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

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16
17 **Abstract**

18
19 Remains of animal fuel and driftwood fires are evident in Birnirk and Thule sites of northwestern
20 Alaska (AD 11th-14th century). To better understand these fires, a robust experimental protocol was
21 designed to study the effects of multi-fuel fires, in particular, the addition of fat to woody fuels. In Arctic
22 regions, permafrost and climate conditions do not allow for the development of tree vegetation. Marine
23 mammal oil and bones served as fuel substitutes, as did locally shrubby vegetation and driftwood
24 accumulations. The excavation of numerous thick burnt areas in many Arctic sites confirms the use of
25 multiple fuels including wood, animal fat, and bone in large quantities. These burnt areas correspond to a
26 wide range of fire activities—cooking, smoking, firing ceramics, and others—but the actions and effects
27 of each fuel are still poorly known.

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

40
41 **Keywords**

42
43 Fire Experiments; Statistical analysis; Animal fuels; Driftwood; Arctic Archaeology

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 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 heat¹. 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 (2014, 2017). 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 (Figure 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

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

91 have rarely been conducted, we chose to highlight the experimental results related to the action of animal
92 fat on driftwood and on the combustion deposit.

93 **2. Material and Methods**

94

95 **2.1. Materials and Experimental protocol**

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

103 We used seal fat (blended oil and blubber) and/or caribou bones to fuel hearths in outdoor conditions.
104 We fragmented all caribou bones and measured all fragments (length, diameter) before combustion.
105 Laboratory experiments were performed with pork fat (lard) marketed in France. Even though it differs
106 from marine mammal oil, pork fat was the best choice due to its 100% fat composition and low melting
107 point (36°C-40°C). Pork fat falls between the melting point range of seal oil [-8°C to 15°C] (Iverson,
108 2009) and of the marrow of caribou bones [40°C-48°C for femur and tibia, 15°C-22°C for metatarsus]
109 (Meng et al., 1969).

110 We replicated a total of 55 fires: 19 wood-only fires, and 33 “mixed” fires combining wood with fat
111 and/or bones (Figure 2). Each fire of the same context (laboratory or outdoor) used identical fuel
112 quantities and types. We recorded all pre-combustion characteristics (Table 3). Twenty-one controlled
113 archaeological experiments were conducted in the laboratory under fixed conditions. Our variables were
114 wood composition – driftwood or non-drifted wood – and the addition of fat – soaked or deposited. Each
115 of the 21 controlled fires had an equal wood mass of 600 to 900g., depending on the type of wood
116 (driftwood or non-drifted wood) using identical species composition. In fat and wood fires, we added 200
117 to 600g. of pork fat. Thirty-four outdoor archaeological experiments at Cape Espenberg aimed to create
118 fires under conditions close to those encountered in the past environment. We dug small basin-shaped pits
119 into the natural beach sand (50cm in diameter and 10cm deep). A series of combustion events using the
120 same fuel types took place in the same pits. Outdoor fires had an equal wood mass (3kg). We used either
121 driftwood-only, or mixed driftwood with fat fuel (150 to 220g. of seal oil per fire) and/or caribou bones
122 (approximately 200g., Table 2, Figure 2). Fuel weights were kept constant within each type of fire. In all
123 cases, the total fuel mass of each fire was accounted for in the analyses because it can have a direct
124 impact on the duration and the temperatures reached by the fire.

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

132 At the end of each combustion, we collected the fuel residues (charcoals and burnt materials).
133 Charcoals were sorted and counted to assess the rate of fragmentation of each wood taxa. We identified
134 charcoal fragments greater than 4 mm using a reflected light microscope. We also produced a reference

135 collection of wood samples used in the experiments for future reference². At the end of all outdoor
136 combustions, we recorded the nature of the fire bed's encrustation (thickness, friability) and collected
137 micromorphological samples from the bottom of the four different pits following sampling and analysis
138 procedures implemented by J. Watez³ (Watez, 1988, 1992, 2000; Vanlandeghem et al., 2016).

139

140 2.2. Statistical analysis

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

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

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

162

163 3. Results

164

165 3.1. Statistical significant results and emerging tendencies

166 3.1.1 All 55 fires: the experimental conditions stand out

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

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

174 experiments), and medium or high temperatures (below or above 957°C for outdoor experiments and
175 below or above 525°C for laboratory experiments).
176

177 3.1.2. Outdoor experiments: Adding fat significantly increases the duration of fires

178 An MCA was performed on 32 of the outdoor experimental fires. Two fires were excluded from the
179 analysis due to unexpected technical failure during the experiment which led to missing values (Table 5).
180 Figure 4 shows the correlations between some of the variables. Based on the counts provided by a Burt
181 Table (symmetric matrix of all two-way cross-tabulations between the variables, Table 6), the results of
182 the Yates's chi-squared tests and the Fisher's exact tests (Table 7) show significance between the
183 variables "temperature" and "quantities of charcoal", and between "addition of fat" and "fire duration".
184 There is no statistically significant correlation between "addition of fat" and "temperature", or between
185 "addition of fat" and "amount of charcoal".

186 The significant correlation between "addition of fat" and "duration of fire" can be interpreted
187 archaeologically: adding fat to hearths may correspond to the need for a longer flame duration or longer
188 pyrolysis. This result is a statistical confirmation of hypotheses and observations described in previous
189 archaeological and ethnographic studies (Saario, 1962, p. 51; Costamagno et al., 1998; Chabal et al.,
190 1999, p. 55; Théry-Parisot, 2000, 2002; Hoffecker, 2005; Glazewski et al., 2006, p. 18,23). Animal fat
191 (oil, blubber, bones grease, marrow) is an important fuel that contributes to the versatility of hearth
192 functions. The control of flames may have helped gain a higher luminosity, useful for manufacturing
193 tools, socializing, and/or storytelling. Longer pyrolysis would have been required for heating, indirect
194 cooking, slow roasting, fire maintenance (Théry-Parisot, 2013), and specialized combustion activities
195 such as ceramic firing.

196 The other significant correlation, between "temperature" and "amount of charcoal" has a natural
197 explanation: a higher temperature leads to more complete combustion and a smaller quantity of residual
198 charcoal.
199

200 3.1.3 Laboratory experiments: Adding fat tends to increase the duration of fires

201 We ran an MCA on all 21 fires (Table 4, Table 8). This plot shows that adding fat results in a longer fire
202 (± 15 -20min), although this relationship is not statistically significant (Burt Table test $P > 0.1$).

203 This relationship however is similar to that tested as significant in the above outdoor experiments.
204 This suggests that it is the same information which is conveyed in the two sets of experiments, outdoor
205 and laboratory, and that the lack of statistical significance of the laboratory experimental results is due to
206 a lower number of repeated fires than in the outdoor experiments. Especially since the MCA points to
207 another minor association between the variables "temperature" and "quantities of charcoal", which is also
208 not statistically significant but reflects the result obtained from the outdoor experiments as well (Figure
209 5).
210

211 3.1.4. Discussion: Establishing a minimum number of observations for experimental studies

212 How many observations are needed for a meaningful statistical analysis? This question has no
213 absolute answer. A number of studies quote the value of $n=30$ as sufficient for any statistical analysis
214 (Hogg and Tanis, 2006; Sullivan and LaMorte, 2016). Here, we tested the relationships between variables
215 by means of contingency tables crossing two variables. The minimum total number of observations to
216 obtain meaningful results depends on the number of rows and columns (number of modalities of the two
217 variables). The more this number increases, the greater the total number of observations must be. By
218 using variables with only two modalities, we achieved significant results with 32 observations (outdoor
219 experiments), but not with only 21 observations (laboratory experiments). This difference corroborates

220 the threshold of $n=30$ mentioned above. So, further experimentation will use comparisons between two
221 samples with a minimum size of 15 fires (i.e. the threshold of 30 individuals minimum), within each
222 population defined by the experimental conditions (outdoors, and in the laboratory). We now know that
223 this minimum of 30 individuals is needed to reach significance in statistical analyses of results in terms of
224 differences based on one or a combination of parameters (with up to 10% risk for the observed difference
225 to be due to chance). In all cases, the priority is to increase the number of laboratory experiments to reach
226 this minimum threshold.

227 **3.2. Beyond statistical evidence, future research avenues**

228 3.2.1. Different fire behavior of driftwood and non-drifted wood

229
230 In our laboratory experiments, we observe that driftwood has a greater sensitivity to the addition of
231 fat in comparison to non-drifted wood. Six fires were operated in the laboratory with driftwood, including
232 three where fat was added; the other 15 laboratory fires used non-drifted wood, including 10 where fat
233 was added (Table 4). As discussed, these numbers of test assays are too small to meet statistical
234 significance. However, our laboratory experiments show that the average maximum temperatures (557°C)
235 reached by the three driftwood and fat fires is higher than that of driftwood only fires (501°C , Table 9).
236 We do not observe such difference in experiments where non-drifted wood is used: the average maximum
237 temperature of the 10 non-drifted wood and fat fires is, in fact, lower (510°C) than that of the 5 fires
238 without fat (559°C).

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

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

248
249 With our laboratory fires, we observe that “driftwood only” fires reach a lower maximum
250 temperature (501°C) than “non-drifted wood only” fires (559°C). It can be suggested that driftwood, or at
251 least this combination of driftwood used, has less calorific value than the same non-drifted wood species.
252 On the other hand, driftwood burned with fat (here pork fat) allows a maximum temperature of 557°C
253 to be obtained. This result approaches those obtained by a “non-drifted wood only” fire (559°C , Table 9).
254 This result is major because it seems that the addition of fat increases the efficiency of driftwood and
255 therefore this fuel combination is “improved” and places them on the same level of fuel as wood in a
256 forest environment.

257 This observed difference may be due to certain properties of driftwood, such as mineral salts
258 [sodium (Na^+)] soaked in the wood cell structure due to seawater contamination (Caruso Fermé et al.,
259 2014; Yamada et al., 2014; Steelandt et al., 2016; Mooney, 2018). This could depend on the consequences
260 of drifting (washout, drying, etc.) on the mechanical qualities of wood (Alix, 2001, pp. 117–118, 2004, p.
261 117).

262 This result allows us to better describe the fuel behavior of these resources, which are available but
263 limited in the Arctic coast because these results do not correspond to what people say about driftwood in
264 certain contexts. Interior Alaska people identify driftwood as lighter in weight, usually warmer than other
265 wood if dried, a wood that burns well and throws a lot of heat (Williams, Sr., 2002). In other regions,
266 driftwood is also described as a “clean fuel” due to the absence of sap (Russell, 1994; Lepofsky et al.,
267 2003). On the northwest coast of Alaska, Burch (2006) and Saario and Kessel (1966) state that adding fat
268 to a wood fire served to improve the heat capacity of a hearth.

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

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

277 In addition to this important result, our observations in the laboratory also show the tendency for
278 spruce to be better preserved when fat is added to a driftwood fire. Larger pieces of charcoal are
279 produced; a phenomenon not observed when non-drifted spruce wood is burned. While spruce (*Picea* sp.)
280 largely dominates Arctic driftwood deposits (Alix, 2005; Steelandt et al., 2015), our results suggest that
281 the high ratio of spruce charcoal regularly identified in archaeological sites of northwestern coastal
282 Alaska where fat is omnipresent as fuel, may also result from issues of differential species preservation
283 leading to an overrepresentation of spruce. However, it may also reflect a deliberate selection of the
284 abundant spruce driftwood preferred for certain hearths functions. Future experimental and archaeological
285 work is needed to assess these questions.
286

287 3.2.2. The question of mass and fragmentation of charcoal fragments

288 Charcoal analyses in Arctic contexts are rare and detailed data on driftwood used as fuel scant (Alix,
289 2016). Experimental combustion allows for better documenting the physico-chemical and mechanical
290 transformations of wood when fat is added and how this can affect residual mass and fragmentation in
291 archaeological assemblages.
292

293 Laboratory experiments showed that the addition of animal fat to a fire contributed to a higher
294 quantity of charcoal remains and ashes (Table 10 and Table 11). In all our experiments, the presence of
295 fat correlates with more combustion deformation of the wood's structure (radial cracks, shrinkage,
296 vitrification, greasy appearance). This is consistent with the results obtained by Théry-Parisot (2000,
297 2002) in contexts where bones are used as fuel. These experiments may encourage anthracologists to look
298 for these specific anatomical alterations (*i.e.* cracks, local deformations, vitrification) which may be
299 discrete indicators of fat addition in fires. The inclusion of fatty residues within the cell structure of
300 charcoal remains has been proposed as a key feature to identify the use of fat as fuel in hearths (Crawford,
301 2012). However, during the microscopic observation of charcoal remains from fires with fat, we found no
302 trace or deposit of fat within the cell structures of the wood (Table 11).
303

304 3.2.3. The development of fire bed encrustations

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

- 307 - Six driftwood fires burned the sand only superficially, producing a thin red layer, with white and
308 black ash stains, which was hardened but friable (Figure 6-1).
- 309 - Seal fat in a driftwood fire left a thin crust after only one combustion test assay. After two
310 successive assays, the walls of the firepit were burned and some agglomerates of fat-cemented
311 sand and red ash stains were clearly visible. At the end of the third assay, these fatty and sandy
312 agglomerates were even thicker and, after six successive combustions, the soil was completely
313 burned and a 3cm thick hardened crust was formed (Figure 6-2).
- 314 - Caribou bones in driftwood fires did not produce the same hardened crust than when driftwood
315 was burnt with seal oil. This is not surprising since the amount of fat present in 200 gr. of caribou
316 bones is much lower than 200 gr. of pure seal oil. At the end of the six assays, a thin and brittle

317 burned layer covered the loose sand of the surface and walls of the hearth pit (Figure 6-3). The
318 ash was thick (red, white and black) and we observed a loose and fatty mixture of ash and bone
319 powder.

320 - Fires with driftwood, seal fat, and caribou bones produced a cemented sand crust at the bottom of
321 the pit, similar to that created by the driftwood and seal fire, but this time, embedded with caribou
322 bones (Figure 6-4).

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

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

337

338 3.2.4. The question of fire-related activities

339

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

347

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

355

356 4. Conclusion: implications for the archaeological record

357

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

362 Using the threshold of 30 test assays as a necessary condition to reach statistical significance, future
363 research will examine additional variables to further test for fuel characteristics of wood types (driftwood
364 vs. non-drifted wood), of bone and fat (impact of animal products on fire brightness and smoke, incidence

365 of burning wood soaked in fat vs. coated in fat), as well as charcoal taphonomy (effect of fragmentation
366 on quantifying wood charcoal; effect of animal fuel on differential preservation of charcoals).

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

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Author contributions

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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.

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Main Appendices

List of Figures

Figure 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)-----	17
Figure 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.-----	18
Figure 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)---	19
Figure 4: Scatter plot of individuals in the first plan of the MCA for the 32 experimental outdoor fires at Cape Espenberg-----	20
Figure 5: Scatter plot of individuals in the first plan of the MCA for the 21 experimental laboratory fires-----	21
Figure 6: Encrustation of firebeds after six trials of each experimental outdoor combustion type at Cape Espenberg-----	22

List of Tables

Table 1: Composition of the fire in wood taxa-----	24
Table 2: Composition of the fire and wood batches for outdoor experiments (above) and laboratory experiments (below) prior to combustion-----	24
Table 3: Complete instrumentation chain, from sample preparation to experimental combustions' data processing-----	26
Table 4: Results from the different types of experiments and their values (55 individuals x 21 variables) used for the multidimensional analysis (Figure 3) where the measured variables were grouped into two classes separated by the median. The underscore symbol means that data were not obtained.-----	27
Table 5: Results from the outdoors experiments and their values (32 individuals x 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-----	30
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-----	31
Table 7: Chi-square test on different values tested statistically for the 32 experimental outdoor fires at Cape Espenberg-----	31
Table 8: Results from the laboratory experiments and their values (21 individuals x 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-----	32
Table 9 : Mean calculated from the results of the experimental fires-----	33

Table 10: Observations after our experiments, concerning all types of fuels used ----- 34
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----- 35

Figure 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)

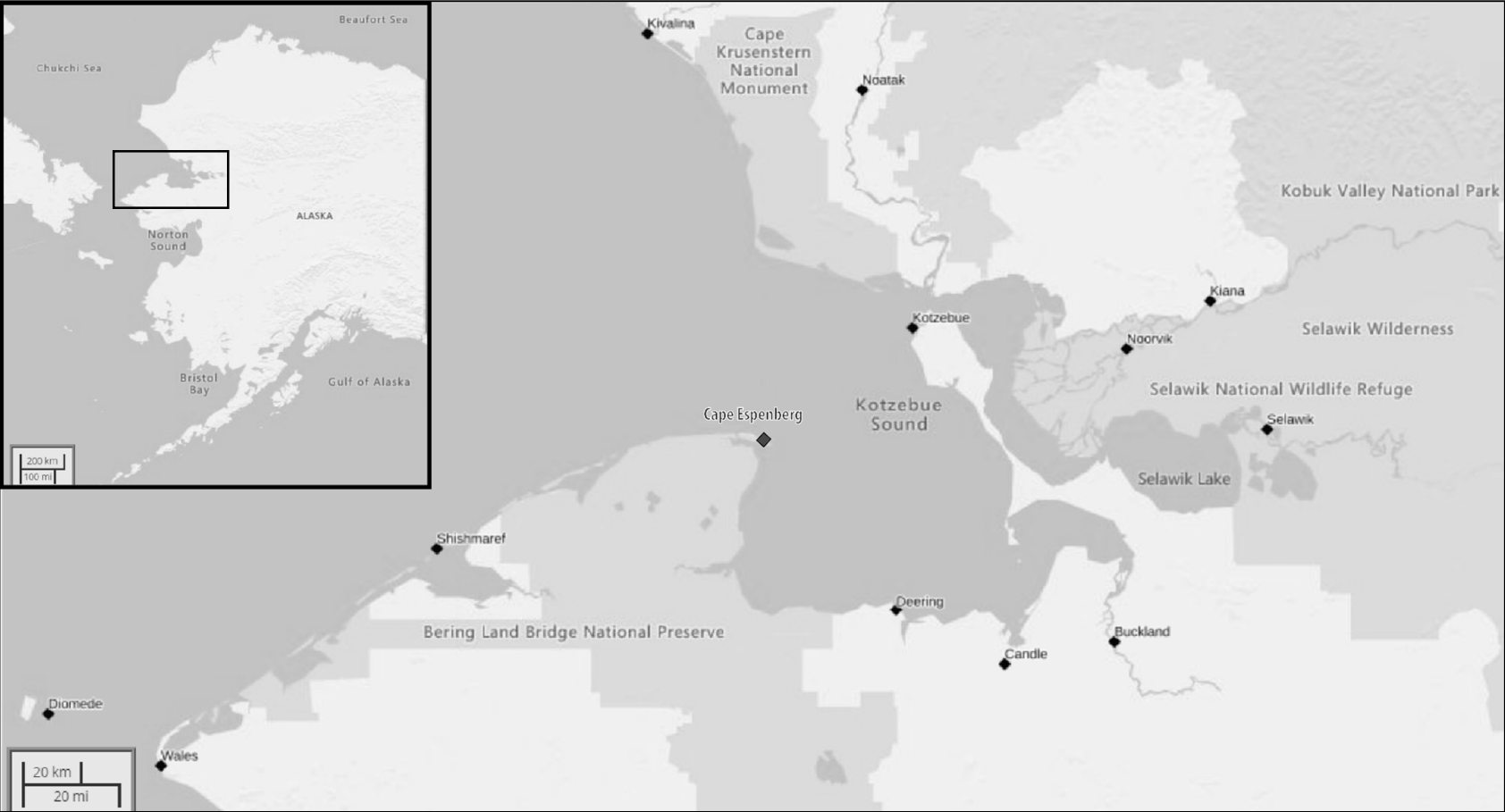


Figure 2: Schematic representation illustrating the several types of fire set up in this experimental protocol, in laboratory conditions in France and in outdoor arctic conditions at Cape Espenberg, Alaska.

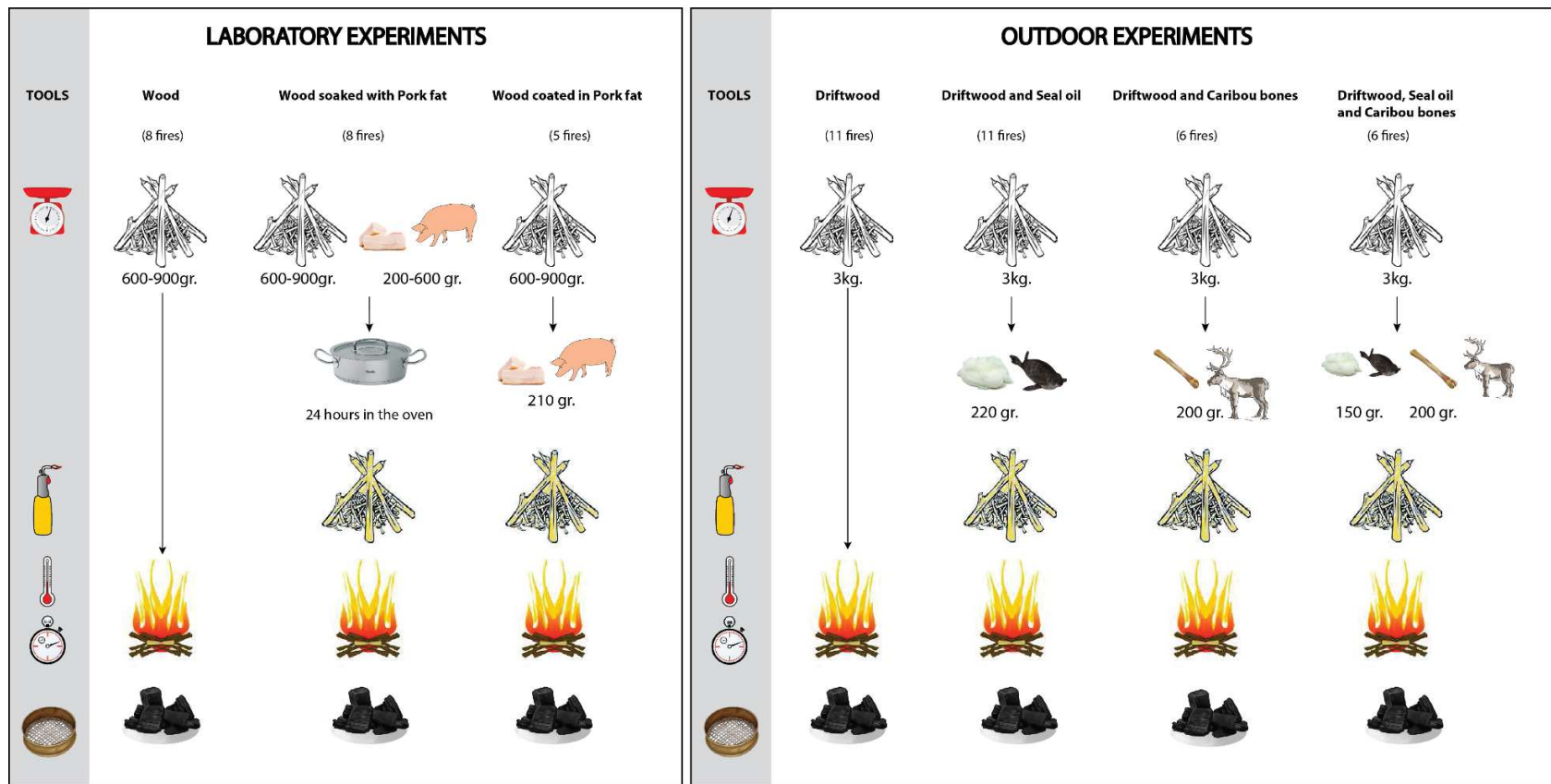


Figure 3: Hierarchical ascendant classification tree (left) and Symmetric Correspondence Map (right) with net partition between laboratory fires (triangle) and outdoor fires at Cape Espenberg (square)

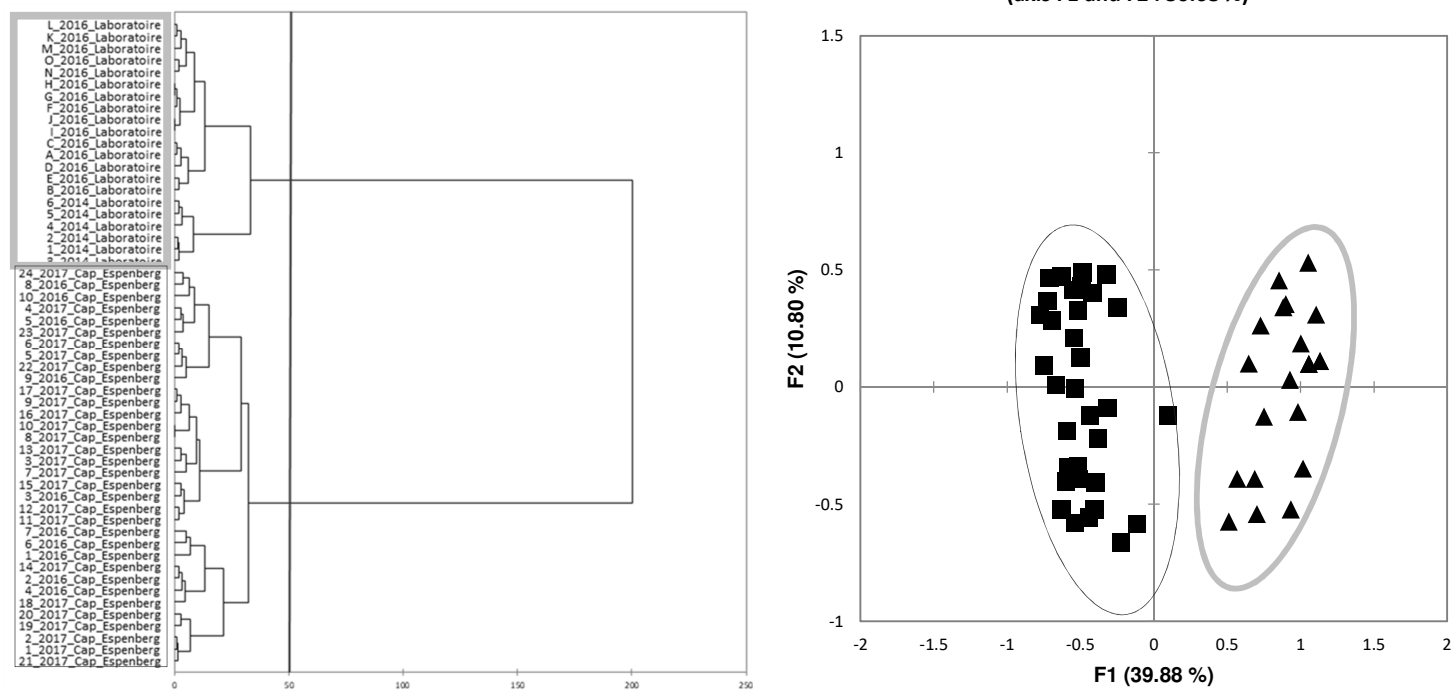


Figure 4: Scatter plot of individuals in the first plan of the MCA for the 32 experimental outdoor fires at Cape Espenberg

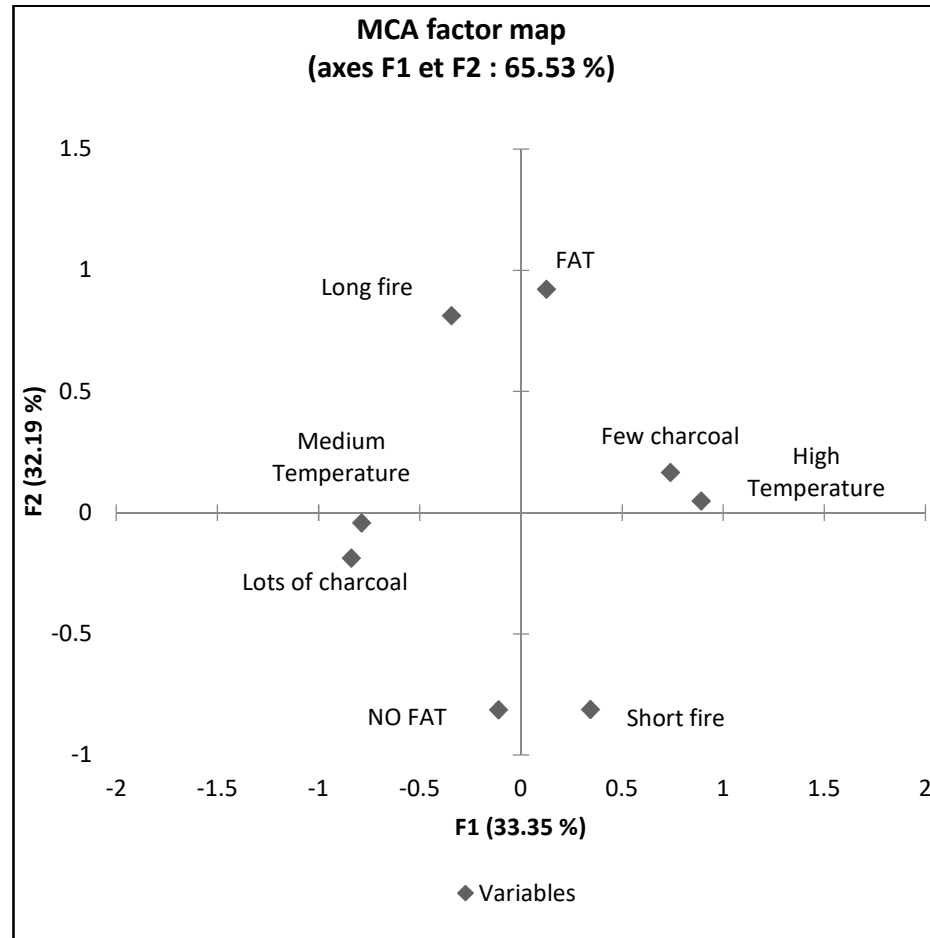


Figure 5: Scatter plot of individuals in the first plan of the MCA for the 21 experimental laboratory fires

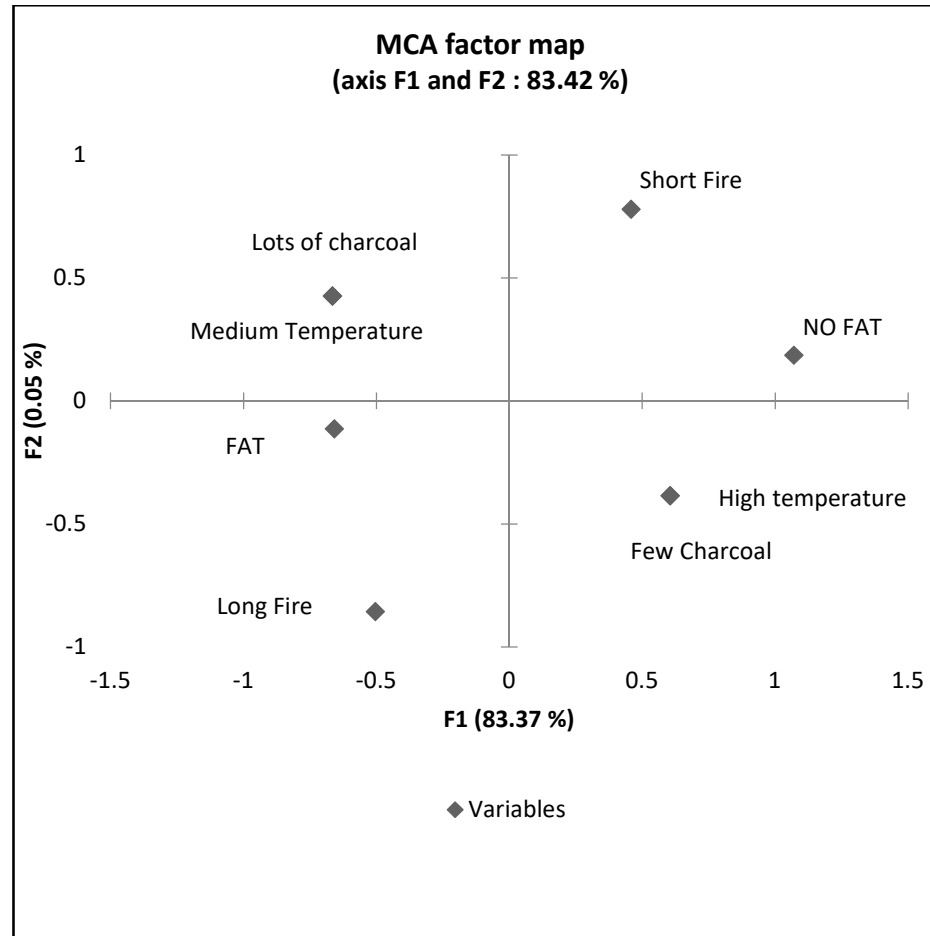


Figure 6: Encrustation of firebeds after six trials of each experimental outdoor combustion type at Cape Espenberg

1. Driftwood only fires

Driftwood only fire after the 6th assay



2. Driftwood and Seal oil fires

Driftwood and Seal oil fire after the 2nd assay

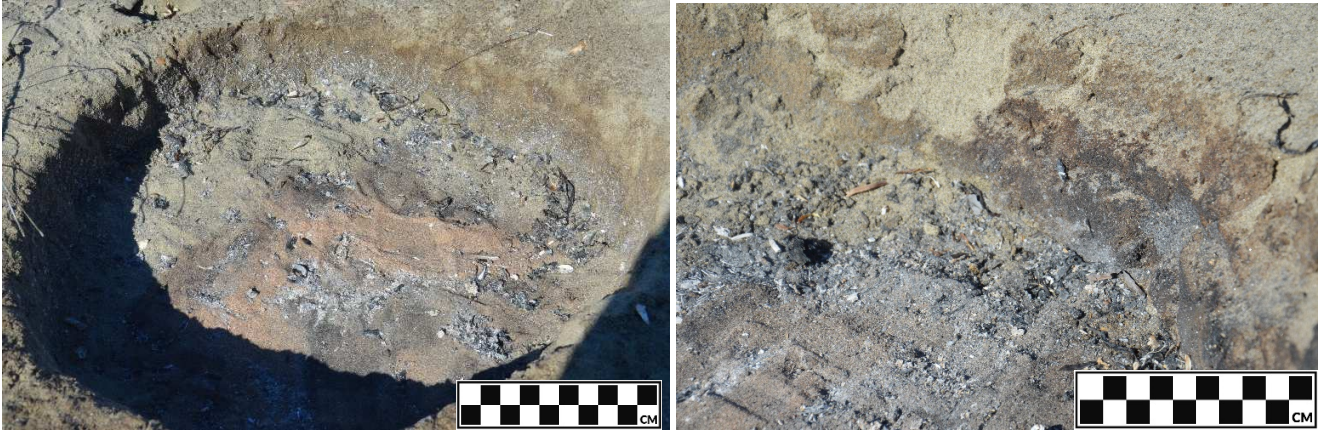


Driftwood and Seal oil fire after the 6th assay



3. Driftwood and Caribou bones fires

Driftwood and Caribou bones fire after the 6th assay



4. Driftwood, Seal oil and Caribou bones fires

Driftwood, Seal oil and Caribou bones fire after the 4th assay



Table 1: Composition of the fire in wood taxa

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

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 (<i>Picea</i> , <i>Salix</i> , <i>Populus</i>)	<i>Picea</i> sp.	<i>Salix</i> sp.	<i>Populus</i> sp.
Outdoor - Cape Espenberg		111911	3320	2810	105781	25580	43951	36250
<i>Driftwood</i>		111911	3320	2810	105781	25580	43951	36250
Driftwood fire		33771	0	0	33771	8110	14091	11570
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		36750	2420	0	34330	8440	14380	11510
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		20550	0	1670	18880	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		20840	900	1140	18800	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

Fuel Mass (grams) # Experiments	Total Mass (Fat, Wood)	Fat	Wood	<i>Picea</i> sp.	<i>Larix</i> sp.	<i>Picea/Larix cf. Picea</i> sp.	<i>Salix</i> sp.	<i>Populus</i> sp.	<i>Populus/Salix</i> sp.	<i>Alnus</i> sp.	<i>Betula</i> sp.	<i>Empetrum</i> sp.
Laboratory	18132	4054	14078	2672	1833	40	4133	2170	99	1425	1457	258
<i>Driftwood</i>	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
<i>Non-drifted wood</i>	10930	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
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

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




	<p>Pre-combustion</p> 	<p>Combustion</p> 	<p>Post-combustion</p> 
Fire	<p>Preparation of the experimental form</p> <ul style="list-style-type: none"> - Fire identification number - Date and time - Combustion surface (shape, size) - Fuel setting up - Installation of probes with thermal sensors for simultaneous recording 	<p>Weather conditions measurement</p> <ul style="list-style-type: none"> - Atmospheric humidity - Wind speed - Atmospheric temperature <p>Fire conduct measurements</p> <ul style="list-style-type: none"> - Duration of the three phases (ignition, flames, pyrolysis) - Total duration of the fire - Temperatures reached during these three phases (average and maximum temperatures) 	<p>Observations and photographs</p> <ul style="list-style-type: none"> - Encrustation of the fire bed - Fire residues <p>Analyzes</p> <ul style="list-style-type: none"> - Impact of the addition of animal fuel on the duration and temperature of wood fire <p>Other studies</p> <ul style="list-style-type: none"> - Micromorphology - Lipids and Isotopes - Magnetic Susceptibility
Fuel	<p>Preparation</p> <ul style="list-style-type: none"> - Wood cutting devices - Drying oven - Cutting of bones and extraction of the marrow <p>Measures</p> <ul style="list-style-type: none"> - Mass, volume, humidity and wood size - Mass of fat - Mass and size of bones - Total fuel mass <p>Batch registration</p> <ul style="list-style-type: none"> - 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 	<p>Setting up</p> <ul style="list-style-type: none"> - Lighting of wood with a blowtorch - Addition of animal fuel when lighting the wood (T = 10min) - Notes and photographs 	<p>Anthracological analysis</p> <ul style="list-style-type: none"> - Use of a 5 mesh-screen (4 mm, 2 mm, 1 mm, 0.5 mm, vat), - Mass of charcoal (4mm, 2mm, 1 mm, 500 µm, tank) - Amount of charcoal (4mm, 2mm) - Total residual mass of wood - 4mm charcoal's study: wood deformations, taxonomic assemblage' representativity, diagnostic anatomical signatures of fat and bone used as fuels. <p>Other analyzes</p> <ul style="list-style-type: none"> - Size and appearance of burned bones - Total residual mass of fuels - Total residual mass of bones

Table 4: Results from the different types of experiments and their values (55 individuals x 21 variables) used for the multidimensional analysis (Figure 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 <i>Picea</i> (g.) / Total Wood Mass	Flame phase duration (min)	Pyrolysis phase duration (min)	Fire total duration (min)	Maximum temperatures (° 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 <i>Picea</i> sp. Charcoal (>4mm)
1_2016_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	None	Coated	3070	29	0.28	-	-	-	-	-	-	-	191	36	72	83	0.188481675
1_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	None	None	3120	34	0.26	60	82	142	992	562	86	2.3	156	46	110	0	0.294871795
10_2016_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	None	None	2900	32	0.21	41	39	80	901,1	393	80	4.8	77	4	60	0	0.051948052
10_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	Caribou	Coated	3080	33	0.27	65	82	147	1095	675	73	2.5	55	37	18	0	0.672727273
11_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	Caribou	Coated	3050	30	0.24	65	46	111	1100	557	90	3.5	107	25	82	0	0.23364486
12_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	Caribou	Coated	3080	34	0.23	65	35	100	887	555	82	5	31	18	13	0	0.580645161
13_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	None	Coated	3160	30	0.20	95	140	235	901	557	87	1.5	114	27	87	0	0.236842105
14_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	None	Coated	3320	31	0.26	70	127	197	1229	526	73	1	130	33	96	1	0.253846154
15_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	None	Coated	3030	36	0.25	75	75	150	1081	570	90	0.8	25	8	17	0	0.32
16_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	None	Coated	3040	34	0.24	55	100	155	1148	466	64	4.2	10	8	2	0	0.8
17_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	None	Coated	3100	35	0.24	60	98	158	924	466	77	3	15	6	9	0	0.4
18_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	None	Coated	3230	34	0.23	65	83	148	960	602	73	5	-	-	-	-	-
19_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	Caribou	None	3190	30	0.24	80	121	201	858	387	87	1.5	194	48	146	0	0.24742268
2_2016_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	None	Coated	3360	30	0.29	73	112	185	745,1	477	67	4.2	157	32	90	35	0.203821656
2_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	None	None	3260	33	0.25	70	74	144	1182	630	73	2	167	58	109	0	0.347305389
20_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	Caribou	None	3120	31	0.24	80	80	160	809	438	73	1	158	51	107	0	0.32278481
21_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	Caribou	None	2940	36	0.26	65	65	130	889	471	90	0.8	178	79	99	0	0.443820225
22_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	Caribou	None	3400	34	0.24	55	65	120	968	465	64	4.2	99	23	76	0	0.232323232
23_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	Caribou	None	2920	35	0.21	70	78	148	974	471	77	3	70	10	60	0	0.142857143
24_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	Caribou	None	3310	34	0.26	65	71	136	945	464	73	5	48	8	38	2	0.166666667

#ID	Experimental conditions	Wood	Fat	Type of Fat	Bones	Addition of fat	Initial mass of wood (g.)	Wood moisture (%)	Ratio <i>Picea</i> (g.) / Total Wood Mass	Flame phase duration (min)	Pyrolysis phase duration (min)	Fire total duration (min)	Maximum temperatures (° 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 <i>Picea</i> sp. Charcoal (>4mm)
3_2016_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	None	Coated	2860	35	0.23	73	82	155	764,8	506	79	4.5	42	9	14	19	0.214285714
3_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	None	None	3140	35	0.22	65	97	162	996	608	76	3	59	31	28	0	0.525423729
4_2016_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	None	Coated	3290	32	0.26	71	104	175	769,35	601	64	1.5	188	25	152	5	0.132978723
4_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	None	None	3170	33	0.22	65	50	115	946	672	73	2.5	79	25	54	0	0.316455696
5_2016_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	None	Coated	2870	29	0.21	73	67	140	947,2	580	57	2.3	53	6	46	0	0.113207547
5_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	None	None	3020	33	0.25	36	68	104	828	541	68	5	114	51	63	0	0.447368421
6_2016_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	None	None	2980	32	0.27	100	100	200	842	438	_	_	173	29	132	12	0.167630058
6_2017_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	None	None	3171	33	0.24	50	40	90	939	612	84	5.5	105	34	71	0	0.323809524
7_2016_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	None	None	2750	31	0.21	60	65	125	731,5	444	79	4.5	194	32	147	15	0.164948454
7_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	Caribou	Coated	3220	32	0.22	60	90	150	932	632	86	2.3	173	53	120	0	0.306358382
8_2016_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	None	None	3010	31	0.25	60	150	210	578,5	390	75	1.2	25	4	15	6	0.16
8_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	Caribou	Coated	3210	32	0.24	75	85	160	1063	568	73	2	92	33	59	0	0.358695652
9_2016_Cap_Espenberg	Cape Espenberg	Driftwood	None	None	None	None	3250	33	0.25	50	75	125	661,5	530	70	0.8	171	61	83	6	0.356725146
9_2017_Cap_Espenberg	Cape Espenberg	Driftwood	Fat	Seal	Caribou	Coated	3160	34	0.24	75	107	182	1194	552	76	3	62	24	38	0	0.387096774
1_2014_Laboratoire	Laboratory	Driftwood	None	None	None	None	877	10.54	0.24	28	111	139	447	305	_	_	115	22	86	1	_
2_2014_Laboratoire	Laboratory	Driftwood	None	None	None	None	871	10.55	0.23	33	77	110	569	406	_	_	23	0	12	5	0.00
3_2014_Laboratoire	Laboratory	Driftwood	None	None	None	None	871	10.55	0.21	36	94	130	486	358	_	_	37	4	11	10	0.027027027
4_2014_Laboratoire	Laboratory	Driftwood	Fat	Pork	None	Soaked	873	10.55	0.22	40	116	156	494	342	_	_	102	5	95	2	_
5_2014_Laboratoire	Laboratory	Driftwood	Fat	Pork	None	Soaked	874	10.55	0.24	40	100	140	606	408	_	_	53	14	20	11	0.26
6_2014_Laboratoire	Laboratory	Driftwood	Fat	Pork	None	Soaked	862	10.55	0.23	45	106	151	571	369	_	_	65	6	26	16	0.030769231
A_2016_Laboratoire	Laboratory	Non-drifted wood	None	None	None	None	590	13	0.17	42	83	125	549	382	_	_	167	40	94	4	0.131736527
B_2016_Laboratoire	Laboratory	Non-drifted wood	None	None	None	None	567	13	0.17	40	125	165	587	398	_	_	160	20	132	19	0.05

#ID	Experimental conditions	Wood	Fat	Type of Fat	Bones	Addition of fat	Initial mass of wood (g.)	Wood moisture (%)	Ratio <i>Picea</i> (g.) / Total Wood Mass	Flame phase duration (min)	Pyrolysis phase duration (min)	Fire total duration (min)	Maximum temperatures (° 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 <i>Picea</i> sp. Charcoal (>4mm)
C_2016_Laboratoire	Laboratory	Non-drifted wood	None	None	None	None	592	13	0.17	33	97	130	556	400	-	-	184	33	144	29	0.027173913
D_2016_Laboratoire	Laboratory	Non-drifted wood	None	None	None	None	590	13	0.17	32	83	115	611,25	435	-	-	166	35	123	0	0.114457831
E_2016_Laboratoire	Laboratory	Non-drifted wood	None	None	None	None	586	13	0.17	35	125	160	493,13	344	-	-	164	25	123	0	0.024390244
F_2016_Laboratoire	Laboratory	Non-drifted wood	Fat	Pork	None	Soaked	593	13	0.16	50	140	190	572	393	-	-	172	30	112	35	0.029069767
G_2016_Laboratoire	Laboratory	Non-drifted wood	Fat	Pork	None	Soaked	597	13	0.17	50	90	140	634	366	-	-	159	28	122	28	0.031446541
H_2016_Laboratoire	Laboratory	Non-drifted wood	Fat	Pork	None	Soaked	590	13	0.17	35	105	140	495	387	-	-	184	32	130	32	0.02173913
I_2016_Laboratoire	Laboratory	Non-drifted wood	Fat	Pork	None	Soaked	596	13	0.16	33	92	125	516	366	-	-	224	44	167	0	0.049107143
J_2016_Laboratoire	Laboratory	Non-drifted wood	Fat	Pork	None	Soaked	592	13	0.17	35	110	145	457	282	-	-	246	26	190	0	0.06097561
K_2016_Laboratoire	Laboratory	Non-drifted wood	Fat	Pork	None	Coated	590	13	0.16	34	81	115	458	348	-	-	175	24	111	41	0.022857143
L_2016_Laboratoire	Laboratory	Non-drifted wood	Fat	Pork	None	Coated	595	13	0.16	35	110	145	525	399	-	-	144	24	91	38	0.055555556
M_2016_Laboratoire	Laboratory	Non-drifted wood	Fat	Pork	None	Coated	585	13	0.17	33	117	150	581	466	-	-	168	21	105	48	0.011904762
N_2016_Laboratoire	Laboratory	Non-drifted wood	Fat	Pork	None	Coated	593	13	0.17	30	135	165	446	320	-	-	205	40	136	0	0.048780488
O_2016_Laboratoire	Laboratory	Non-drifted wood	Fat	Pork	None	Coated	593	13	0.16	35	140	175	415	299	-	-	243	-	-	-	-

Table 5: Results from the outdoors experiments and their values (32 individuals x 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

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

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

Tests (null hypothesis tested: there is no link between rows and columns)	Variables	“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 x 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 (> 4mm)
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

Fires Variables	Laboratory conditions		Outdoor conditions		
	Driftwood + Pork fat <i>versus</i> Driftwood only	Non-drifted wood + Pork fat <i>versus</i> Non-drifted wood only	Driftwood + Seal oil <i>versus</i> Driftwood only	Driftwood + Caribou bones <i>versus</i> Driftwood only	Driftwood + Seal oil + Caribou bones <i>versus</i> Driftwood only
Temperatures	<ul style="list-style-type: none"> • Driftwood + Pork fat = Higher Temperature (56°C) 	<ul style="list-style-type: none"> • Non-drifted wood + Pork fat: Lower Temperature (-48°C). 	<ul style="list-style-type: none"> • Driftwood + Seal oil = Higher temperatures (107°C) 	<ul style="list-style-type: none"> • Driftwood + Caribou bones = Lower temperatures 	<ul style="list-style-type: none"> • Driftwood + Seal oil + Caribou bones = Higher temperatures reached abruptly
Duration	<ul style="list-style-type: none"> • Driftwood + Pork fat = Longer fire (23 min.) 	<ul style="list-style-type: none"> • Non-drifted wood + Pork fat = Longer fire (10 min.) 	<ul style="list-style-type: none"> • Driftwood + Seal oil = Longer Fire (±20 min) 	<ul style="list-style-type: none"> • Driftwood + Caribou bones = Longer Fire (±10 min) 	<ul style="list-style-type: none"> • Driftwood + Seal oil + Caribou bones = Longer Fire (±15 min)
Charcoal preservation	<ul style="list-style-type: none"> • Driftwood + Pork fat = Higher residual mass (ashes and charcoals) • Driftwood + Pork fat = Larger and tougher 2mm- and 4mm charcoal • Driftwood + Pork fat = More deformation of the wood's anatomical structures 	<ul style="list-style-type: none"> • Non-drifted wood + Pork fat = Higher residual mass (ashes and charcoals) • Non-drifted wood + Pork fat = Larger and tougher 2mm- and 4mm charcoal • Non-drifted wood + Pork fat = More deformation of the wood's anatomical structures 	<ul style="list-style-type: none"> • Driftwood + Seal oil = Higher residual mass (charcoals) • Driftwood + Seal oil = Larger and tougher 2mm- and 4mm charcoal • Driftwood + Seal oil = More deformation of the wood's anatomical structures 	<ul style="list-style-type: none"> • <i>No difference</i> 	<ul style="list-style-type: none"> • Driftwood + Seal oil + Caribou bones = More deformation of the wood's anatomical structures
Taxa preservation	<ul style="list-style-type: none"> • Driftwood + Pork fat = Better preservation of spruce (<i>Picea</i> sp.) charcoal fragments 	<ul style="list-style-type: none"> • <i>No difference</i> 	<ul style="list-style-type: none"> • Driftwood + Seal oil = Better preservation of spruce (<i>Picea</i> sp.) charcoal fragments 	<ul style="list-style-type: none"> • <i>No difference</i> 	<ul style="list-style-type: none"> • Driftwood + Seal oil + Caribou bones = Better preservation of spruce (<i>Picea</i> 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

Fires Variables		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	✗	✗	✗	✗