lux properties may change with the addition of a fuel with higher lux values relative to the other fuels (pine versus fresh bone) average peak values of 37.9 and 26 were recorded across both refuelling episodes, which lasted for 75 mins.

Average lux values for the mixed wood and grass fire were 26.6 and 19.5 for the duration of the experiment. Grass was added to the fire which increased peak values to 47 and 39 for AQM1 and AQM2 for 10 min during one refuelling episode.

3.2.3. *Test 4: Lux measurements from glowing fires*

Average lux values for the duration of the glowing oak fire for AQM1 and AQM2 for the duration of 4.4 and 1, respectively. For the glowing pine fire, the lux measurements were 4.2 and 1 for AQM1 and AQM2 respectively.

3.3. *Results radiative heat*

Radiative heat was measured in degrees Celsius for the different fuel types in and for both air quality monitor stations. The types of fuels and data are listed in Table 4 and are further shown as time series data in Fig. 5.

3.3.1. *Test 2: Radiative heat values from single fuel type flaming fires*

Average radiative heat temperature for the fresh bone fire experiment were 20.5 °C and 17.3 °C for the full experiment for AQM1 and AQM2, respectively. Peak values lasted for 75 min and were 24.3 and 20.2 °C for AQM1 and AQM2. For the fresh bone epiphyses fire, the average radiative heat temperatures were 21 and 17.6 °C for the full ex-

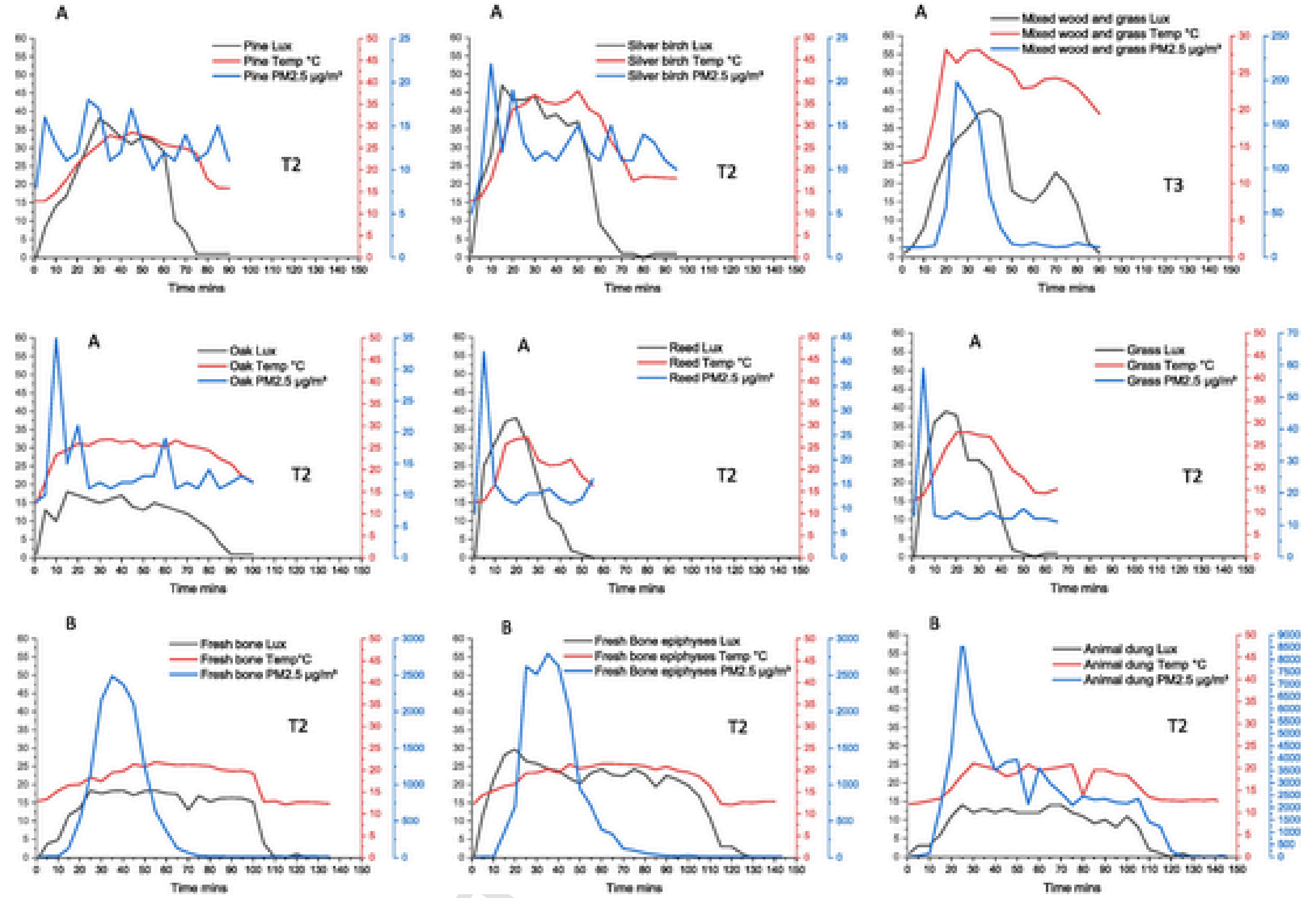

Fig. 6. Time series graphs showing the combined light (lux) radiative heat output (temperature ˚C) and concentration of PM2.5 (µg/m³) of the different experimental fuels with: A. the lowest PM2.5 emission and highest light and heat properties and B. the highest PM2.5 emissions and lowest light and heat properties. The corresponding data in the graphs for each of the experiments conducted in tests 1 to 5 are marked as T1 to T5.

periment, with peak values lasting 75 mins of 24.8 and 20.4 ˚C for AQM1 and AQM2.

Average radiative heat temperature for the duration of the animal dung fire experiments were 17.1 and 14 ˚C whilst peak temperature lasted for 85 mins and were 18.5 and 15 ˚C for AQM1 and AQM2.

For the wood fuel fire (silver birch), average radiative heat temperatures were 33.4 and 26.2 ˚C for the full experiment whilst peak values lasting 30 mins were 43.2 and 35.5 ˚C for stations AQM1 and AQM2. The oak fire yielded average radiative heat temperatures of 27.7 and 23.2 ˚C for the full experiment, and peak temperatures of 30.2 and 25.8 ˚C lasting 60 mins for stations AQM1 and AQM2. The pine fire yielded average radiative heat temperatures of 27.8 and 21.9 ˚C for the full experiment, and peak temperatures of 32 and 2.85 ˚C for a period of 45 mins for AQM1 and AQM2, respectively.

Average radiative heat temperatures for the grass fire were 25.4 and 20.2 ˚C for the full experiment, whilst peak values lasting for 15 min were 35.5 and 27.4 ˚C for AQM1 and AQM2. For the reed fire, average radiative heat temperatures for the full experiment were 24.7 and 20.2 ˚C whilst peak values were 34 and 26.6 ˚C lasting for 10 min each for AQM1 and AQM2 stations.

3.3.2. Test 3: Radiative heat values from mixed fuel fires

Average radiative heat temperatures for the mixed fuel fresh bone and pine fire were 22.6 and 17.3 ˚C for AQM1 and AQM2. Temperatures were increased to 26 and 19 ˚C with the addition of extra pine across two refuelling episodes totalling 80 mins. The mixed pine and grass fire yielded average radiative heat temperatures of 28.5 and 22.5 ˚C for AQM1 and AQM2 for the full experiment. Peak temperatures occurred with the addition of grass, of 34 and 27 ˚C for 15 mins for AQM1 and AQM2.

3.3.3. Test 4: Radiative heat values from glowing fires

Radiative heat temperatures were taken at 10 cm distance from the glowing fires and averaged 19.5 and 19.8 ˚C for both the Oak and Pine fires for the duration of both experiments for 101 min. No increase above ambient temperature was recorded at 100 cm.

3.4. Results summary

In terms of both peak and average PM2.5 emissions, the fuels are ranked in order from highest to lowest with, animal dung > fresh bone & fresh bone epiphyses > fresh bone and wood > grass, reed and wood and grass > wood fuels. There were no observable differences between the individual wood species. With regards to smoking fires, using rotten wood fuel, peak emissions were similar to those of flaming wood fires, however, average values more than doubled in relation to duration of heating. Glowing fires yielded the lowest PM2.5 values of all fuels in terms of average and peak emissions.

At station AQM2, which was 100 cm distance from the fire, the PM2.5 concentration levels were substantially lower than at AQM1. In terms of both peak and average PM2.5 emissions, the fuels are ranked in order from highest to lowest, with rotten wood > animal dung > fresh bone and fresh bone epiphyses > wood fuels, grasses and reeds. Woody fuels and grasses yielded average values for the duration of the experiments barely above the background levels.

The lux properties of the different types of fuels from flaming fires can be classified as either high (34–41) or low (15–23) based on peak measurements at 100 cm distance from the fire. In relation to duration of heating, animal dung, fresh bone and oak yielded low light values for the longest duration. The fuels emitting high light properties for the longest duration were the wood fuels (pine and silver birch) and fresh bone epiphyses, whilst grasses and reeds yielded high lux values for short periods. Adding fuels (grass and pine) with higher lux properties to fuels (fresh bone and oak) with lower lux properties increases the lux values. Glowing fires using wood fuels emit very low lux properties (average 5 lux) at 10 cm from the fire and 0 to 1 lux at 100 cm.

The radiative heat properties of the fuels can also be classified as either high (25–35.5 °C) or low (15–20.4 °C) based on peak measurements at 100 cm distance from the fires. In relation to duration of heating, animal dung, fresh bone and fresh bone epiphyses yielded the lowest temperatures for the longest durations. The highest temperatures emitted for a short duration were from grass and reed fuels. The highest temperatures emitted for the longest durations were from the woody fuels, with silver birch > mixed grass and wood > pine > oak > mixed bone and wood.

4. The use of fuels in closed and semi-open dwellings

Our results show that the combustion properties measured in the experimental fires (heat, light and PM2.5 concentration in smoke) vary between the types of fuels, fires, smouldering and flaming, and activities (e.g., sleeping or smoking). This variation may well have influenced fuel selection criteria for specific burning properties for specific tasks along with determining the position of fireplaces relative to smoke output and air quality in habitation spaces. Combined with the previous study of Hoare (2020), our results provide data which can be used to further examine how hunter-gatherer communities exploited the various combustion properties fires in terms of maximising the by products, such as heat, light and smoke, at optimal distances from fires whilst minimising exposure to smoke. Fig. 6 shows the combined light, heat and PM2.5 data for the different fuels used in the experiments.

As the concentration of the more dangerous particles in the smoke (PM2.5) varies significantly between the fuels used in our experiments, e.g., animal dung versus wood, this makes some fuels less hazardous to human health when used inside closed or semi-open dwellings. The core temperature of some of these fires also varies. For example, the smoke from some fuels, such as wood and grasses, will disperse upwards relative to air currents or smoke holes more efficiently than other fuels, such as animal dung, rotten wood and fresh bone, because they burn with a higher core temperature and heat (e.g., 705–830 °C versus 420, 307 and 555 °C, respectively). Glowing ember fires emit little or no smoke. However, when smoke is produced, the temperature is very low compared to flaming woody fuel fires, so would not disperse as efficiently relative to the air circulation. Medina-Alcaide et al. (2021) state that lux values need to be 3 lx or greater in darker spaces to provide useable light for the human visual system. However, glowing fires only emit useable light and heat, e.g., lux measurements >3, at around 10 cm from the fire. These fires could only be used to provide light in dark spaces for activities that require direct or no contact with the fire, e.g., cooking in embers and sleeping fires for warmth of preservation of embers. The combined heat, light and smoke properties of the different fuels used in the experiments and shown in Fig. 6, show that woody fuels appear to be the most efficient in internal spaces. This is because they emit high heat and light at distance from the fire (especially the resinous woods) have a high core temperature of the fire, aiding in smoke dispersal, and the lowest concentration of PM2.5 relative to other fuels examined. This allows the maximisation of the fires by products, light and heat, at optimal distances from the fire so as to avoid smoke. However, whilst smoke can be detrimental to human health in most internal spaces, it is also a valuable tool for hunter-gatherers used for food preservation, hide working and as an insect repellent. Rotten woods are commonly used to create smoking fires by contemporary hunter-gatherers and Palaeolithic populations. However, smoking fires, using rotten wood fuels, would need to be positioned away from any living area in internal spaces due the amount of smoke produced, concentration of PM2.5 in the smoke and low core temperature of the fire. It is important to note here that there are no good or bad fuels. All types of fuels and fires, other than the smoking or rotten wood fire, produce light, heat and smoke of varying levels, which can be exploited for different tasks in different ways (Hoare, 2020). For example, whilst the use of animal dung may be detrimental to human health indoors with inadequate ventilation, if used outdoors, it can provide a much longer duration of heating than other fuels such as wood and grasses. A previous experimental fire study by Gowlett et al. (2017) points to the availability of smouldering patches of animal dung, as an in situ or easily transported resource on the landscape after natural fires for early humans, which could point to the use of burning animal dung as one of the earliest sources of fuel along with wood.

4.1. *Effects of dwelling structures and ventilation on smoke dispersal and air quality*

We now consider how reductions in air quality from smoke and mitigation of the risk of prolonged exposure may vary according to dwelling structure and ventilation. We consider our data alongside the previously published work of Kedar and Barkai (2019); Kedar et al (2022); Shillito et al. (2022); Skov et al (2000) and Ryhl-Svendsen et al. (2010) in three different habitation scenarios, 1. open air. 2. Semi-open, e.g., rock shelters. 3. closed e.g., deep caves, huts and houses. To further our understanding of human-environment interactions around fire and fuel over time we also consider differences between Palaeolithic hunter-gatherers and their relationship with fire and fuel in internal spaces relative to more sedentary populations in the Neolithic and Iron Age. We compare all results in terms of likely levels of exposure to WHO (World Health Organisation) guidelines for daily levels determined to be safe. European standards and WHO guidelines for daily exposure levels considered to be safe are 25 $\mu g\ m^{-3}$ and 20 $\mu g\ m^{-3}$ in any 24 h period.

4.2. *Open air settings*

In open air settings smoke from fires presents little or no risk to human health as it dissipates very quickly due to the effects of air currents (convection and radiation) and wind. Heat and light are transferred at distances from the fire up to 2 to 3 m (Hoare, 2020). We conducted two further experiments measuring air quality outdoors of wood fuel (silver birch) and animal dung (cow) with AQM stations at 1 and 2 m from the experimental fires. These experiments are detailed in SI material and show no increase of PM2.5 above background levels at either 1 or 2 m in wood fuels. Levels of PM2.5 in smoke from animal dung were slightly higher at 1 m (averaging 23 $\mu g/m^3$ for the duration of the fire) but showed no increase at 2 m. Exposure to PM2.5 outdoors would therefore only occur during activities requiring very close contact with the fire and for limited durations unlikely to affect human health.

4.3. *Semi-open and closed settings (rock shelters and deep caves)*

The position of fireplaces in deep caves and rock shelters has been shown to be important from both the ethnographic record of contemporary hunter-gatherers and at Palaeolithic sites where fire dynamic simulator was used to model smoke output relative to fireplace position and air circulation patterns (Galanidou, 2000; Kedar and Barkai, 2019; Kedar et al., 2022). The most comprehensive study of fireplace location in rock shelters inhabited by contemporary hunter-gatherers documents the position of fires either inside towards the back of the rock shelter or outside by the drip lines (Galanidou, 2000).

Concerning closed spaces like deep caves Kedar et al (2022) demonstrate in their study of Lazaret cave that fireplaces are positioned in areas of ca. 5 × 5 m and are located optimally in terms of air circulation patterns to facilitate smoke dispersal when the cave is occupied. They further suggest that the fireplace location should be selected to facilitate areas for occupations of longer duration whereby distance from the fireplace allows exploitation of the fire's advantages and functionalities (light and heat) while minimizing exposure to smoke. In other Palaeolithic sites, such as Abric Romani, Kedar and Barkai (2019) demonstrate that sleeping areas inside the rock shelter use hearths with smaller diameter size that emit less smoke. These were also located optimally at the back of the shelter, so the smoke was directed upwards and flowed out of the shelter. Other hearths were located at the mouth of the rock shelter under the drip line so the smoke would flow directly outside. Fireplace position in semi-open settings would also be influenced by wind speed and direction. The importance of social factors, such as family groupings, has also been considered alongside function as an influence on fireplace position at some settlement sites such as Abric Romani e.g., Vaquero et al (2001).

4.4. Closed settings (huts and houses)

4.4.1. Huts

Our experiments measured levels of PM2.5 for the duration of the fires ranging from 55 to 140 min and at distances of 10 and 100 cm. During each of the experiments the levels of PM2.5 reduced after the peak values of the emissions and then again after the flaming phase of the fire died down. For all experiments, the levels of PM2.5 inside the shelter and at both AQM1 and AQM2 had reduced to 11–94 at the end of the experiments, which were defined as the point when the flaming phase of the fire died down and the fire had become a glowing fire, or had died out completely, in the case of the rotten wood and bone fires. Levels of PM2.5 were taken 2 h after each experiment and had returned to background levels. Therefore, exposure to unsafe levels in terms of respiratory illnesses would only occur as the fire burnt rather than over a full day, unless multiple fires were used. At distances of 100 cm and greater from the fire, exposure to levels above WHO guidelines was shown to be dependent on the type of fuel and activity (animal dung, fresh bone and smoking fires). Exposure levels within a shelter would also depend on how long a person spent in the hut near a fire, which may or may not have been much of their day, depending on, for example, tasks being performed, season, weather, or use of sleeping fires. Standing up when a fire is lit would also increase the likelihood of exposure to smoke, as could the height of a person whether sitting on the floor or on a log.

In a systematic review of uses of fire amongst contemporary hunter-gatherers, McCauley et al (2020) present information on fireplace function and location. Their study reports fireplace location in relation to task (cooking, warmth and sleeping fires) from 68 ethnographic groups. Most fires used for cooking or warmth were in the centre of the dwelling or outside just in front. Our experiments show that when fires are in the centre of a dwelling most of the smoke is directed up towards the smoke hole and dissipates as the flaming phase of the fire dies down. Some fires were reported outside at the centre of the camp (communal cooking), and by sleeping places at the back of dwellings (warmth). Our data on PM2.5 levels in smoke suggests that exposure to harmful levels would only be high during the flaming phase of the fire inside a dwelling for the duration of a task, if in close contact with the fire. At distance and depending on the type of fuel used (e.g., woods and grasses), exposure to dangerous levels can, to a certain degree, be avoided at 100 cm or greater distance. Glowing ember fires emit little or no smoke, and sleeping fires used for warmth or for the preservation of embers overnight yielded average PM2.5 levels similar to the background levels in our experiments. Exposure levels to smoke from these fires even overnight would be below WHO guidelines regardless of fireplace position. For fires located outside in front of dwellings or in the centre of communal camp areas, exposure levels would also be low as the smoke would be removed via air currents during the fire. The McCauley et al (2020) study does not report the size of fires or fire maintenance strategies, e.g., smaller diameter fires may be used inside to reduce smoke output, and fires may not be in continuous use, but simply reignited from embers when necessary. Contemporary hunter-gatherers position their fires to minimize exposure to smoke relative to task, with most fires used for cooking located outside the dwelling, in a central area of a communal camp or under a smoke hole inside. In the McCauley et al (2020) study, only one fire used for cooking was reported to be located at the back of the shelter.

4.4.2. Houses

Shillito et al. (2022) examine levels of PM2.5 in prehistoric settlements at Çatalhöyük, Turkey, in the Neolithic. Concentration levels of PM2.5 in the smoke from open fires and ovens using animal dung and wood were recorded to be well above WHO guidelines for most of the day and shown to affect all inhabitants regardless of their distance from the actual fire. When comparing the data of Shillito et al. (2022) to experiments inside a Danish Iron age dwelling with a chimney conducted by Skov et al (2000) similarly high levels of PM2.5 were also documented. In both these experiments, the authors suggest that the structure of the dwellings and lack of much ventilation accounts for the persistence of smoke inside the houses after the fires had died down.

In our structure, the fires were placed directly beneath a smoke hole. Fireplace position and the breathable nature of the shelter (covered using dried grasses) allowed the smoke to dissipate quickly both during and after the fires have died down. The PM2.5 concentrations returned to background levels within an hour of the experiments ending, and in the case of wood and grass fuels, during the experiment. Levels of PM2.5 were well above WHO guidelines for all fuels at AQM1 during the flaming phase of the fires. However, at AQM2 the levels were much lower and only above WHO guidelines for animal dung, fresh bone and rotten wood. When using fire inside a breathable shelter with the fire placed directly below the smoke hole, exposure to dangerous levels would only occur if a person was using fuels with lower combustion temperatures and flame heights such as animal dung and rotten woods. However, in huts that do not have smoke holes or are covered by different materials, such as muds or hides, the breathable nature of the habitation structure would be limited, thereby reducing the time it takes for smoke to disperse during a fire and resulting in longer duration of PM2.5 in the air and increased exposure times.

5. A deep time perspective

When considered alongside results of other studies on air quality from the Palaeolithic through to early prehistoric settlements including the Neolithic and Iron Age (Kedar and Barkai, 2019; Kedar et al., 2022; Shillito et al., 2022; Skov et al., 2000; Ryhl-Svendsen et al., 2010), our results provide further information on variation in levels of PM2.5 in smoke, along with outgoing lux and radiative heat properties of different types of fuel, fires and activities. Combined, we can now offer a limited deep time perspective on the potential effects of fire and smoke on human health in different types of living structures relative to daily survival tasks.

The effects of prolonged exposure to smoke inhalation on the respiratory systems of Palaeolithic hunter-gatherers could have been disastrous for population survival, not only in terms of their dependence on active lifestyles for daily survival needs, such as hunting, but also in terms of smaller population sizes (Hardy et al., 2012; 2016). Our results show that there would be little risk to health using open fires either outside or in a breathable shelter with a smoke hole. However, there are exceptions to this which depend on the type of fuel being used and the activity. Animal dung and fresh bone as fuels, and smoking fires as activities, emit concentration levels of PM2.5 well above WHO guidelines for the duration of the fires and at 1 m distance from the fire for animal dung outside. In larger structures, e.g., >4 × 4 m, exposure to smoke would likely be further reduced by sitting at greater distance from the fire, e.g., >1 m. Air quality could be further improved in these settings by using smaller diameter fires to reduce smoke output. However, it must be noted that we actually do not know how much time was spent in contact with fire by prehistoric peoples.

Our results further explain the details of fireplace position in closed living structures such as huts in contemporary hunter-gatherer populations in terms of placement due to reduction of smoke inhalation relative to activity and type of fire (McCauley et al., 2020). In deep caves and rock shelters (closed and semi-open), other studies have also demonstrated the importance of fireplace positions relative to patterns of air circulation for flaming wood fires, and relative to activity, e.g., smoking hearths, (Kedar and Barkai, 2019; Kedar et al., 2022). As with contemporary hunter-gatherers, Palaeolithic populations clearly understood the importance of fireplace position relative to smoke dispersal, fire type and activity, and were able to use this knowledge of fire combustion properties to reduce potential impact of fire use and its effects on air quality and health in a variety of contexts, whether open, semi-open and closed living spaces, such as huts, caves and rockshelters.

Our results contrast starkly with those of Shillito et al. (2022) and Skov et al (2000) in terms of the potential impacts of smoke PM2.5 from open flaming fires and enclosed ovens on human health in some living structures in later periods of prehistory (Neolithic and Iron age). In both studies, exposure to harmful levels of PM2.5 in smoke occurred with all fires whether open or ovens and filled the full structure. Exposure to harmful levels were well above safe daily exposure levels in WHO guidelines and shown to effect inhabitants regardless of proximity to the fire. In both these studies, the authors suggest that the enclosed nature of the building and lack of smoke holes leads to much lower ventilation and results in dense accumulation of smoke. Further contrast can be drawn with a study at the experimental site of Lejre, Denmark in 17th to 19th Century farmhouse (Ryhl-Svendsen et al., 2010). In this study, the placement of a fireplace under a chimney created a draw effect which removed most of the smoke and resulted in only individuals directly near to the fire being exposed to unsafe levels of PM2.5. It is not possible to draw general conclusions on levels of smoke that populations in later time periods, such as the Neolithic and Iron age, may have been exposed to due to the lack of available data. Prehistoric populations inhabited a range of different habitation structures built from different materials, with and without smoke holes, resulting in different ventilation within the dwellings. They used a range of different types of fuels according to specific fire management strategies, therefore not all within a given population would have been exposed to the hazardous levels of PM2.5 in the above studies (Skov et al., 2000; Shillito et al., 2022).

Burning fuel in internal spaces can affect air quality and human wellbeing through exposure to dangerous levels of PM2.5 in smoke, the inhalation of which can have major consequences to human health in terms of respiratory illnesses. In some Neolithic populations, more sedentary lifestyles, and larger population sizes relative to the Palaeolithic, may have led to an increased need for more readily available fuels and combined with animal domestication, resulted in an increased reliance on animal dung as a fuel source relative to other fuels (Shillito et al., 2022). Over time, changes in both the types of ventilation within some living structures and fuel management strategies may have increased exposure to smoke in some populations in later time periods of prehistory relative to the Palaeolithic, with some consequences to human health. It is clear from Palaeolithic studies that the key to reducing exposure to smoke in internal spaces is fireplace position relative to ventilation and air circulation along with consideration of fuel type, activity and perhaps seasonality. However, in some internal spaces in later time periods (Neolithic and Iron Age), fireplace position appears to make little difference to exposure levels due to the type of building structure and lack of ventilation (e.g., Shillito et al., 2022). Given the variety of habitation structures and dwellings in prehistory, we should not expect to observe a linear increase in the frequency and severity of health issues, such as respiratory illnesses and fertility problems, as the use of fire increases over time. Rather, we should expect health problems to only occur within a given population, because of exposure to smoke, if ventilation within specific dwelling structures is inadequate for smoke dispersal, and fire management strategies include the use of fuels with high concentrations of PM2.5, e.g., animal dung.

6. Conclusion

The potential effects of smoke from fires on air quality and human health in prehistory is a relatively new area of research. Here, we present a new methodological protocol by combining measurements of air quality (PM2.5 in smoke) with those of radiative heat, light and temperatures of our fires to investigate the impact of fire use on human health in inhabited spaces. Our study produces the first quantified data sets on concentration levels of (PM2.5) in smoke from open fires relative to other combustion properties, such as light, smoke and radiative heat, and from different types of fuels, fires and activities. Furthermore, our results are comparable with measurements of PM2.5 in open fires using animal dung and wood fuels from Shillito et al. (2022), and with details of fireplace position relative to activity (smoking, sleeping, cooking) in huts, caves and rock shelters provided in Kedar and Barkai (2019); McCauley et al (2020) and Kedar et al (2022). Our results further confirm that Palaeolithic hunter-gatherers were positioning their fires in some internal spaces to mitigate risks to human health and wellbeing.

Our results demonstrate:

1. Air quality will vary between open, semi-open and enclosed settings according to fuel type, activity, fireplace location and proximity to the fire.
2. PM2.5 in smoke varies according to fuel type, with animal dung > fresh bone and fresh bone epiphyses > grassed and reeds > rotten wood > wood.
3. PM2.5 in smoke varies at 100 cm distance from the fireplace due to differences in combustion temperature of the smoke column, rotten wood > animal dung > fresh bone and fresh bone epiphyses > grasses, reeds and wood.
4. PM2.5 in smoke varies according to type of fire and activity, with smoking fires (insect repellent, smoking meats and fish and hide curing) > flaming fires (light, heat, cooking, tool maintenance) > glowing ember fires (sleeping fires, warmth, cooking, tool maintenance).
5. Palaeolithic hunter-gatherers may have reduced their exposure to smoke by carefully positioning their fireplaces in internal spaces (e.g., caves, huts and rock shelters) relative to patterns of air circulation, activities and fuel type, thus reducing the impact of smoke on air quality and human health relative to use of other combustion properties.
6. Fuels emitting low concentrations of PM2.5 in their smoke and high lux and radiative heat properties for the longest durations have the least impact on air quality and human health indoors as they permit the maximisation of the fires by products (light and heat) whilst minimising exposure to smoke. In this regard, wood fuels > mixed wood and grass > grasses and reeds > fresh bone > animal dung.
7. The type and size of the living structure along with ventilation within the structure (e.g., breathable covering and ventilation

hole) is also important in terms of exposure levels to harmful particulate matter in smoke.

8. A change in human environment interactions around fire and habitability is apparent between the Palaeolithic and some populations in later time periods (Neolithic and Iron Age), linked to changes in patterns of mobility, fuel management strategies and animal domestication, resulting in increased exposure to PM2.5 in smoke and reduction air quality in some living structures.
9. Palaeolithic populations were clearly able to lead healthy lives by limiting their exposure levels to smoke in semi-open and enclosed settings.

Given that major variation exists in the types of dwelling structures, ventilation within these structures and fire management strategies in prehistory, more detailed case studies from individual archaeological sites in the Palaeolithic and later time periods are now necessary to further examine the potential effects of smoke from open fires on air quality and human health. Future studies could also focus on examining how changes in the diameter sizes of woody fuels could further impact PM2.5 concentrations in the smoke.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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