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Ancient arctic pyro-technologies: Experimental fires to document the impact of animal origin fuels on wood combustion

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ABSTRACT

Remains of animal fuel and driftwood fires are evident in Birnirk and Thule sites of northwestern Alaska (AD 11th-14th century). To better understand these fires, a robust experimental protocol was designed to study the effects of multi-fuel fires, in particular, the addition of fat to woody fuels. In Arctic regions, permafrost and climate conditions do not allow for the development of tree vegetation. Marine mammal oil and bones served as fuel substitutes, as did locally shrubby vegetation and driftwood accumulations. The excavation of numerous thick burnt areas in many Arctic sites confirms the use of multiple fuels including wood, animal fat, and bone in large quantities. These burnt areas correspond to a wide range of fire activities—cooking, smoking, firing ceramics, and others—but the actions and effects of each fuel are still poorly known.

We describe conditions necessary to achieve a reproducible and statistically representative experimental fire sample. We compared fuel combinations of driftwood or non-drifted wood, animal fat, and caribou bones over 55 combustions. Experiments were conducted under controlled conditions in a laboratory in France and on the coast of northwestern Alaska. We found that a minimum of 30 test assays was needed to obtain statistically significant results but many research avenues can be obtained from smaller series. We obtained key figures and descriptive data on the impact of different animal fuels on fire temperature and duration, as well as on the firewood spectrum, with important implications for the representation of different woody fuels and the fragmentation patterns of charcoals. We report a relatively rapid rate of formation for blackened and crusted sediments when seal oil is burned along with driftwood. This means that thick accumulations of burnt material may not be a reliable signal of long-term occupations and that the relationship between the duration of site occupation and fuel management deserves further study.

1. Introduction

In Arctic regions, permafrost and climate conditions do not allow for the development of tree vegetation, with driftwood and willow shrubs as the only woody fuels available in northwestern Alaska (Giddings, 1952; Saario, 1962, p. 5,6; Saario and Kessel, 1966, p. 972; Burch, 1985, p. 101; Alix, 2016). Woody fuels were supplemented with marine mammal fat and bones. Marine mammal fats improve the heat capacity of a hearth, producing significant amounts of light and heat with little smoke (Lyon, 1824, p. 246; Jenness, 1922, 1946; Birket-Smith, 1929, p. 98; Heizer, 1963, p. 188; Hall, 1975, p. 65; Schledermann, 1990, p. 50; Mason, 1998, p. 1991; Morseth, 1997, p. 250; Burch, 1998, 2006; Møbjerg, 1999; McGhee, 2001; Odgaard, 2003; Alix, 2008, p. 47). Bone-fueled fires provide heat and light and help eliminate waste (Spennemann and Colley, 1989, p. 51; Costamagno et al., 2005, p. 5; Cain, 2005, p. 882; Hoare, 2020). While fuel sources may have been limited in the Arctic, communities were never completely devoid of them.

Hearths and fuel management hold an important place in the Arctic domestic economy. Oil lamps and hearths provided heat and light needed to live and cook in dwellings (Damas, 1984, p. 308; Plumet, 1989). During the Neo-Inuit period, in particular, at Thule sites in the

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Fig. 1. Cape Espenberg spit, in northwestern Alaska, location where the archaeological burnt areas were excavated and the outdoor experiments carried out. Inset map shows the study area (modified map © Alaska Office of History and Archaeology).

western Arctic, combustion features have been uncovered outside houses. These burnt areas contain fire-cracked bone flakes, charcoals, and thick concentrations of marine mammal fat welded together by heat[1]. Some external combustion features, unconnected to the house, might have been used for "specialized" combustion, such as ceramics firing (Anderson, 2011, 2017; Anderson et al., 2017), smoking skins, or drying food (Foote and Cooke, 1960, p. 44,46; Burch, 2006, pp. 106, 165,187). Despite extensive archaeological excavations conducted at western Arctic Thule sites, these burnt areas remain poorly understood, including their function, the process by which residues accumulated, and the meaning of fuel ratios (intentional choice vs. selection-driven by fuel availability).

Experimentation is the most appropriate method to investigate these questions since certain variables can be controlled and the experiment can be replicated. The main objective of our experimental program is to obtain numerical data and quantitative information about the combustion of different fuel types within a hearth, specifically using fuel resources available in the Arctic. Most combustion experiments are conducted using "regular" wood sources but see Caruso Fermé (2012, 2014) and Vanlandeghem (2017, 2014). Comparing driftwood and non-drifted wood fuels provides further data on the properties of woody fuels. Recently, a number of experiments have examined the use of bone as a main or secondary fuel source (Théry-Parisot, 2002; Théry-Parisot et al., 2005; Costamagno et al., 2005; Crass and Behm, 2005; Crass et al., 2011; Lejay et al., 2016; Lejay, 2018; Buonasera et al., 2019; Hoare, 2020). Even more limited are experiments focused on animal fat as fuel (Odgaard 2003). Our experiments provide details on how animal material and woody fuels burn and highlight the advantages of combining them. We also investigate if the presence of fat in the combustion processes differentially affects the representation, morphology, and anatomical deformations of woody species in the charcoal remains. These fire experiments provide preliminary data on the number of combustion episodes needed to form the burnt areas uncovered at archaeological sites and to examine the range of activities related to fire in northwestern Alaska sites.

In this paper, we present 55 initial fire experiments conducted under controlled laboratory conditions and in an outdoor setting at Cape Espenberg on the coast of northwestern Alaska (Fig. 1). Fifty-five fires provide scientifically valid results that will guide our future protocol and experimentation of a larger number of fires to test a wider set of fuels. Considering that experimental combustions with animal fat have rarely been conducted, we chose to highlight the experimental results related to the action of animal fat on driftwood and on the combustion deposit.

2. Material and methods

2.1. Materials and experimental protocol

Local driftwood collected along the beach at Cape Espenberg was used for the 34 outdoor experiments (*Picea* sp. *Salix* sp., *Populus* sp.) and for six of the laboratory experiments (*Picea* sp. *Salix* sp., *Populus* sp., *Larix* sp., *Alnus* sp., *Betula* sp., Table 1, Table 2). Due to a limited supply of driftwood for the laboratory experiments, 15 fires were conducted using only European non-drifted wood taxa corresponding to the genera used for the driftwood experiments. The use of non-drifted wood also makes it possible to initiate a comparison of fire behaviors using these two types of potential wood sources. All wood was dried to a moisture content measured with a Wöhler HF300 hygrometer at 12%.

We used seal fat (blended oil and blubber) and/or caribou bones to fuel hearths in outdoor conditions. We fragmented all caribou bones and measured all fragments (length, diameter) before combustion. Laboratory experiments were performed with pork fat (lard) marketed in France. Even though it differs from marine mammal oil, pork fat was the best choice due to its 100% fat composition and low melting point (36 °C–40 °C). Pork fat falls between the melting point range of seal oil [−8 °C to 15 °C] (Iverson, 2009) and of the marrow of caribou bones [40 °C–48 °C for femur and tibia, 15 °C–22 °C for metatarsus] (Meng et al., 1969).

We replicated a total of 55 fires: 19 wood-only fires, and 33 "mixed" fires combining wood with fat and/or bones (Fig. 2). Each fire of the

[1] This baked and fused fat-cemented sand is often called « clinker ».

Table 1
Composition of the fire in wood taxa.

Wood taxa	Genera	Outdoor	Laboratory	
		Driftwood	Driftwood	Non-drifted wood
Spruce	*Picea glauca, Picea mariana*	X	X	X
Poplar	*Populus tremuloides, Populus balsamifera*	X	X	X
Willow	*Salix* sp.	X	X	X
Birch	*Betula nana, Betula papyrifera, Betula neoalaskana*		X	X
Alder	*Alnus crispa*		X	X
Tamarack	*Larix laricina*		X	X
Local crowberry shrubs	*Empetrum nigrum*		X	

same context (laboratory or outdoor) used identical fuel quantities and types. We recorded all pre-combustion characteristics (Table 3). Twenty-one controlled archaeological experiments were conducted in the laboratory under fixed conditions. Our variables were wood composition – driftwood or non-drifted wood – and the addition of fat – soaked or deposited. Each of the 21 controlled fires had an equal wood mass of 600 to 900 g., depending on the type of wood (driftwood or non-drifted wood) using identical species composition. In fat and wood fires, we added 200 to 600 g. of pork fat. Thirty-four outdoor archaeological experiments at Cape Espenberg aimed to create fires under conditions close to those encountered in the past environment. We dug small basin-shaped pits into the natural beach sand (50 cm in diameter and 10 cm deep). A series of combustion events using the same fuel types took place in the same pits. Outdoor fires had an equal wood mass (3 kg). We used either driftwood-only, or mixed driftwood with fat fuel (150 to 220 g. of seal oil per fire) and/or caribou bones (approximately 200 g., Table 2, Fig. 2). Fuel weights were kept constant within each type of fire. In all cases, the total fuel mass of each fire was accounted for in the analyses because it can have a direct impact on the duration and the temperatures reached by the fire.

To measure fire temperatures throughout the combustion process, we placed thermocouple K sensors (Oakton™, Testo™) connected to 4 channel thermometers (Dostmann-Electronic™ TC309, REED-Instruments SD-947) in each fire. We systematically recorded the progression of each combustion (ignition, phase with flame, pyrolysis: phase without flame). For the outdoor combustion, we also recorded atmospheric conditions (wind velocity, humidity, ambient temperature) prior to each ignition using a Multifunction Anemometer (PCE-THA10). We followed previous fire experiments (Théry-Parisot, 2013, p. 68) in arbitrarily setting the end of combustion at the conventional temperature of 100 °C.

At the end of each combustion, we collected the fuel residues (charcoals and burnt materials). Charcoals were sorted and counted to assess the rate of fragmentation of each wood taxa. We identified charcoal fragments > 4 mm using a reflected light microscope. We also produced a reference collection of wood samples used in the experiments for future reference[2]. At the end of all outdoor combustions, we recorded the nature of the fire bed's encrustation (thickness, friability) and collected micromorphological samples from the bottom of the four different pits following sampling and analysis procedures implemented by J. Wattez[3] (Wattez, 1988, 1992, 2000; Vanlandeghem et al., 2016).

2.2. Statistical analysis

Data from the experiments are heterogeneous, including measures and qualitative modalities. There is no statistical procedure that would allow for the simultaneous processing of such a heterogeneous set of variables (Table 4). This is a common issue in archaeology. One solution is to group the values of the quantitative variables into a number of intervals (or "classes") which may be processed as qualitative modalities. This discretization method minimizes information loss while transforming continuous to discrete values and making data evaluation easier. The resulting table is entirely composed of qualitative values and can be processed using a correspondence analysis and an automatic classification (Bouroche and Saporta, 1980; Djindjian, 1991).

Due to a low number of observations (55 fires), we dichotomized each qualitative variable into only two modalities. Similarly, each quantitative values series was split at the fixed value of the median to form two categories (50% of the values are below the median and 50% of the values are above the median), described as "Low" and "High" for instance (Rucker et al., 2015). The goal of such a dichotomization strategy is to highlight the major association and opposition in a statistical way, at the risk of losing some subtleties and temporarily putting aside a finer analysis of all the parameters observed.

We use a multidimensional approach to analyze the data. A multiple correspondence analysis (MCA) was applied. It involves transforming the table for qualitative data into a binary table (coded 1 if the individuals present value above the median, 0 if not) and running a correspondence analysis directly on the binary table (Bouroche and Saporta, 1980). A cluster analysis was then performed on the coordinates of the individuals obtained from the MCA. To evaluate the risk that our results are due to chance, we then ran Yates's chi-squared tests and a Fisher's exact tests, which are applicable to low numbers of observations (Mialaret, 1996; Baxter, 2003).

3. Results

3.1. Statistical significant results and emerging tendencies

3.1.1. All 55 fires: the experimental conditions stand out

The results of the MCA and cluster analysis on all 55 fires (Table 4, Fig. 3) show a clear distinction between the two groups that corresponds to the two sets of experiments—laboratory (controlled) and outdoor (contextual). This confirms the need to analyze the two series of experiments separately. Given the small size of each set of experiments, we retained four key variables following the median split: with or without fat, few or many charcoal fragments produced (below or above 102 charcoals for outdoor experiments and below or above 166 charcoals for laboratory experiments), short or long fire duration (below or above 149 min for outdoor experiments and below or above 140 min for laboratory experiments), and medium or high temperatures (below or above 957 °C for outdoor experiments and below or above 525 °C for laboratory experiments).

3.1.2. Outdoor experiments: Adding fat significantly increases the duration of fires

An MCA was performed on 32 of the outdoor experimental fires. Two fires were excluded from the analysis due to unexpected technical

[2] It is housed and available at the Archaeobotany Laboratory of the Maison de l'Archéologie et de l'Ethnologie (MAE) in Nanterre, France.

[3] Julia Wattez is a french geoarchaeologist at the 'Institut National d'Archéologie Préventive (INRAP)' (UMR 5140 ASM). She specialises in hearths micromorphology.

Table 2
Composition of the fire and wood batches for outdoor experiments (above) and laboratory experiments (below) prior to combustion.

# Experiments	Fuel Mass (grams)						
	Total Mass (Fat, bones, wood)	Fat	Bones	Wood (*Picea, Salix, Populus*)	*Picea* sp.	*Salix* sp.	*Populus* sp.
Outdoor - Cape Espenberg	**111,911**	**3320**	**2810**	**105,781**	***25,580***	***43,951***	***36,250***
Driftwood	111,911	3320	2810	105,781	*25,580*	*43,951*	*36,250*
Driftwood fire	**33,771**	0	0	33,771	*8110*	*14,091*	*11,570*
1	3120	0	0	3120	*820*	*1290*	*1010*
2	3260	0	0	3260	*800*	*1330*	*1130*
3	3140	0	0	3140	*700*	*1270*	*1170*
4	3170	0	0	3170	*690*	*1360*	*1120*
5	3020	0	0	3020	*770*	*1250*	*1000*
6a	2980	0	0	2980	*800*	*1200*	*980*
6b	3171	0	0	3171	*770*	*1281*	*1120*
7	2750	0	0	2750	*570*	*1250*	*930*
8	3010	0	0	3010	*750*	*1240*	*1020*
9	3250	0	0	3250	*820*	*1400*	*1030*
10	2900	0	0	2900	*620*	*1220*	*1060*
Driftwood and seal oil fire	**36,750**	2420	0	34,330	*8440*	*14,380*	*11,510*
1	3290	220	0	3070	*850*	*1280*	*940*
2	3580	220	0	3360	*990*	*1300*	*1070*
3	3080	220	0	2860	*650*	*1250*	*960*
4	3510	220	0	3290	*850*	*1420*	*1020*
5	3090	220	0	2870	*610*	*1340*	*920*
13	3380	220	0	3160	*640*	*1320*	*1200*
14	3540	220	0	3320	*870*	*1350*	*1100*
15	3250	220	0	3030	*760*	*1250*	*1020*
16	3260	220	0	3040	*730*	*1290*	*1020*
17	3320	220	0	3100	*740*	*1160*	*1200*
18	3450	220	0	3230	*750*	*1420*	*1060*
Driftwood and caribou bones fire	**20,550**	0	1670	18,880	*4540*	*7770*	*6570*
19	3540	0	350	3190	*760*	*1350*	*1080*
20	3540	0	420	3120	*740*	*1330*	*1050*
21	3220	0	280	2940	*760*	*1140*	*1040*
22	3590	0	190	3400	*810*	*1390*	*1200*
23	3110	0	190	2920	*620*	*1240*	*1060*
24	3550	0	240	3310	*850*	*1320*	*1140*
Driftwood, seal oil, and caribou bones fire	**20,840**	900	1140	18,800	*4490*	*7710*	*6600*
7	3560	150	190	3220	*710*	*1440*	*1070*
8	3550	150	190	3210	*770*	*1280*	*1160*
9	3500	150	190	3160	*750*	*1310*	*1100*
10	3420	150	190	3080	*830*	*1230*	*1020*
11	3390	150	190	3050	*730*	*1210*	*1110*
12	3420	150	190	3080	*700*	*1240*	*1140*

# Experiments	Fuel Mass (grams)											
	Total Mass (Fat, Wood)	**Fat**	**Wood**	*Picea* sp.	*Larix* sp.	*Picea/Larix* cf. *Picea* sp.	*Salix* sp.	*Populus* sp.	*Populus/Salix* sp.	*Alnus* sp.	*Betula* sp.	*Empetrum* sp.
Laboratory	**18,132**	**4054**	**14,078**	***2672***	***1833***	***40***	***4133***	***2170***	***99***	***1425***	***1457***	***258***
Driftwood	7201	1972	5229	*1204*	*0*	*40*	*2554*	*939*	*99*	*82*	*54*	*258*
Driftwood soaked in pork fat fire	**4581**	1972	2609	*606*	*0*	*20*	*1262*	*473*	*54*	*40*	*25*	*129*
4	1537	664	873	*193*	*0*	*9*	*428*	*161*	*14*	*16*	*10*	*43*
5	1538	664	874	*213*	*0*	*6*	*407*	*169*	*16*	*12*	*7*	*44*
6	1506	644	862	*201*	*0*	*5*	*427*	*143*	*24*	*13*	*8*	*42*
Driftwood fire	**2620**	0	2620	*598*	*0*	*20*	*1292*	*466*	*45*	*41*	*29*	*129*
1	877	0	877	*214*	*0*	*7*	*429*	*146*	*15*	*13*	*11*	*43*
2	871	0	871	*200*	*0*	*7*	*425*	*157*	*15*	*15*	*10*	*43*
3	871	0	871	*184*	*0*	*7*	*439*	*162*	*15*	*13*	*8*	*43*
Non-drifted wood	10,930	2082	8848	*1469*	*1833*	*0*	*1579*	*1232*	*0*	*1343*	*1403*	*0*
Wood fire	**2925**	0	2925	*490*	*611*	*0*	*526*	*409*	*0*	*445*	*465*	*0*
A	590	0	590	*98*	*121*	*0*	*106*	*82*	*0*	*89*	*95*	*0*
B	567	0	567	*97*	*122*	*0*	*105*	*82*	*0*	*88*	*93*	*0*
C	592	0	592	*98*	*124*	*0*	*104*	*82*	*0*	*89*	*95*	*0*
D	590	0	590	*98*	*123*	*0*	*106*	*82*	*0*	*90*	*92*	*0*
E	586	0	586	*99*	*121*	*0*	*106*	*81*	*0*	*89*	*90*	*0*
Wood coated with pork fat fire	**4006**	1050	2956	*489*	*610*	*0*	*528*	*409*	*0*	*447*	*472*	*0*
K	800	210	590	*96*	*124*	*0*	*106*	*82*	*0*	*89*	*94*	*0*
L	805	210	595	*98*	*122*	*0*	*105*	*85*	*0*	*89*	*96*	*0*
M	795	210	585	*98*	*120*	*0*	*106*	*81*	*0*	*88*	*91*	*0*
N	803	210	593	*100*	*121*	*0*	*106*	*80*	*0*	*90*	*95*	*0*

(*continued on next page*)

Table 2 (*continued*)

	Fuel Mass (grams)											
# Experiments	Total Mass (Fat, Wood)	**Fat**	**Wood**	*Picea* sp.	*Larix* sp.	*Picea/Larix* cf. *Picea* sp.	*Salix* sp.	*Populus* sp.	*Populus/Salix* sp.	*Alnus* sp.	*Betula* sp.	*Empetrum* sp.
O	803	210	593	*97*	*123*	*0*	*106*	*81*	*0*	*90*	*96*	*0*
Wood soaked in pork fat fire	**4000**	1032	2968	*489*	*612*	*0*	*524*	*414*	*0*	*451*	*467*	*0*
F	816	223	593	*97*	*122*	*0*	*105*	*82*	*0*	*93*	*94*	*0*
G	799	202	597	*99*	*123*	*0*	*106*	*86*	*0*	*89*	*94*	*0*
H	787	197	590	*98*	*123*	*0*	*105*	*82*	*0*	*90*	*92*	*0*
I	786	190	596	*97*	*121*	*0*	*105*	*81*	*0*	*90*	*92*	*0*
J	812	220	592	*98*	*124*	*0*	*105*	*82*	*0*	*89*	*95*	*0*

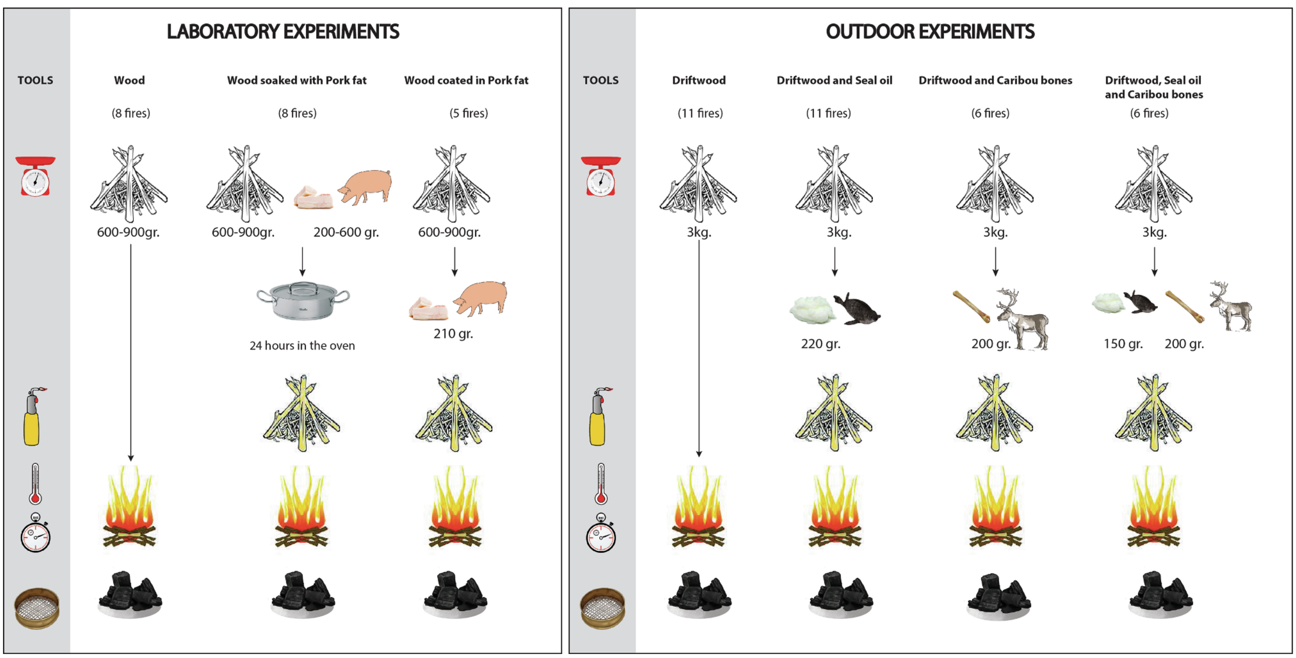

Fig. 2. Schematic representation illustrating the several types of fire set up in this experimental protocol, in laboratory conditions in France and in outdoor arctic conditions at Cape Espenberg, Alaska.

failure during the experiment which led to missing values (Table 5). Fig. 4 shows the correlations between some of the variables. Based on the counts provided by a Burt Table (symmetric matrix of all two-way cross-tabulations between the variables, Table 6), the results of the Yates's chi-squared tests and the Fisher's exact tests (Table 7) show significance between the variables "temperature" and "quantities of charcoal", and between "addition of fat "and "fire duration". There is no statistically significant correlation between "addition of fat" and "temperature", or between "addition of fat" and "amount of charcoal".

The significant correlation between "addition of fat" and "duration of fire" can be interpreted archaeologically: adding fat to hearths may correspond to the need for a longer flame duration or longer pyrolysis. This result is a statistical confirmation of hypotheses and observations described in previous archaeological and ethnographic studies (Saario, 1962, p. 51; Costamagno et al., 1998; Chabal et al., 1999, p. 55; Théry-Parisot, 2000, 2002; Hoffecker, 2005; Glazewski et al., 2006, p. 18,23).

Table 3
Complete instrumentation chain, from sample preparation to experimental combustions' data processing.

	Pre-combustion 	Combustion 	Post-combustion 
Fire	**Preparation of the experimental form** - Fire identification number - Date and time - Combustion surface (shape, size) - Fuel setting up - Installation of probes with thermal sensors for simultaneous recording	**Weather conditions measurement** - Atmospheric humidity - Wind speed - Atmospheric temperature **Fire conduct measurements** - Duration of the three phases (ignition, flames, pyrolysis) - Total duration of the fire - Temperatures reached during these three phases (average and maximum temperatures)	**Observations and photographs** - Encrustation of the fire bed - Fire residues **Analyzes** - Impact of the addition of animal fuel on the duration and temperature of wood fire **Other studies** - Micromorphology - Lipids and Isotopes - Magnetic Susceptibility
Fuel	**Preparation** - Wood cutting devices - Drying oven - Cutting of bones and extraction of the marrow **Measures** - Mass, volume, humidity and wood size - Mass of fat - Mass and size of bones - Total fuel mass **Batch registration** - Standardization of identical batches of wood and animal fuel - Organization of reference fires (wood only) and specialized fires (with fat and/or bones) and duplicates of these experiments	**Setting up** - Lighting of wood with a blowtorch - Addition of animal fuel when lighting the wood (T = 10 min) - Notes and photographs	**Anthracological analysis** - Use of a 5 mesh-screen (4 mm, 2 mm, 1 mm, 0.5 mm, vat), - Mass of charcoal (4 mm, 2 mm, 1 mm, 500 µm, tank) - Amount of charcoal (4 mm, 2 mm) - Total residual mass of wood - 4 mm charcoal's study: wood deformations, taxonomic assemblage' representativity, diagnostic anatomical signatures of fat and bone used as fuels. **Other analyzes** - Size and appearance of burned bones - Total residual mass of fuels - Total residual mass of bones

Animal fat (oil, blubber, bones grease, marrow) is an important fuel that contributes to the versatility of hearth functions. The control of flames may have helped gain a higher luminosity, useful for manufacturing tools, socializing, and/or storytelling. Longer pyrolysis would have been required for heating, indirect cooking, slow roasting, fire maintenance (Théry-Parisot, 2013), and specialized combustion activities such as ceramic firing.

The other significant correlation, between "temperature" and "amount of charcoal" has a natural explanation: a higher temperature leads to more complete combustion and a smaller quantity of residual charcoal.

3.1.3. *Laboratory experiments: Adding fat tends to increase the duration of fires*

We ran an MCA on all 21 fires (Table 4, Table 8). This plot shows that adding fat results in a longer fire (± 15–20 min), although this relationship is not statistically significant (Burt Table test $P > 0.1$).

This relationship however is similar to that tested as significant in the above outdoor experiments. This suggests that it is the same information which is conveyed in the two sets of experiments, outdoor and laboratory, and that the lack of statistical significance of the laboratory experimental results is due to a lower number of repeated fires than in the outdoor experiments. Especially since the MCA points to another minor association between the variables "temperature" and

Table 4
Results from the different types of experiments and their values (55 individuals × 21 variables) used for the multidimensional analysis (Fig. 3) where the measured variables were grouped into two classes separated by the median. The underscore symbol means that data were not obtained.

#ID	Experimental conditions	Wood	Fat	Type of Fat	Bones	Addition of fat	Initial mass of wood (g.)	Wood moisture (%)	Ratio *Picea* (g.) / Total Wood Mass	Flame phase duration (min)
1_2016_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	None	Coated	3070	29	0.28	_
1_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	None	None	3120	34	0.26	60
10_2016_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	None	None	2900	32	0.21	41
10_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	Caribou	Coated	3080	33	0.27	65
11_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	Caribou	Coated	3050	30	0.24	65
12_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	Caribou	Coated	3080	34	0.23	65
13_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	None	Coated	3160	30	0.20	95
14_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	None	Coated	3320	31	0.26	70
15_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	None	Coated	3030	36	0.25	75
16_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	None	Coated	3040	34	0.24	55
17_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	None	Coated	3100	35	0.24	60
18_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	None	Coated	3230	34	0.23	65
19_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	Caribou	None	3190	30	0.24	80
2_2016_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	None	Coated	3360	30	0.29	73
2_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	None	None	3260	33	0.25	70
20_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	Caribou	None	3120	31	0.24	80
21_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	Caribou	None	2940	36	0.26	65
22_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	Caribou	None	3400	34	0.24	55
23_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	Caribou	None	2920	35	0.21	70
24_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	Caribou	None	3310	34	0.26	65
3_2016_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	None	Coated	2860	35	0.23	73
3_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	None	None	3140	35	0.22	65
4_2016_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	None	Coated	3290	32	0.26	71
4_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	None	None	3170	33	0.22	65
5_2016_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	None	Coated	2870	29	0.21	73
5_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	None	None	3020	33	0.25	36
6_2016_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	None	None	2980	32	0.27	100
6_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	None	None	3171	33	0.24	50
7_2016_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	None	None	2750	31	0.21	60
7_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	Caribou	Coated	3220	32	0.22	60
8_2016_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	None	None	3010	31	0.25	60
8_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	Caribou	Coated	3210	32	0.24	75
9_2016_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	None	None	3250	33	0.25	50
9_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	Caribou	Coated	3160	34	0.24	75
1_2014_Laboratoire	Laboratory	Driftwood	None	None	None	None	877	10.54	0.24	28
2_2014_Laboratoire	Laboratory	Driftwood	None	None	None	None	871	10.55	0.23	33
3_2014_Laboratoire	Laboratory	Driftwood	None	None	None	None	871	10.55	0.21	36
4_2014_Laboratoire	Laboratory	Driftwood	Fat	Pork	None	Soaked	873	10.55	0.22	40
5_2014_Laboratoire	Laboratory	Driftwood	Fat	Pork	None	Soaked	874	10.55	0.24	40
6_2014_Laboratoire	Laboratory	Driftwood	Fat	Pork	None	Soaked	862	10.55	0.23	45
A_2016_Laboratoire	Laboratory	Non-drifted wood	None	None	None	None	590	13	0.17	42
B_2016_Laboratoire	Laboratory	Non-drifted wood	None	None	None	None	567	13	0.17	40
C_2016_Laboratoire	Laboratory	Non-drifted wood	None	None	None	None	592	13	0.17	33
D_2016_Laboratoire	Laboratory	Non-drifted wood	None	None	None	None	590	13	0.17	32
E_2016_Laboratoire	Laboratory	Non-drifted wood	None	None	None	None	586	13	0.17	35
F_2016_Laboratoire	Laboratory	Non-drifted wood	Fat	Pork	None	Soaked	593	13	0.16	50
G_2016_Laboratoire	Laboratory	Non-drifted wood	Fat	Pork	None	Soaked	597	13	0.17	50
H_2016_Laboratoire	Laboratory	Non-drifted wood	Fat	Pork	None	Soaked	590	13	0.17	35
I_2016_Laboratoire	Laboratory	Non-drifted wood	Fat	Pork	None	Soaked	596	13	0.16	33
J_2016_Laboratoire	Laboratory	Non-drifted wood	Fat	Pork	None	Soaked	592	13	0.17	35
K_2016_Laboratoire	Laboratory	Non-drifted wood	Fat	Pork	None	Coated	590	13	0.16	34
L_2016_Laboratoire	Laboratory	Non-drifted wood	Fat	Pork	None	Coated	595	13	0.16	35

(*continued on next page*)

Table 4 (*continued*)

#ID	Experimental conditions	Wood	Fat	Type of Fat	Bones	Addition of fat	Initial mass of wood (g.)	Wood moisture (%)	Ratio *Picea* (g.) / Total Wood Mass	Flame phase duration (min)
M_2016_Laboratoire	Laboratory	Non-drifted wood	Fat	Pork	None	Coated	585	13	0.17	33
N_2016_Laboratoire	Laboratory	Non-drifted wood	Fat	Pork	None	Coated	593	13	0.17	30
O_2016_Laboratoire	Laboratory	Non-drifted wood	Fat	Pork	None	Coated	593	13	0.16	35

#ID	Pyrolysis phase duration (min)	Fire total duration (min)	Maximum tempera-tures (° C)	Average temperatures during flame phase (° C)	Atmospheric humidity (%)	Wind speed (m/s)	Amount of charcoal (> 4mm)	Amount of coniferous charcoal fragments (> 4mm)	Amount of deciduous charcoal fragments (> 4mm)	Amount of indeterminate charcoal fragments (> 4mm)	Ratio Fragments of *Picea* sp. Charcoal (> 4mm)
1_2016_Cap_Espenberg	-	-	-	-	-	-	191	36	72	83	0.188481675
1_2017_Cap_Espenberg	82	142	992	562	86	2.3	156	46	110	0	0.294871795
10_2016_Cap_Espenberg	39	80	901,1	393	80	4.8	77	4	60	0	0.051948052
10_2017_Cap_Espenberg	82	147	1095	675	73	2.5	55	37	18	0	0.672727273
11_2017_Cap_Espenberg	46	111	1100	557	90	3.5	107	25	82	0	0.23364486
12_2017_Cap_Espenberg	35	100	887	555	82	5	31	18	13	0	0.580645161
13_2017_Cap_Espenberg	140	235	901	557	87	1.5	114	27	87	0	0.236842105
14_2017_Cap_Espenberg	127	197	1229	526	73	1	130	33	96	1	0.253846154
15_2017_Cap_Espenberg	75	150	1081	570	90	0.8	25	8	17	0	0.32
16_2017_Cap_Espenberg	100	155	1148	466	64	4.2	10	8	2	0	0.8
17_2017_Cap_Espenberg	98	158	924	466	77	3	15	6	9	0	0.4
18_2017_Cap_Espenberg	83	148	960	602	73	5	-	-	-	-	-
19_2017_Cap_Espenberg	121	201	858	387	87	1.5	194	48	146	0	0.24742268
2_2016_Cap_Espenberg	112	185	745,1	477	67	4.2	157	32	90	35	0.203821656
2_2017_Cap_Espenberg	74	144	1182	630	73	2	167	58	109	0	0.347305389
20_2017_Cap_Espenberg	80	160	809	438	73	1	158	51	107	0	0.32278481
21_2017_Cap_Espenberg	65	130	889	471	90	0.8	178	79	99	0	0.443820225
22_2017_Cap_Espenberg	65	120	968	465	64	4.2	99	23	76	0	0.232323232
23_2017_Cap_Espenberg	78	148	974	471	77	3	70	10	60	0	0.142857143
24_2017_Cap_Espenberg	71	136	945	464	73	5	48	8	38	2	0.166666667
3_2016_Cap_Espenberg	82	155	764,8	506	79	4.5	42	9	14	19	0.214285714
3_2017_Cap_Espenberg	97	162	996	608	76	3	59	31	28	0	0.525423729
4_2016_Cap_Espenberg	104	175	769,35	601	64	1.5	188	25	152	5	0.132978723
4_2017_Cap_Espenberg	50	115	946	672	73	2.5	79	25	54	0	0.316455696
5_2016_Cap_Espenberg	67	140	947,2	580	57	2.3	53	6	46	0	0.113207547
5_2017_Cap_Espenberg	68	104	828	541	68	5	114	51	63	0	0.447368421
6_2016_Cap_Espenberg	100	200	842	438	-	-	173	29	132	12	0.167630058
6_2017_Cap_Espenberg	40	90	939	612	84	5.5	105	34	71	0	0.323809524
7_2016_Cap_Espenberg	65	125	731,5	444	79	4.5	194	32	147	15	0.164948454
7_2017_Cap_Espenberg	90	150	932	632	86	2.3	173	53	120	0	0.306358382
8_2016_Cap_Espenberg	150	210	578,5	390	75	1.2	25	4	15	6	0.16
8_2017_Cap_Espenberg	85	160	1063	568	73	2	92	33	59	0	0.358695652
9_2016_Cap_Espenberg	75	125	661,5	530	70	0.8	171	61	83	6	0.356725146
9_2017_Cap_Espenberg	107	182	1194	552	76	3	62	24	38	0	0.387096774
1_2014_Laboratoire	111	139	447	305	-	-	115	22	86	1	-
2_2014_Laboratoire	77	110	569	406	-	-	23	0	12	5	0.00
3_2014_Laboratoire	94	130	486	358	-	-	37	4	11	10	0.027027027
4_2014_Laboratoire	116	156	494	342	-	-	102	5	95	2	-
5_2014_Laboratoire	100	140	606	408	-	-	53	14	20	11	0.26
6_2014_Laboratoire	106	151	571	369	-	-	65	6	26	16	0.030769231
A_2016_Laboratoire	83	125	549	382	-	-	167	40	94	4	0.131736527
B_2016_Laboratoire	125	165	587	398	-	-	160	20	132	19	0.05
C_2016_Laboratoire	97	130	556	400	-	-	184	33	144	29	0.027173913
D_2016_Laboratoire	83	115	611,25	435	-	-	166	35	123	0	0.114457831

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Table 4 (*continued*)

#ID	Pyrolysis phase duration (min)	Fire total duration (min)	Maximum tempera-tures (° C)	Average temperatures during flame phase (° C)	Atmospheric humidity (%)	Wind speed (m/s)	Amount of charcoal (> 4mm)	Amount of coniferous charcoal fragments (> 4mm)	Amount of deciduous charcoal fragments (> 4mm)	Amount of indeterminate charcoal fragments (> 4mm)	Ratio Fragments of *Picea* sp. Charcoal (> 4mm)
E_2016_Laboratoire	125	160	493,13	344	-	-	164	25	123	0	0.024390244
F_2016_Laboratoire	140	190	572	393	-	-	172	30	112	35	0.029069767
G_2016_Laboratoire	90	140	634	366	-	-	159	28	122	28	0.031446541
H_2016_Laboratoire	105	140	495	387	-	-	184	32	130	32	0.02173913
I_2016_Laboratoire	92	125	516	366	-	-	224	44	167	0	0.049107143
J_2016_Laboratoire	110	145	457	282	-	-	246	26	190	0	0.06097561
K_2016_Laboratoire	81	115	458	348	-	-	175	24	111	41	0.022857143
L_2016_Laboratoire	110	145	525	399	-	-	144	24	91	38	0.055555556
M_2016_Laboratoire	117	150	581	466	-	-	168	21	105	48	0.011904762
N_2016_Laboratoire	135	165	446	320	-	-	205	40	136	0	0.048780488
O_2016_Laboratoire	140	175	415	299	-	-	243	-	-	-	-

"quantities of charcoal", which is also not statistically significant but reflects the result obtained from the outdoor experiments as well (Fig. 5).

3.1.4. Discussion: Establishing a minimum number of observations for experimental studies

How many observations are needed for a meaningful statistical analysis? This question has no absolute answer. A number of studies quote the value of n = 30 as sufficient for any statistical analysis (Hogg and Tanis, 2006; Sullivan and LaMorte, 2016). Here, we tested the relationships between variables by means of contingency tables crossing two variables. The minimum total number of observations to obtain meaningful results depends on the number of rows and columns (number of modalities of the two variables). The more this number increases, the greater the total number of observations must be. By using variables with only two modalities, we achieved significant results with 32 observations (outdoor experiments), but not with only 21 observations (laboratory experiments). This difference corroborates the threshold of n = 30 mentioned above. So, further experimentation will use comparisons between two samples with a minimum size of 15 fires (i.e. the threshold of 30 individuals minimum), within each population defined by the experimental conditions (outdoors, and in the laboratory). We now know that this minimum of 30 individuals is needed to reach significance in statistical analyses of results in terms of differences based on one or a combination of parameters (with up to 10% risk for the observed difference to be due to chance). In all cases, the priority is to increase the number of laboratory experiments to reach this minimum threshold.

3.2. Beyond statistical evidence, future research avenues

3.2.1. Different fire behavior of driftwood and non-drifted wood

In our laboratory experiments, we observe that driftwood has a greater sensitivity to the addition of fat in comparison to non-drifted wood. Six fires were operated in the laboratory with driftwood, including three where fat was added; the other 15 laboratory fires used non-drifted wood, including 10 where fat was added (Table 4). As discussed, these numbers of test assays are too small to meet statistical significance. However, our laboratory experiments show that the average maximum temperatures (557 °C) reached by the three driftwood and fat fires is higher than that of driftwood only fires (501 °C, Table 9). We do not observe such difference in experiments where non-drifted wood is used: the average maximum temperature of the 10 non-drifted wood and fat fires is, in fact, lower (510 °C) than that of the 5 fires without fat (559 °C).

In addition, when looking at fire duration, we observe, although with no statistical significance (see above 3.1.3), that fat has a greater lengthening effect when added on a driftwood fire. The average duration of fires using driftwood and fat (149′) is 23 min longer than that of driftwood fires without fat (126′); it is only 10 min longer for fires using non-drifted wood (average duration is 139′ for fires without fat, and 149′ when fat is added, Table 9).

In our outdoor experiments using only driftwood to which fat was added, we also measured a statistically significant increase in fire duration. In terms of temperatures, even though the results are not all statistically significant, adding fat on driftwood in our outdoor fires did have an impact on the temperature of the fire (an increase of over 100°, Table 10).

With our laboratory fires, we observe that "driftwood only" fires reach a lower maximum temperature (501 °C) than "non-drifted wood only" fires (559 °C). It can be suggested that driftwood, or at least this combination of driftwood used, has less calorific value than the same non-drifted wood species. On the other hand, driftwood burned with fat (here pork fat) allows a maximum temperature of 557 °C to be obtained. This result approaches those obtained by a "non-drifted wood only" fire (559 °C, Table 9). This result is major because it seems that the addition

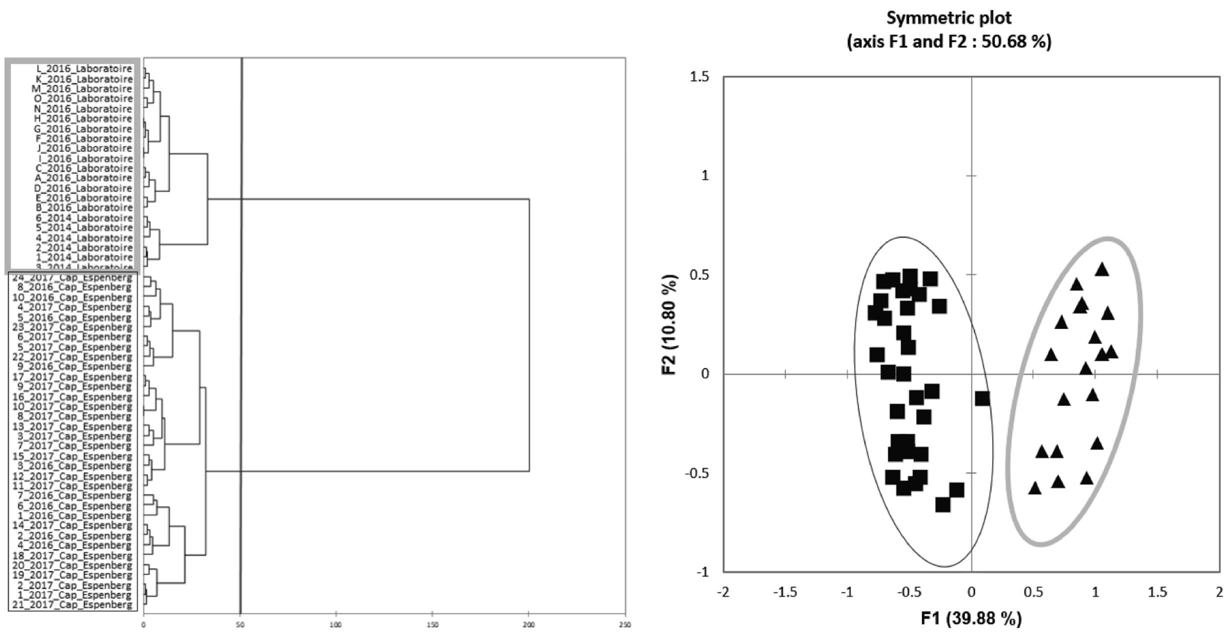

Fig. 3. Hierarchical ascendant classification tree (left) and Symmetric Correspondence Map (right) with net partition between laboratory fires (triangle) and outdoor fires at Cape Espenberg (square).

Table 5
Results from the outdoors experiments and their values (32 individuals × 4 variables) used for the multidimensional analysis; the measured variables (amount of charcoal, fire duration and temperatures) were each grouped into two classes separated by the median of Cape Espenberg observations.

#ID	Fat	Fire duration (min)	Max. Temperatures (°C)	Charcoal fragments (> 4mm)
1_2017_Cap_Espenberg	None	Short fire	High Temperature	Lots of charcoal
10_2016_Cap_Espenberg	None	Short fire	Medium Temperature	Few charcoal
10_2017_Cap_Espenberg	Fat	Short fire	High Temperature	Few charcoal
11_2017_Cap_Espenberg	Fat	Short fire	High Temperature	Lots of charcoal
12_2017_Cap_Espenberg	Fat	Short fire	Medium Temperature	Few charcoal
13_2017_Cap_Espenberg	Fat	Long fire	Medium Temperature	Lots of charcoal
14_2017_Cap_Espenberg	Fat	Long fire	High Temperature	Lots of charcoal
15_2017_Cap_Espenberg	Fat	Long fire	High Temperature	Few charcoal
16_2017_Cap_Espenberg	Fat	Long fire	High Temperature	Few charcoal
17_2017_Cap_Espenberg	Fat	Long fire	Medium Temperature	Few charcoal
19_2017_Cap_Espenberg	None	Long fire	Medium Temperature	Lots of charcoal
2_2016_Cap_Espenberg	Fat	Long fire	Medium Temperature	Lots of charcoal
2_2017_Cap_Espenberg	None	Short fire	High Temperature	Lots of charcoal
20_2017_Cap_Espenberg	None	Long fire	Medium Temperature	Lots of charcoal
21_2017_Cap_Espenberg	None	Short fire	Medium Temperature	Lots of charcoal
22_2017_Cap_Espenberg	None	Short fire	High Temperature	Few charcoal
23_2017_Cap_Espenberg	None	Short fire	High Temperature	Few charcoal
24_2017_Cap_Espenberg	None	Short fire	High Temperature	Few charcoal
3_2016_Cap_Espenberg	Fat	Long fire	Medium Temperature	Few charcoal
3_2017_Cap_Espenberg	None	Long fire	High Temperature	Few charcoal
4_2016_Cap_Espenberg	Fat	Long fire	Medium Temperature	Lots of charcoal
4_2017_Cap_Espenberg	None	Short fire	High Temperature	Few charcoal
5_2016_Cap_Espenberg	Fat	Short fire	High Temperature	Few charcoal
5_2017_Cap_Espenberg	None	Short fire	Medium Temperature	Lots of charcoal
6_2016_Cap_Espenberg	None	Long fire	Medium Temperature	Lots of charcoal
6_2017_Cap_Espenberg	None	Short fire	Medium Temperature	Few charcoal
7_2016_Cap_Espenberg	None	Short fire	Medium Temperature	Lots of charcoal
7_2017_Cap_Espenberg	Fat	Long fire	Medium Temperature	Lots of charcoal
8_2016_Cap_Espenberg	None	Long fire	Medium Temperature	Few charcoal
8_2017_Cap_Espenberg	Fat	Long fire	High Temperature	Few charcoal
9_2016_Cap_Espenberg	None	Short fire	Medium Temperature	Lots of charcoal
9_2017_Cap_Espenberg	Fat	Long fire	High Temperature	Few charcoal

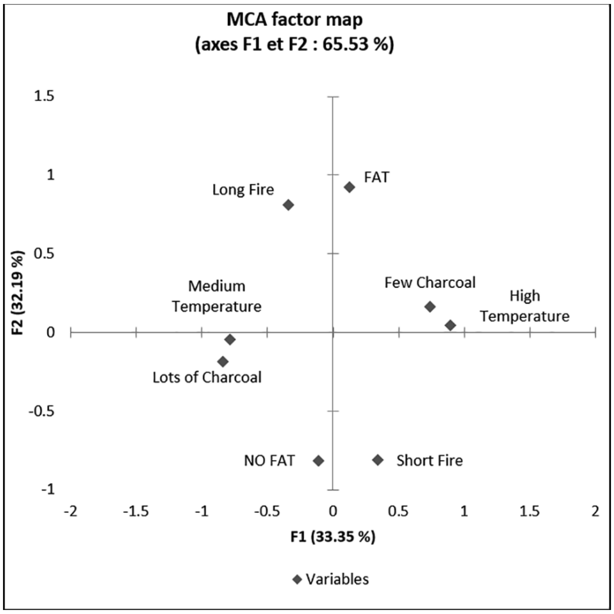

Fig. 4. Scatter plot of individuals in the first plan of the MCA for the 32 experimental outdoor fires at Cape Espenberg.

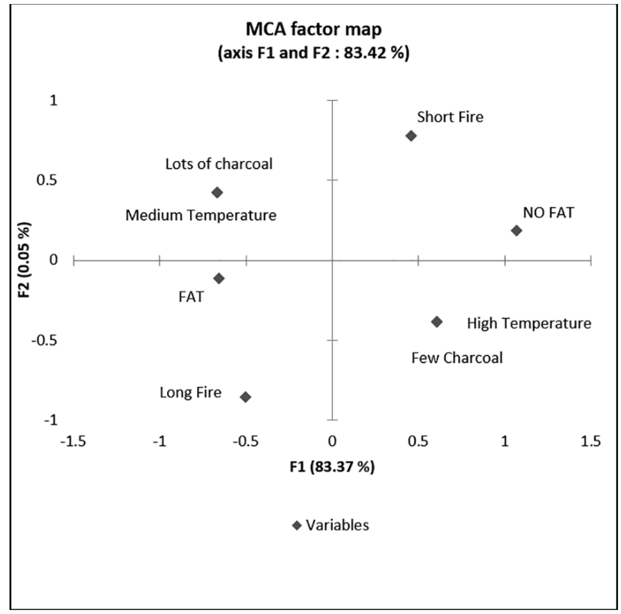

Fig. 5. Scatter plot of individuals in the first plan of the MCA for the 21 experimental laboratory fires.

of fat increases the efficiency of driftwood and therefore this fuel combination is "improved" and places them on the same level of fuel as wood in a forest environment.

This observed difference may be due to certain properties of driftwood, such as mineral salts [sodium (Na+)] soaked in the wood cell structure due to seawater contamination (Caruso Fermé et al., 2014; Yamada et al., 2014; Steelandt et al., 2016; Mooney, 2018). This could depend on the consequences of drifting (washout, drying, etc.) on the mechanical qualities of wood (Alix, 2001, pp. 117–118, 2004, p. 117).

This result allows us to better describe the fuel behavior of these resources, which are available but limited in the Arctic coast because these results do not correspond to what people say about driftwood in certain contexts. Interior Alaska people identify driftwood as lighter in weight, usually warmer than other wood if dried, a wood that burns well and throws a lot of heat (Williams, 2002). In other regions, driftwood is also described as a "clean fuel" due to the absence of sap (Russell, 1994; Lepofsky et al., 2003). On the northwest coast of Alaska, Burch (2006) and Saario and Kessel (1966) state that adding fat to a wood fire served to improve the heat capacity of a hearth.

These first concrete data on the fire behavior of driftwood, if confirmed, will have important implications for future studies of fireplaces in the Arctic and subarctic regions, in particular on the performance sought for a hearth according to its function. For our future fire experiments, the increase in test assays, with the same fuels and in the same quantities, will make it possible to reproduce these combinations and to test if they are statistically significant.

In this article, we discuss the modulation that can be obtained with different fuels (fat, bone, wood) in order to adapt the fire as needed. Here, we highlight the ability of people to adapt to available fuels to achieve similar or even better returns and the proof of a well mastered and optimized pyro-technology.

In addition to this important result, our observations in the laboratory also show the tendency for spruce to be better preserved when fat is added to a driftwood fire. Larger pieces of charcoal are produced;

Table 6
Burt Table for the 32 experimental outdoor fires at Cape Espenberg. Framed in bold: the contingency matrices (Burt's table sub-tables) that gave us significant results.

	Fat - No	Fat - Yes	Charcoal - A lot	Charcoal - Few	Duration - Shorter	Duration - Longer	Temperatures - High	Temperatures - Medium
Fat-No	17	0	9	8	12	5	7	10
Fat-Yes	0	15	6	9	4	11	8	7
Charcoal-A lot	9	6	15	0	7	8	4	11
Charcoal -Few	8	9	0	17	9	8	11	6
Duration-Shorter	12	4	7	9	16	0	9	7
Duration-Longer	5	11	8	8	0	16	6	10
Temperatures -High	7	8	4	11	9	6	15	0
Temperatures -Medium	10	7	11	6	7	10	0	17

a phenomenon not observed when non-drifted spruce wood is burned. While spruce (*Picea* sp.) largely dominates Arctic driftwood deposits (Alix, 2005; Steelandt et al., 2015), our results suggest that the high ratio of spruce charcoal regularly identified in archaeological sites of northwestern coastal Alaska where fat is omnipresent as fuel, may also result from issues of differential species preservation leading to an overrepresentation of spruce. However, it may also reflect a deliberate selection of the abundant spruce driftwood preferred for certain hearths functions. Future experimental and archaeological work is needed to assess these questions.

3.2.2. The question of mass and fragmentation of charcoal fragments

Charcoal analyses in Arctic contexts are rare and detailed data on driftwood used as fuel scant (Alix, 2016). Experimental combustion allows for better documenting the physico-chemical and mechanical transformations of wood when fat is added and how this can affect residual mass and fragmentation in archaeological assemblages.

Laboratory experiments showed that the addition of animal fat to a fire contributed to a higher quantity of charcoal remains and ashes (Table 10 and Table 11). In all our experiments, the presence of fat correlates with more combustion deformation of the wood's structure (radial cracks, shrinkage, vitrification, greasy appearance). This is consistent with the results obtained by Théry-Parisot (2000, 2002) in contexts where bones are used as fuel. These experiments may encourage anthracologists to look for these specific anatomical alterations (i.e. cracks, local deformations, vitrification) which may be discrete indicators of fat addition in fires. The inclusion of fatty residues within the cell structure of charcoal remains has been proposed as a key feature to identify the use of fat as fuel in hearths (Crawford, 2012). However, during the microscopic observation of charcoal remains from fires with fat, we found no trace or deposit of fat within the cell structures of the wood (Table 11).

Table 7
Chi-square test on different values tested statistically for the 32 experimental outdoor fires at Cape Espenberg.

		Variables			
Tests (null hypothesis tested: there is no link between rows and columns)		“Temperatures” and “Amount of charcoal”	“Fat” and “Fire duration”	“Fat” and “Amount of charcoal”	“Fat” and “Temperatures”
Chi-Squared test (with Yate’s Correction for Continuity)	**Chi² (observed value)**	3.229	4.518	0.142	0.111
	Chi² (critical value)	2.706	2.706	2.706	2.706
	DDL	1	1	1	1
	p-value (bilateral)	0.072	0.034	0.706	0.739
	Probability of rejecting the null hypothesis when it is actually true	< 7.24% null hypothesis can be rejected (alpha 0.1)	< 3.35% null hypothesis can be rejected (alpha 0.05)	70.61% null hypothesis cannot be rejected	73.93% null hypothesis cannot be rejected
Fisher’s exact test	**p-value (bilateral)**	0.042	0.032	0.502	0.723
	Probability of rejecting the null hypothesis when it is actually true	< 4.16% null hypothesis can be rejected (alpha 0.05)	< 3.20% null hypothesis can be rejected (alpha 0.05)	50.23% null hypothesis cannot be rejected	72.35% null hypothesis cannot be rejected

Table 8
Results from the laboratory experiments and their values (21 individuals × 4 variables) used for the multidimensional analysis; the measured variables (amount of charcoal, fire duration and temperatures) were each grouped into two classes separated by the median of laboratory observations.

#ID	Fat	Fire duration (min)	Max. Temperatures (°C)	Charcoal fragments (> 4 mm)
1_2014_Laboratoire	None	Short fire	Medium temperature	Few charcoal
2_2014_Laboratoire	None	Short fire	High temperature	Few charcoal
3_2014_Laboratoire	None	Short fire	Medium temperature	Few charcoal
4_2014_Laboratoire	Fat	Long fire	Medium temperature	Few charcoal
5_2014_Laboratoire	Fat	Short fire	High temperature	Few charcoal
6_2014_Laboratoire	Fat	Long fire	High temperature	Few charcoal
A_2016_Laboratoire	None	Short fire	High temperature	Lots of charcoal
B_2016_Laboratoire	None	Long fire	High temperature	Few charcoal
C_2016_Laboratoire	None	Short fire	High temperature	Lots of charcoal
D_2016_Laboratoire	None	Short fire	High temperature	Few charcoal
E_2016_Laboratoire	None	Long fire	High temperature	Few charcoal
F_2016_Laboratoire	Fat	Long fire	High temperature	Lots of charcoal
G_2016_Laboratoire	Fat	Short fire	High temperature	Few charcoal
H_2016_Laboratoire	Fat	Short fire	Medium temperature	Lots of charcoal
I_2016_Laboratoire	Fat	Short fire	Medium temperature	Lots of charcoal
J_2016_Laboratoire	Fat	Long fire	Medium temperature	Lots of charcoal
K_2016_Laboratoire	Fat	Short fire	Medium temperature	Lots of charcoal
L_2016_Laboratoire	Fat	Long fire	Medium temperature	Few charcoal
M_2016_Laboratoire	Fat	Long fire	High temperature	Lots of charcoal
N_2016_Laboratoire	Fat	Long fire	Medium temperature	Lots of charcoal
O_2016_Laboratoire	Fat	Long fire	Medium temperature	Lots of charcoal

Table 9
Mean calculated from the results of the experimental fires.

Outdoor Fires	**Fire total duration (min)**	**Maximum temperatures (°C)**	**Average temperatures during flame phase (° C)**
Mean Driftwood + Fat *(n = 15)*	159	1043	556
Mean Driftwood only *(n = 17)*	141	936	501
Laboratory Fires	**Fire total duration (min)**	**Maximum temperatures (°C)**	**Average temperatures during flame phase (° C)**
Mean Driftwood + Fat *(n = 3)*	149	557	373
Mean Driftwood only *(n = 3)*	126	501	356
Mean Non-drifted wood + Fat *(n = 10)*	149	510	363
Mean non-drifted wood only *(n = 5)*	139	559	392
Mean all wood + fat *(n = 13)*	149	521	365
Mean all wood only *(n = 8)*	134	537	378.5

Table 10
Observations after our experiments, concerning all types of fuels used.

Variables	Fires				
	Laboratory conditions		Outdoor conditions		
	Driftwood + Pork fat *versus* Driftwood only	Non-drifted wood + Pork fat *versus* Non-drifted wood only	Driftwood + Seal oil *versus* Driftwood only	Driftwood + Caribou bones *versus* Driftwood only	Driftwood + Seal oil + Caribou bones *versus* Driftwood only
Temperatures	Driftwood + Pork fat = Higher Temperature (56 °C)	Non-drifted wood + Pork fat: Lower Temperature (–48 °C).	Driftwood + Seal oil = Higher temperatures (107 °C)	Driftwood + Caribou bones = Lower temperatures	Driftwood + Seal oil + Caribou bones = Higher temperatures reached abruptly
Duration	Driftwood + Pork fat = Longer fire (23 min.)	Non-drifted wood + Pork fat = Longer fire (10 min.)	Driftwood + Seal oil = Longer Fire (± 20 min)	Driftwood + Caribou bones = Longer Fire (± 10 min)	Driftwood + Seal oil + Caribou bones = Longer Fire (± 15 min)
Charcoal preservation	Driftwood + Pork fat = Higher residual mass (ashes and charcoals)	Non-drifted wood + Pork fat = Higher residual mass (ashes and charcoals)	Driftwood + Seal oil = Higher residual mass (charcoals)	*No difference*	Driftwood + Seal oil + Caribou bones = More deformation of the wood's anatomical structures
	Driftwood + Pork fat = Larger and tougher 2 mm- and 4 mm charcoal	Non-drifted wood + Pork fat = Larger and tougher 2 mm- and 4 mm charcoal	Driftwood + Seal oil = Larger and tougher 2 mm- and 4 mm charcoal		
	Driftwood + Pork fat = More deformation of the wood's anatomical structures	Non-drifted wood + Pork fat = More deformation of the wood's anatomical structures	Driftwood + Seal oil = More deformation of the wood's anatomical structures		
Taxa preservation	Driftwood + Pork fat = Better preservation of spruce (*Picea* sp.) charcoal fragments	*No difference*	Driftwood + Seal oil = Better preservation of spruce (*Picea* sp.) charcoal fragments	*No difference*	Driftwood + Seal oil + Caribou bones = Better preservation of spruce (*Picea* sp.) charcoal fragments

Table 11
Comparison table between fires where fat has been added (wood fires are used as reference): ✓variables that seem to be impacted by the addition of animal fat, ×variables that do not show any difference following the addition of animal fat.

Variables		**Fires**			
		Laboratory conditions		**Outdoor conditions**	
		Driftwood + Pork fat	Non-drifted wood + Pork fat	Driftwood + Seal oil	Driftwood + Seal oil + Caribou bones
Temperatures	Higher Temperature	✓	×	✓	✓
Duration	Longer flame phase	✓	✓when soaked × when coated	✓	✓
	Longer Pyrolysis	✓	✓	✓	✓
	Longer fire	✓	✓	✓	✓
Charcoal Fragmentation	Better spruce preservation	✓	×	✓	✓
Charcoal Analysis	Higher quantities of remains	✓	✓	✓	×
	Higher deformation of wood's structures	✓	✓	✓	✓
	Fat-like substance deposits	×	×	×	×

3.2.3. The development of fire bed encrustations

The action of each fire assays left visible physical traces in the sandy soil of outdoor fire pits with noticeable differences according to fuel types.

- Six driftwood fires burned the sand only superficially, producing a thin red layer, with white and black ash stains, which was hardened but friable (Fig. 6-1).
- Seal fat in a driftwood fire left a thin crust after only one combustion test assay. After two successive assays, the walls of the firepit were burned and some agglomerates of fat-cemented sand and red ash stains were clearly visible. At the end of the third assay, these fatty and sandy agglomerates were even thicker and, after six successive combustions, the soil was completely burned and a 3 cm thick hardened crust was formed (Fig. 6-2).
- Caribou bones in driftwood fires did not produce the same hardened crust than when driftwood was burnt with seal oil. This is not surprising since the amount of fat present in 200 gr. of caribou bones is much lower than 200 gr. of pure seal oil. At the end of the six assays, a thin and brittle burned layer covered the loose sand of the surface and walls of the hearth pit (Fig. 6-3). The ash was thick (red, white and black) and we observed a loose and fatty mixture of ash and bone powder.
- Fires with driftwood, seal fat, and caribou bones produced a cemented sand crust at the bottom of the pit, similar to that created by the driftwood and seal fire, but this time, embedded with caribou bones (Fig. 6-4).

Given the rapid formation of this crust when fat is burned, we suggest that the thick burnt layers found in archaeological contexts (e.g. 50 cm to 1 m thick pits at the *Rising Whale* site) are not necessarily a sign of long-term occupation over many seasons, nor a period of extended hearth use. For future work, we will address questions such as: what does this mean when you have a large hearth (or small hearths lit in the same area)? If the fire goes on for an extended period of time, what is the rate of soil surface crusting thickening? Does the crust compact over time? Experimentation allows us to test the statistical significance of different fire configurations to create experimental references that can inform future analyses of archaeological combustion features.

Soil micromorphology analyses of our experimental pits are ongoing using Wattez methodological approach (Wattez, 1988, 1992, 2000; Vanlandeghem et al., 2016). This will help study the sedimentary expression of temperature's actions and address taphonomical and post-depositional questions. The future protocol will also stress the study of thermal alteration on the substrate of the combustion structures, and increasing the number of outdoor fires will help in obtaining statistically significant results for our analysis.

Fig. 6. Encrustation of firebeds after six trials of each experimental outdoor combustion type at Cape Espenberg.

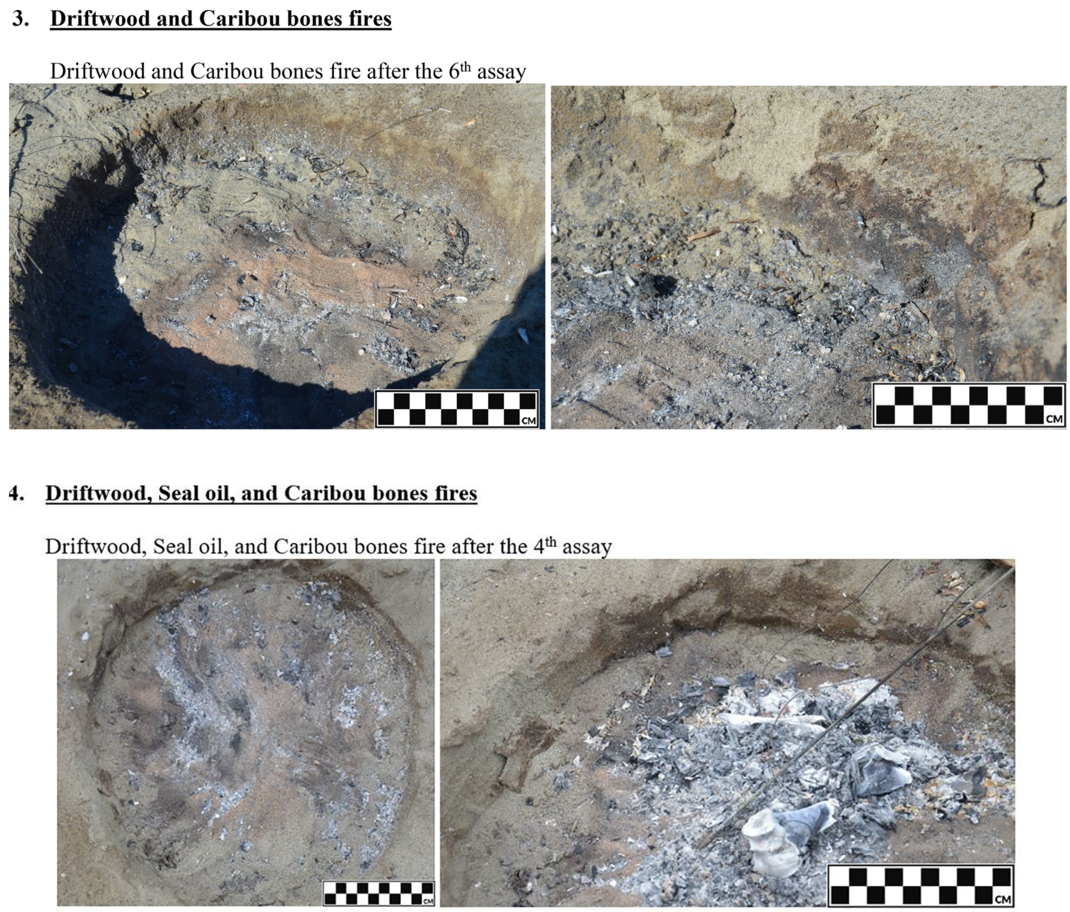

Fig. 6. (*continued*)

3.2.4. The question of fire-related activities

Based on our results (Table 11), and considering the different characteristics of fuel types, past Arctic inhabitants may have strategized their use of fuel resources for specific activities. The wood-only fire heats quickly and powerfully but is of short duration. The temperatures reached in a driftwood and caribou bones fire are lower than in fires with seal oil but produce enough heat to meet basic energy requirements and intermediate heat needs for boiling, heating, or lighting. Seal oil seems to be an ideal fuel for activities requiring higher temperatures over a longer period, potentially for craft functions (firing of ceramics) or the thermal treatment of the specific resources (meat drying, hide smoking).

The presence of marine mammal fat and burned bones in relatively high quantities in burned areas of some Arctic archaeological sites is unlikely to represent only the disposal of food refuse. Fat and bones recovered from these contexts are more likely the results of "secondary burning", meaning "not being prepared for consumption but rather burned as fuel during the process of cooking, heating, or lighting" (Norman, 2015, p. 126). Deliberately adding animal products as fuel to the fire would have allowed past inhabitants of coastal northwestern Alaska to alter the functions of their hearths according to their needs and supplement woody resources.

4. Conclusion: Implications for the archaeological record

Our results show that to statistically test two variables, a minimum of 30 observations is needed. We have found significant correlations between fire duration and the use of fat, and between fire temperature and the amount of charcoal. Observations also indicate that charcoal preservation changes with the addition of fat and that driftwood and non-drifted wood tend to burn differently in the presence of fat.

Using the threshold of 30 test assays as a necessary condition to reach statistical significance, future research will examine additional variables to further test for fuel characteristics of wood types (driftwood vs. non-drifted wood), of bone and fat (impact of animal products on fire brightness and smoke, incidence of burning wood soaked in fat vs. coated in fat), as well as charcoal taphonomy (effect of fragmentation on quantifying wood charcoal; effect of animal fuel on differential preservation of charcoals).

Results from our laboratory and outdoor experiments provide a framework to discuss why, when, and how past inhabitants of coastal northern Alaska used fires. Based on our experimental protocol, we are able to test how our empirical knowledge of archaeological data compares to the technical realities of past societies. This research encourages to further explore the taphonomic processes of fuel residues formation and contributes to developing additional research on past pyrotechnology.

Author contributions

MV, CA, CP, ME and IT-P contributed to the design and implementation of the research.

MV, CA, TB, LN and AC have helped with collecting and preparing samples, performing the analyses, and collecting the data.

MV, CA, and BD contributed to the analysis tools, discussed the results, performed the statistical analyses, and wrote the paper.

All authors validated the results and contributed to the editing of this manuscript.

Declaration of Competing Interest

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

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