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1 **Title: The socio-ecological legacies of centuries-old charcoal making practices in a mountain forest of the**
2 **Northern Pyrenees**

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14

15

16 Highlights

17 • Past charcoal making practices were reconstructed through analysis of charcoal remains

18 • These practices were transmitted over centuries without significant change

19 • Management shifted from coppice-with-standard to coppice-selection to high forest

20 • The resulting forest homogenization induced a decrease in biodiversity hosting capacity

21 • The socio-cultural legacy of this ancient forest is currently threatened

22

23 **Abstract**

24 Centuries of charcoal making has profoundly shaped European mountain forest ecosystems. However, it
25 remains difficult to assess this impact due to a lack of knowledge about the full operational sequence and related
26 silvicultural systems. To accurately reconstruct such practices and shed light on the resulting legacies, we
27 carried out an interdisciplinary study in the Bernadouze forest, a 46 ha mountain forest of European beech
28 (*Fagus sylvatica* L.) in the French Pyrenees. We performed a multi-proxy analysis of 7990 charcoal fragments
29 from 28 charcoal kilns to assess the long-term changes in forest composition and structure, but also in
30 harvesting practices and related silvicultural systems. In addition, we assessed the legacy of such practices on
31 the forest's main features, by evaluating the biodiversity on 13 one-hectare plots using the Index of Potential
32 Biodiversity (IBP). The 18 radiocarbon dates showed that charcoal making took place at least from the 9th-10th
33 c. to the 19th-20th c. Beech and silver fir (*Abies alba* Mill.) were the main species used. We discerned
34 sustainable silvicultural practices performed over the centuries without significant change. Charcoal burners
35 harvested well calibrated wood pieces mostly from the end of the growing season until the early spring, and
36 charred after a seasoning period. The forest was managed as a beech coppice with fir standard before being
37 progressively transformed, between the mid 15th-mid 17th c. period, into a monospecific beech coppice,
38 probably treated in a coppice selection system. While this management allowed forest cover to be continuously
39 sustained, it also resulted in the homogeneity of the forest today, both in composition and structure, and led to
40 low hosting capacity for biodiversity. Nevertheless, this ancient forest, which constitutes a high biocultural
41 legacy due to immemorial use rights, needs dedicated management.

42 **Key words: charcoal making practices, technical operational sequence, forest management, anthracology,**
43 **IBP, centuries-old legacies**

44

45 Introduction

46 Current forest research emphasizes the importance of developing more holistic approaches to account for the
47 long-term legacies of human activity (Bergès and Dupouey, 2017; Paradis-Grenouillet et al., 2018a; Rostain and
48 Saulieu, 2018; Bergès and Dupouey, 2020). An evolving framework of interdisciplinary research, called
49 historical ecology, has been developing over the past 40 years with significant advances over the last two
50 decades (Crumley, 1994; Szabó, 2015; Watkins, 2015; Bergès and Dupouey, 2020). In this conceptual field, the
51 forest is considered a constructed heritage, resulting from interactions between societies and the environment
52 over time. This diachronic perspective allows (i) the study of current forest stands to be carried out in historical
53 depth, (ii) a better comprehension of their evolution in the medium and long term, and finally (iii) an
54 understanding of the current structure and functioning of ecosystems in order to better guide conservation
55 objectives and to predict future dynamics (Peterken, 1993; Kirby and Watkins, 1998; Rackham, 2003; Cevalco
56 and Moreno, 2015; Szabó, 2015; Bürgi et al., 2017).

57 Among key analytical approaches developed in the field of historical forest ecology, the study of soil and
58 archaeological charcoal, called anthracology, provided tools to renew our knowledge of woodland landscapes
59 from a historical and socio-environmental perspective in the *longue durée* of forest ecosystems (Nelle et al.,
60 2013; Feiss et al., 2017; Dufraisse and Coubray, 2018; Moreno et al., 2019).

61 In the early 1990s, researchers became increasingly interested in charcoal remains from artisanal and industrial
62 activities, particularly those recorded in former charcoal making terraces, so-called charcoal kilns (CKs). Such
63 charcoal remains testified to pre-industrial logging-induced spatio-temporal changes in the structure and
64 composition of forest ecosystems (Hillebrecht, 1982; Bielenin, 1992; Pott et al., 1992; Davasse, 2000;
65 Montanari et al., 2000; Bonhôte et al., 2002; Ludemann and Nelle, 2002). Contrary to the long-accepted idea
66 that pre-industrial woodfuel supply activities heavily contributed to land clearance, past societies were shown to
67 have introduced management systems that, while degrading forest ecosystems, nonetheless maintained tree
68 cover and woodland resources (Deforce et al., 2013; Py et al., 2013; Samojlik et al., 2013; Schmidt et al., 2016;
69 Benatti et al., 2018).

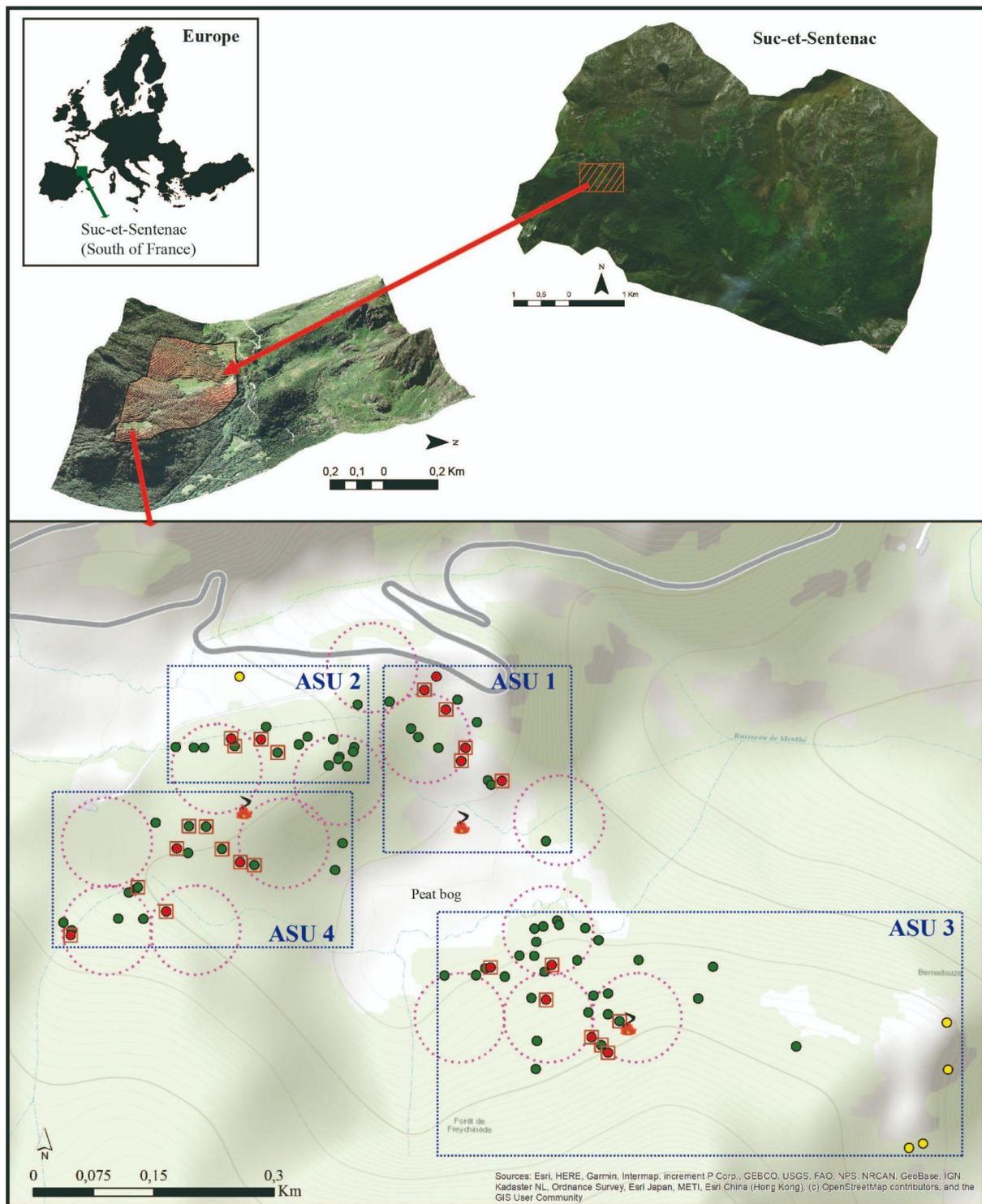
70 A better knowledge of forest management history and woodland changes induced by charcoal making
71 necessarily requires an in-depth understanding of the resulting practices (logging, species and wood caliber
72 selection, etc.) and their temporalities (seasonality, cutting rotation, etc.). Available data mainly rely on
73 ethnographic observation (Acovitsioti-Hameau, 2001; Hanus, 2007; Burri, 2008; Burri et al., 2010), modern

74 scholarly treatises (e.g. Biringuccio, 1556; Della Fratta Montalbano, 1678; Duhamel Du Monceau, 1761;
75 Bellenghi, 1816; Marié de L'Isle, 1835; Malepeyre, 1836; Valerius, 1851; Percy, 1864; Svedelius et al., 1875;
76 Dromart, 1880), and/or experimental approaches (Poggi and Métaillé, 1998; Fregni and Maccaferri, 2010;
77 Paradis-Grenouillet, 2012). However, the only way to develop an understanding of local practices and, more
78 broadly, to learn how people worked before modern times, is to study CK remains. In this perspective, wood
79 scientists are developing dendrometric and dendrochronological tools to accurately reconstruct the entire
80 technical operational sequence of charcoal production, from wood selection and removal to silviculture
81 management and the charring process (Ludemann and Nelle, 2002; Strachan et al., 2013; Raab et al., 2015;
82 Dupin, 2018; Paradis-Grenouillet et al., 2018a; 2018b; Fouédjeu et al., 2021).

83 This study proposes an innovative combination of archaeological, anthracological, and ecological approaches to
84 characterise past charcoal making practices and better understand how related silvicultural systems have driven
85 shifts in the forest trajectories using the well-known example of the Northern central Pyrenees. In this area, the
86 rarefaction of silver fir (*Abies alba* Mill.) and the expansion of beech (*Fagus sylvatica* L.) are commonly
87 considered a consequence of harvesting selection for the production of charcoal needed in the historical iron
88 metallurgy industry (Davasse, 2000; Bonhôte et al., 2002; Py-Saragaglia et al., 2018; 2019). Beech, able to
89 regrow from stump or stool, would have been favoured by coppicing (Davasse and Galop, 1990; Davasse,
90 2000). However, it remains difficult to precisely date the shift from a mixed beech-fir forest to a monospecific
91 beech forest. In addition, while the development of beech coppice silviculture is a common working hypothesis,
92 there is no solid evidence for this from before the 17th c. (Davasse, 2000). Therefore, the origins of coppicing in
93 a northern Pyrenean beech-fir forest, its rise and fall and its relation to charcoal production, need further
94 investigation. Furthermore, the extent to which the legacies of forest conversion has constrained current
95 biodiversity is still unexamined.

96 To address all of these issues, we applied an interdisciplinary approach in the forest of Bernadouze (Suc-et-
97 Sentenac, Ariège), which is representative of most Northern Pyrenean mountain forests deemed to have a long-
98 lasting charcoal making history. We suggest that the current forest structure and composition result from many
99 centuries of charcoal burning practices. We test this assumption by suggesting (i) that charcoal-making history,
100 related forest management practices and their evolution can be reconstructed using charcoal analyses, and (ii)
101 that current biodiversity and habitat functions are still impacted by the legacies of this history of charcoal
102 production. Beyond these research hypotheses, we discuss how the insights of historical ecology could

103 contribute to improving future forest management and, more broadly, to taking forests as biocultural heritage in
104 future policies.



105
106 Fig. 1: Sampling design of the Bernadouze forest green points represent the totality of recorded and sampled
107 CKs (n=80); red points, CKs (n=17) dated by C14; red squares, CKs with dendro-anthracological analysis

108 (n=25); red circles, IBP plots (n=13); “fires” represent pedoanthracological pits (n=3); yellow points represent
109 pastoral sites (n=5) .

110 1. Materials and methods

111 1.1. The survey area

112 The study area (1300 to 1450 m.a.s.l) detailed in Saulnier et al. (2019), is located on the northern slope of the
113 Pyrenees in the upper Vicdessos valley, hosting a permanent Human-Environment Observatory (called in
114 French “OHM Haut-Vicdessos”) aiming at studying long-term human-environment relationships (Fig. 1). Soils
115 (rendisols, calcisols and brunisols), which developed on recrystallized limestone, are characterised by a silty-
116 clayey texture in various proportions and by basic pH values. Current vegetation consists of three main beech
117 stand types: (i) high forest resulting from the conversion of former selection coppice with individuals aged
118 between 130-160 years, with rare and scattered fir trees (Py-Saragaglia et al., 2018; Fouédjeu et al., 2021), (ii)
119 tall-grown coppices of old trees from a coppice selection method, and (iii) tall-grown coppices around the peat
120 bog boundary that have been browsed in the past. A set-aside area (90 ha), which includes the study area and an
121 adjacent peat bog, is managed by the French National Forest Office as a Managed Biological Reserve (RBD),
122 which allows for occasional active management interventions for pre-defined conservation objectives. To this
123 end, group-selection harvesting has been prescribed in the buffer zone surrounding the bog.

124 1.2. Archaeological survey, CK selection and sampling strategy

125 To reconstruct charcoal making chronology and its intensity through time, we carried out a systematic
126 archaeological field survey that afforded the detection of 80 CKs on about 46 ha (Fig. 1). In addition, five
127 undated pastoral sites were georeferenced.

128 The study area was divided into four Analysis Spatial Units (ASU) according to their exposure and topography
129 (Fig.1). In each ASU, for charcoal analysis, we randomly selected 4 to 9 CKs (n=28) in order to be fully
130 representative of the ASU studied, i.e. proportionally of the total numbers of CKs per ASU.

131 Because most CKs exhibited a thick layer of charcoal (ranging from 20 to 120 cm thick) mixed with a very
132 black and homogeneous soil, generally without any stratigraphy, stepwise sampling was carried out using a soil
133 auger, every 20 cm in depth from the first horizon (A) to the ochre sterile and continuous mineral layer as is

134 detailed in Py-Saragaglia et al. (2017). Samples for each 20 cm layer from all sampling points carried out on the
135 same terrace (at least six per CK) work together and form the so-called “charcoal layer” (CL). A total of 57 CLs
136 were analyzed (Fig. 1).

137 Among all studied CKs, we selected 18 charcoal samples from 17 CKs for radiocarbon analysis. These samples
138 are constituted by a mix of several charcoal fragments - preferably young twigs with bark, charcoal fragments
139 with bark, or bark alone -, dated as a single sample. This approach aims to reduce errors that may be associated
140 with dating a single fragment that may be intrusive (Py et al., 2013). Radiocarbon dating by Accelerator Mass
141 Spectrometry (AMS) was calibrated using the OxCal program, version 4.4 Intcal 20 database (Reimer et al.,
142 2020).

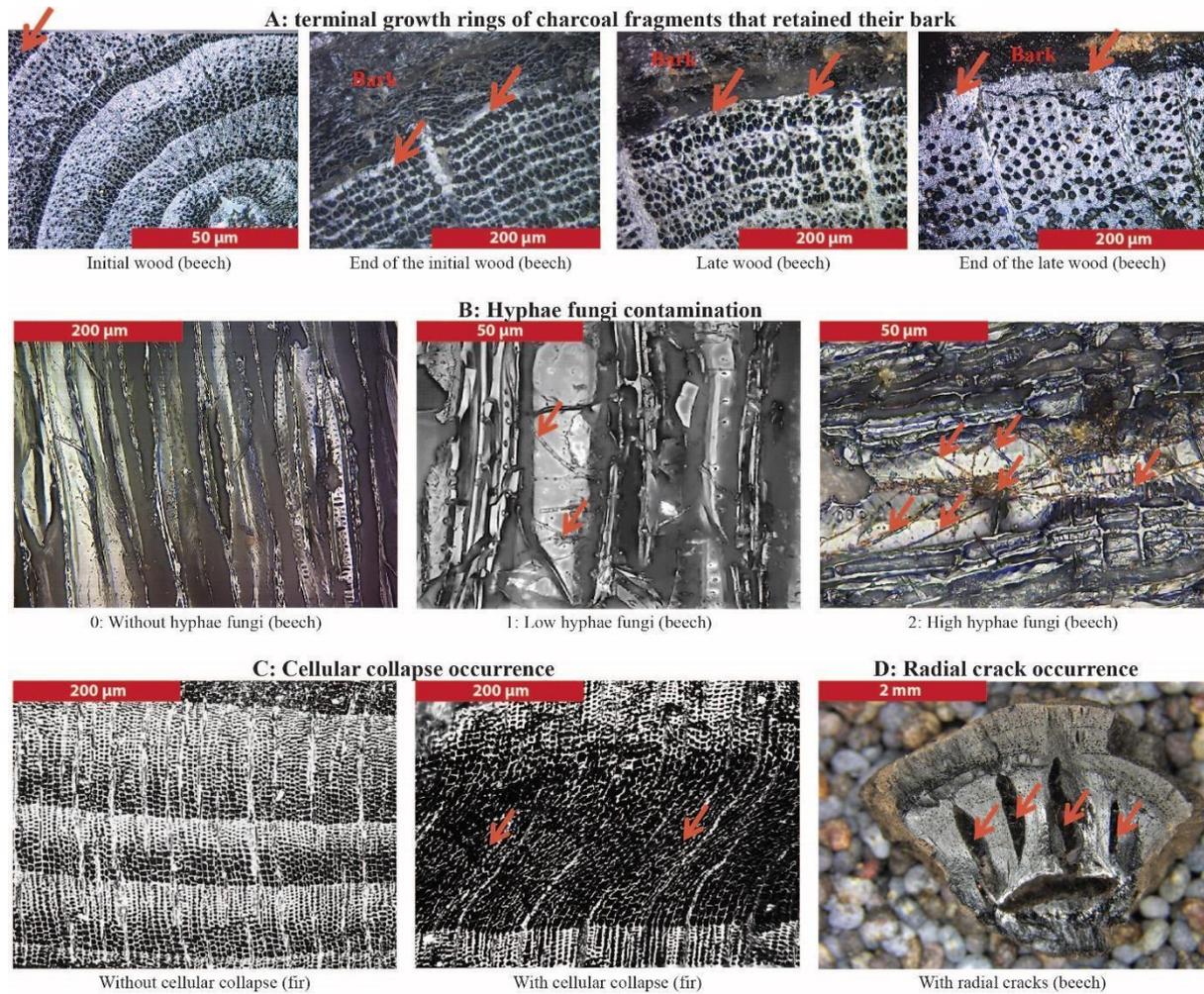
143 1.3. Analysis of the charcoal dataset

144 Tree species used for charcoal production were identified at the species, genus, family or sub-family level using
145 a reflected light microscope (Leica DM4 with magnifications of 100, 200, 500 and 1000), xylological atlases
146 (Schweingruber, 1990; Vernet et al., 2001) and the reference collection of the GEODE laboratory.

147 To determine the annual timing of logging operations, we observed the state of progress of the last ring’s
148 formation when charcoal has retained bark cells (Fig. 2A). We then grouped samples into two categories: (i)
149 vegetative period (last ring ended between early wood and the end of early wood) and (ii) end of vegetative
150 period (last ring ended between late wood and end of late wood). Hereafter, the timing of harvesting was
151 calculated as:

$$152 \quad T_h = ((N_{vp} - N_{evp}) / N_{cb}) * 100$$

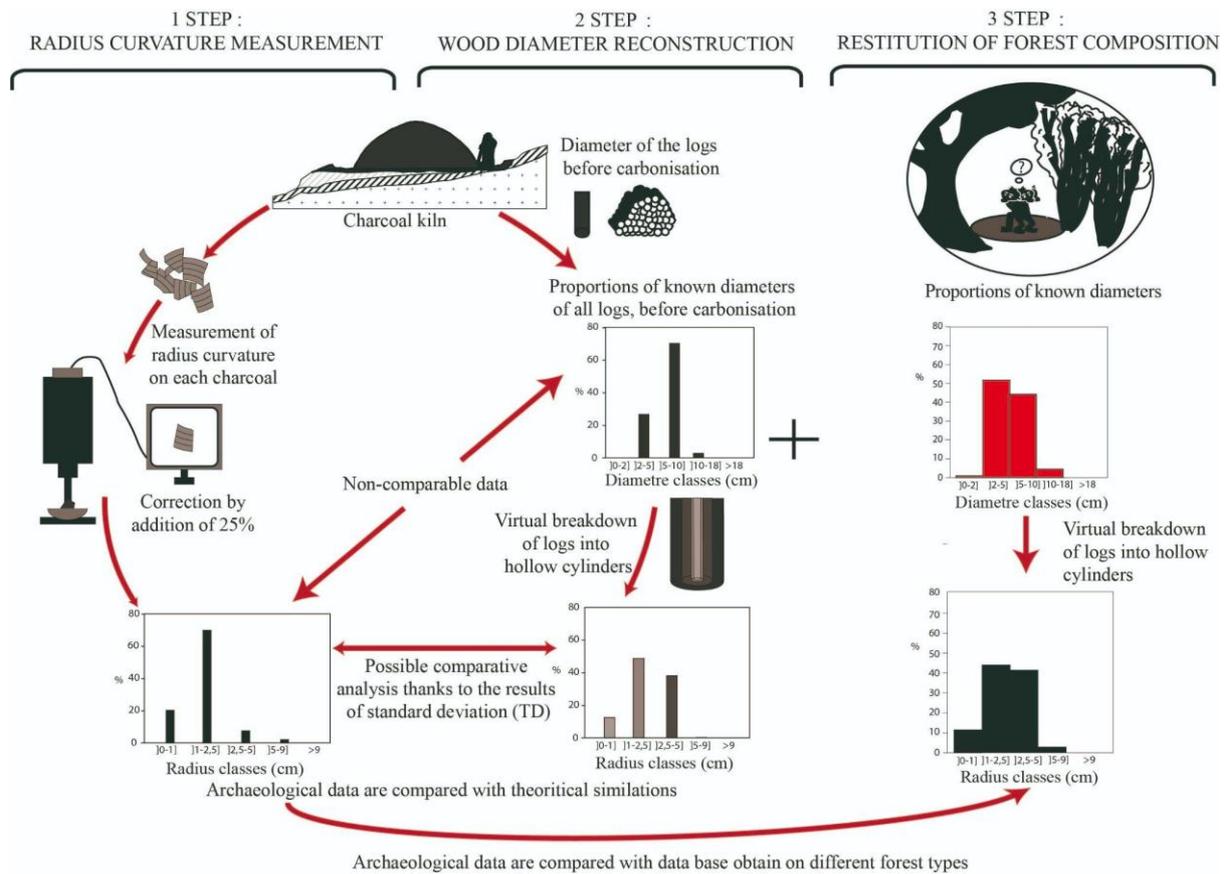
153 where T_h is the timing of harvesting, N_{vp} and N_{evp} are, respectively, the number of charcoal samples for which
154 the terminal ring ended in early wood/late early wood or in late wood, and N_{cb} is the number of charcoal
155 samples with bark remains.



156

157 Fig. 2 Photos illustrating: terminal growth rings of charcoal fragments that retained their bark (A), hyphae fungi
 158 contamination (B), cellular collapse (C), and radial cracks (D)

159 In order to reconstruct harvested wood diameters, we applied the three-step method described in Paradis-
 160 Grenouillet et al. (2015) (see Appendix 1 for more details) (Fig.3) : (step 1) we measure the radius of curvature
 161 of charcoals with at least 3 rings, and a cross-section ≥ 3 mm using the AnthracoloJ program; (step 2) we
 162 reconstitute the different diameters of logs composing the wood pile by comparing archaeological data with 405
 163 mathematical simulations and the Total Deviation (TD) shows the reliability of comparison; (step 3) we
 164 compare the reconstituted wood pile to wood pile references established in current stands in order to
 165 characterize the shape/morphology of the harvested stands (i.e. different types of coppice, high forest).



166

167 Fig. 3. Illustration of the three steps required to find wood diameter (Paradis-Grenouillet et al., 2015, modified).

168 To assess the logging cyclicality and to reconstruct coppicing rotation, we systematically counted the number of
 169 rings observed on charcoal pieces, except for fragments where the number of rings was not readable, giving the
 170 minimum age of wood pieces used by charcoal burners.

171 In order to characterize the state of wood harvested (dead or alive) and test for an eventual storage period in
 172 forest, we characterized the degree of deterioration of the charred wood using (i) the mean number of radial
 173 cracks (RC) per cm² on the transverse plane of the charcoal (Fig. 2D) (Théry-Parisot and Henry, 2012), (ii) the
 174 degree of charred fungal hyphae infestation in cells (Moskal-del Hoyo et al., 2010; Saulnier et al., 2019) and
 175 (iii) the cellular collapse that informs about the decay stage of the wood (healthy or decayed) (Fig. 2B, 2C)
 176 (Henry and Théry-Parisot, 2014). Four contamination levels (Cont. 0 to Cont. 3) were defined (see appendix 4,
 177 Table 1). A Decay Index (DI) was calculated based on a weighted mean average (Théry-Parisot et al., 2016):

178
$$DI = (nb \text{ "Cont.1" } \times 1 + nb \text{ "Cont.2" } \times 2 + nb \text{ "Cont.3" } \times 3) / nb \text{ total.}$$

179 1.4. Assessment of current stand capacity to host biodiversity

180 To assess the effect of former charcoal practices on current stand biodiversity, a diagnosis was carried out using
 181 the Index of Biodiversity Potential (IBP; Larrieu and Gonin, 2008) on 13 one-hectare plots, centered around a
 182 subset of the assessed CKs. The IBP is a biodiversity evaluation tool according to Larsson (2001) that combines
 183 ten key historical, structural, and compositional factors for forest-dwelling species, which are easily and directly
 184 measurable in the field (for more details, see Gosselin and Larrieu (2020) and Appendix 2). It can be used as a
 185 rapid habitat assessment method to evaluate the hosting capacity of stands for forest biodiversity (Larrieu et al.,
 186 2012; Bouget et al., 2014; Larrieu et al., 2019a). The raw number of items (e.g. number of tree species, habitat-
 187 trees, etc.) counted when getting through the stand is compared with thresholds values to set a score for each
 188 factor which ranges from 0 to 5. Then, the sum of the scores given for each of the 10 factors (potential range 0-
 189 50) provides an index of the stand's hosting capacity (Larrieu and Gonin, 2008).

190 2. Results

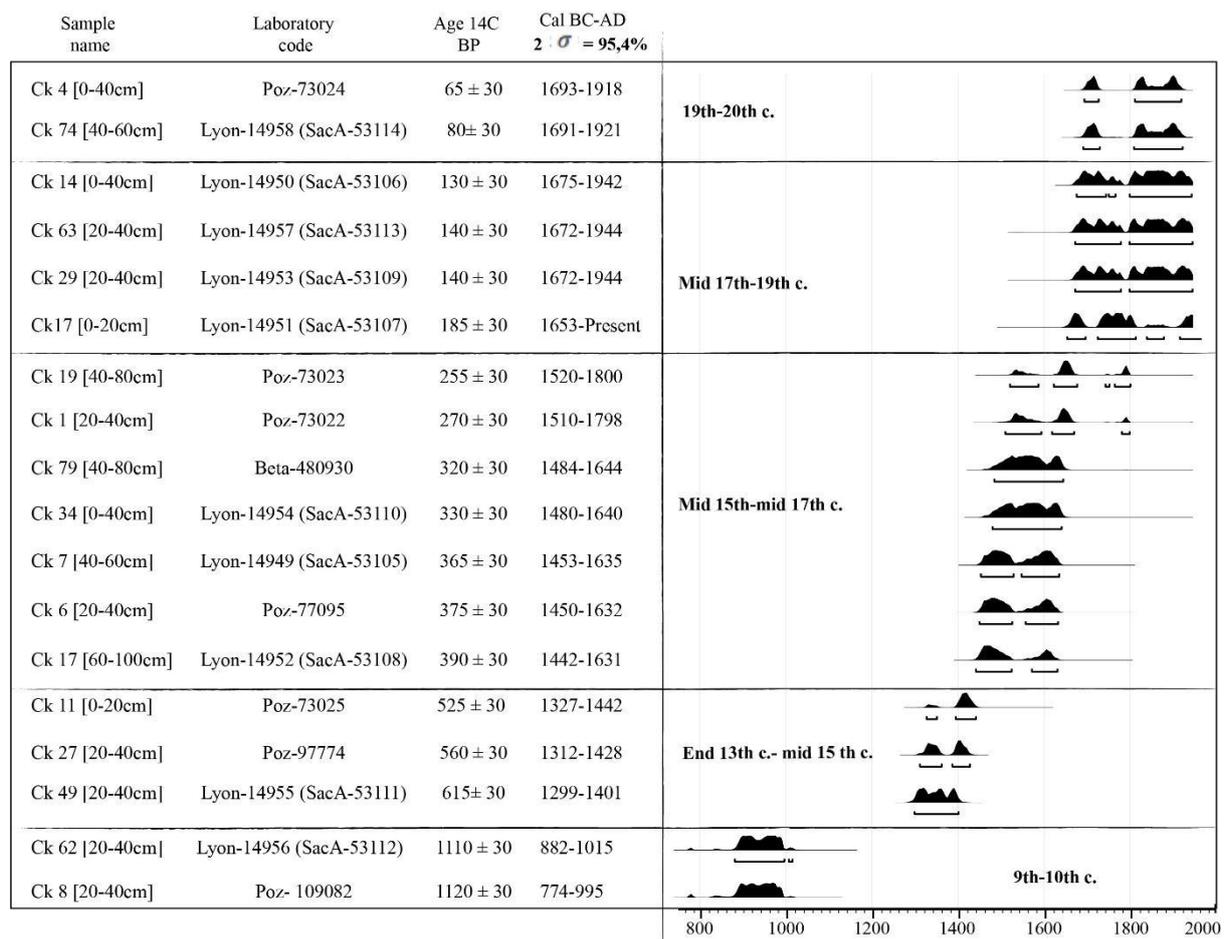
191 2.1. Chronology of charcoal making activity

192 The 18 radiocarbon dates are distributed from the 9th-10th c. to the 19th-20th c., with a maximum number
 193 concentrated from the mid-15th to 19th c. We classified them into five historical periods based on radiocarbon
 194 ranges (Table 1; Fig. 4).

195 Table 1: Historical periods based on radiocarbon range of charcoal production in the Bernadouze forest

Historical periods based on radiocarbon ranges (1 or 2 σ = 70 to 95.4% of probability)	Number of dates	N° charcoal kiln
19th c. - 20th c.	2	4, 74
Mid-17th c. -19th c.	4	14, 17, 29, 63
Mid-15th c. - mid 17th c	7	1, 6, 7, 17, 19, 34, 79
End 13th c. - mid 15th c.	3	11, 27, 49
9th c. - 10th c.	2	8, 62

196



197

198 Fig. 4. Plot of radiocarbon dates for charcoal kilns in the Bernadouze forest distributed into five historical
 199 periods. Data were calibrated with OxCal v4.4.4 Bronk Ramsey (2021); r:5 Atmospheric data from Reimer et al.
 200 2020.

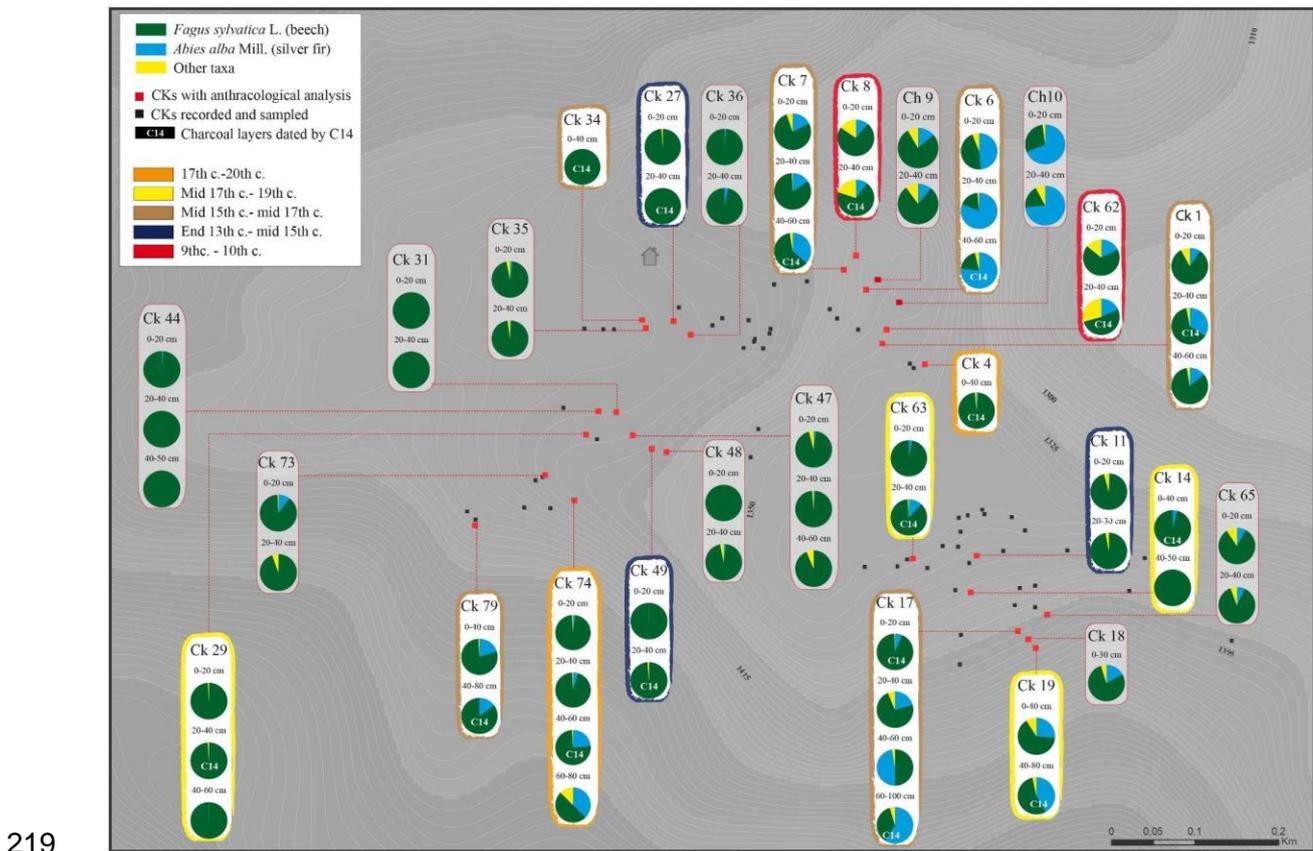
201 2.2. Wood selection for charcoal production

202 2.2.1. Selected tree species and seasonality of logging

203 We identified two main species (Fig. 5 and 6): beech (n=5605) and fir (n=1438). We also identified 19 other tree
 204 taxa with relative frequencies below 1% (Fig. 5 and 7): (i) pioneer taxa, i.e. legume family (Fabaceae), birch
 205 (*Betula*), willow (*Salix*), grey alder (*Alnus incana* L.), alder (*Alnus*), juniper (*Juniperus*), (ii) post-pioneer taxa,
 206 i.e. wild cherry (*Prunus*), scots/mountain pine (*Pinus*), evergreen and deciduous oak (*Quercus*), apple sub-
 207 family (Rosaceae, Maloideae), mountain ash (*Rosaceae, Maloideae cf. Sorbus*), hazel (*Corylus*), ash (*Fraxinus*),
 208 rose (*Rosa*), elm (*Ulmus*), and, (iii) shade-tolerant tree taxa (so-called “dryads”), i.e. holly (*Ilex aquifolium* L.),
 209 common yew (*Taxus baccata* L.) and fir/juniper (*Abies alba/Juniperus*). When similar anthracological (tree taxa

210 proportions) and dendro-anthracological (diameters) spectra were recorded from several CLs of the same CK,
211 they were combined in a single CL (e.g. CKs 4, 14, 17, 18, 19, 31, 34, 74).

212 Regarding seasonality of logging, out of the 7990 charcoal pieces analyzed, 597 charcoal pieces (only 8.1% of
213 the total corpus) have retained their bark. Results show that 3 CLs were dominated by wood felled during the
214 vegetative period, 33 by wood felled during the end of the growing season, and 21 had wood felled during both
215 periods for beech (Appendix 4, Fig.1A). They correspond respectively to CLs 2, 5 and 3 for these same periods
216 for fir (Appendix 4, Fig.1B). Different seasonality of logging is sometimes observed within CLs of the same CK
217 (e.g. CKs 1, 6, 17, 29, 49, 79 etc.). These cases mostly represent CLs where it was not possible to differentiate
218 between timber felled between the vegetative period and the end of the growing season (Appendix 4, Fig.1A,B).



219
220 Fig. 5. Results of charcoal analysis by charcoal kilns (CKs) and by charcoal layers (CLs) in the Bernadouze
221 forest.

222 2.2.2. Wood diameter reconstruction, number of rings and the minimum age of the charred wood

223 We restituted the radius curvature of 3003 charcoal pieces, i.e. those with a minimum transverse section of 3
224 mm, from 45 CLs (Appendix 1), including 2602 beech fragments distributed across 25 CKs (Appendix 4, Fig. 2)
225 and 401 of fir, distributed across 4 CKs (Appendix 4, Fig. 3).

226 Data from 41 CLs out of the total of 43 CLs for beech, and from all CLs for fir highlight good correlation (TD
227 between 20 and 40 %), sometimes very good (TD < 20%), with simulated data (Appendix 4, Fig. 2 and 3).

228 Results for beech show the dominance of small diameters (less than 5 cm), and the low presence of medium (5
229 to 10 cm) and large (10-20 cm) diameters (Fig. 6; Appendix 4, Fig. 2). Regarding fir, we observed a mix of all
230 diameter classes with the dominance of the 2-15 cm diameters and a small proportion of very large wood (>20
231 cm) (Fig. 6; Appendix 4, Fig. 3).

232 The minimum number of rings was counted on 5534 beech charcoal samples and 1436 fir samples (Fig. 6;
233 Appendix 3). We observed the predominance of charcoal with 1 to 5 tree rings preserved: 55.9% for beech and
234 66.1% for fir. Charcoal with 6-15 rings represented 37.1% for beech and 25.6% for fir. In addition, a few
235 samples kept 16-30 rings: 6.2% for beech and 6.7% for fir. Charcoal with more than 30 rings is rare: 0.6% of
236 beech and 1.3% of fir.

237 2.2% of charcoal (n=155) retained pith and bark: 140 beech and 15 fir (Appendix 3). For these samples, the total
238 number of rings is known and, therefore, so is the age of the branch, twig, or stem. Beech charcoal had from 1 to
239 35 rings and fir charcoal from 3 to 21 rings.

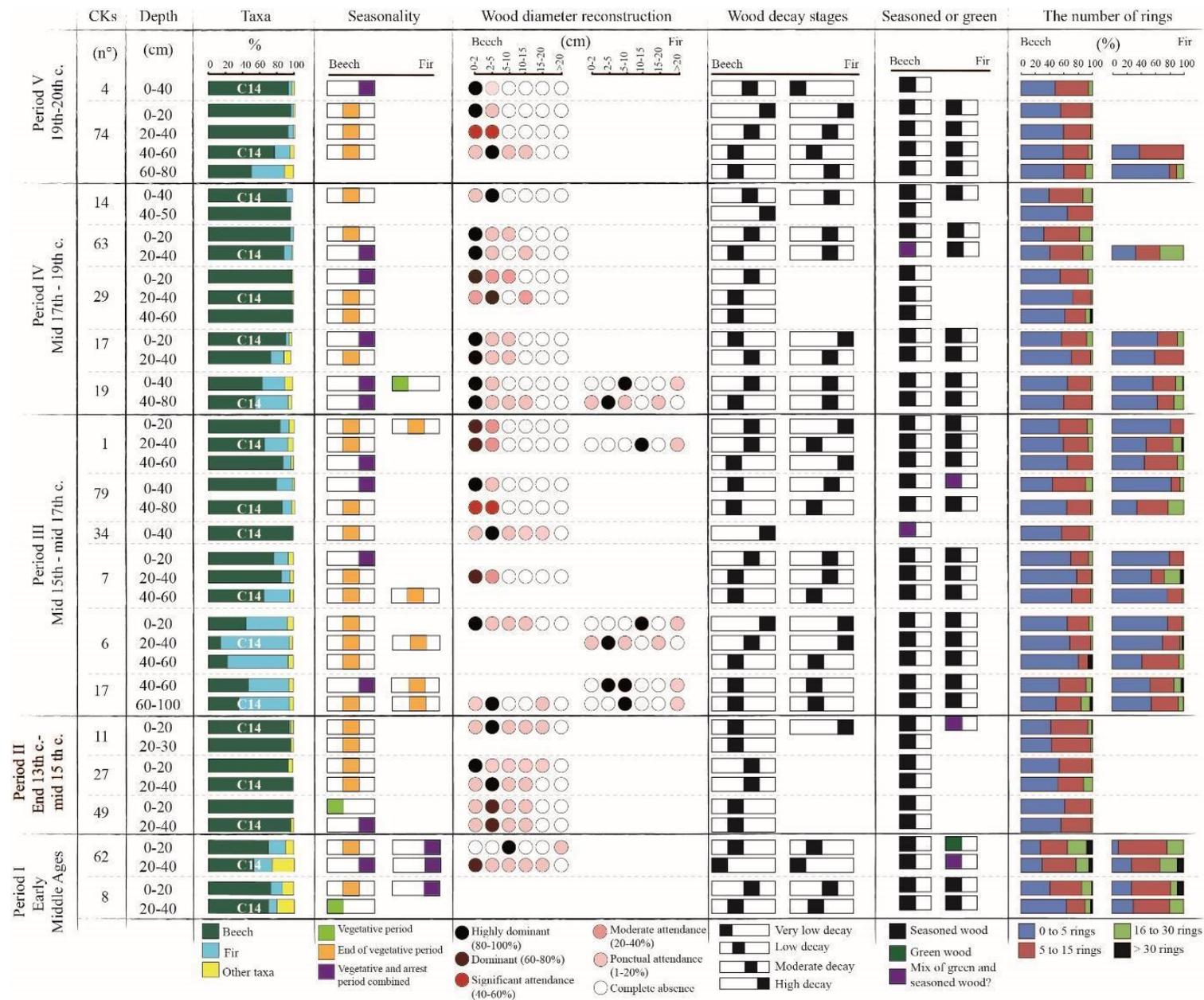
240 2.2.3. State of wood before carbonization

241 The decay index (DI), with a range from 0 to 1.5, was calculated for 7043 charcoal pieces, of which 5605 beech
242 and 1438 fir.

243 Globally, for both taxa (Fig. 6), we observed 25 CLs of beech and 13 CLs of fir with low decay ($0.1 < DI \leq 0.5$).

244 We also observed moderate decay ($0.5 < DI < 1$) in 30 beech CLs and 16 fir CLs and very high decay ($DI \geq 1$) in 6
245 CLs for beech and 12 for fir. Finally, very low decay ($DI \leq 0.1$) was observed in 1 CL for beech and 5 CLs for
246 fir (Appendix 4, Fig. 4A,B).

247 In the same corpus, we identified RCs on 1421 beech charcoal pieces and 156 on fir charcoal pieces. A total of
248 5466 charcoal have no RC. The mean RC/cm² per CLs ranges from 0 to 13.6 for beech charcoal and from 0 to
249 53.1 for fir. Results show the use of seasoned wood in 53 CLs and green wood in 1 CL for beech (Appendix 4,
250 Fig.5A) and the use of seasoned wood in 36 CLs and green wood in 6 CLs for fir (Fig. 6; Appendix 4, Fig.5B).

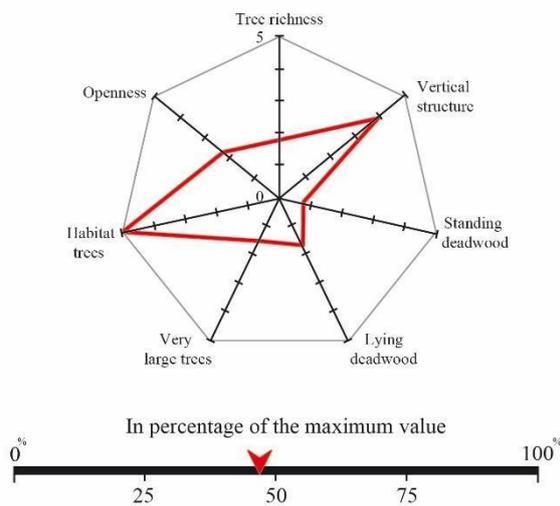


252 Fig. 6. Chronological representation of radiocarbon dated charcoal kilns (CKs). The oldest CKs are at the
 253 bottom and the most recent at the top. All data concerning the taxa found through anthracological analysis have
 254 been represented, including data on harvest seasonality, wood diameter reconstruction, the decay and moisture
 255 stage of the wood, and the number of growth rings.

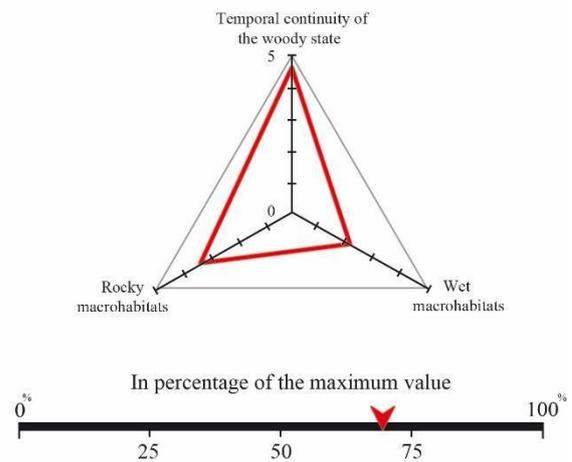
256 2.3. Current stand capacity to host biodiversity

257 The IBP total scores ranged from 22 to 30, i.e. from 40% to 60% of the potential maximum. Values were rather
 258 average for the management score (12-20/35) (Fig. 7A), though the context scores ranged rather high (7-15/15)
 259 (Fig. 7B). The number of tree-species ranged from 1 to 7 per plot; beech always dominated; silver fir occurred
 260 on three plots only. Vegetation generally presents little vertical stratification, with only two or three strata
 261 present (23%). Very few deadwood items occurred, particularly those with large diameters. Very large trees
 262 (diameter at breast height > 67.5 cm) are also rare, occurring on only four plots. However, habitat-trees are
 263 numerous (from 8 to 131/ha) and provide a high diversity of tree-related microhabitat types. Stand openness is
 264 high on average (34%), ranging from 1.5 to 90%. Aquatic and rocky habitats occur on 57 % and 100 % of the
 265 plots, respectively (Fig. 7A).

A/ IBP score (absolute value) for stand and current management



B/ IBP score (absolute value) for context



266

267 Fig. 7. IBP results (in %): A) related to the seven factors describing current stand; B) Related to the three factors
 268 describing context

269 3. Discussion

270 3.1. General trends in the historical charcoal manufacturing practices at Bernadouze

271 3.1.1. Mono- or multi-species CKs depend on wood availability and economic strategies

272 Generally the choice to use one or more species is driven by environmental availability in the supply area as
273 well as technical purposes, i.e. the quality of charcoal wanted and its final use (Davasse, 2000; Durand et al.,
274 2010; Adeniji et al., 2015). For example, beech wood was appreciated by some metallurgists because of its very
275 low ash content and fairly high density, which allows slower burning (Maillat, 1942; Bonhôte and Fruhauf,
276 1990a). Furthermore, as with other hardwoods, beech is known to produce a greater quantity of charcoal and to
277 increase charcoal productivity (Valerius, 1851, 222; Bonhôte and Fruhauf, 1990).

278 In the Bernadouze forest, half of studied CLs (n=32) are nearly monospecific (up to 90 % beech), and 29 CLs
279 are multi-specific, with the co-dominance of beech and fir in varying proportions (Fig. 5 and 6). In a
280 homogeneous environmental context (type of soil, climate, exposure), such results may reflect a change in forest
281 cover, and/or in silvicultural management, and/or in charcoal making practices (e.g. Davasse, 2000; Tolksdorf et
282 al., 2015). To clarify which hypothesis is correct, we need to know if the anthracological records reflect the
283 successive charring of monospecific wood piles with either fir or beech, or a mixture of two dominant species in
284 the same wood pile. An argument in favor of successive monospecific charring is that CL records generally
285 contain residues of several, rather than a single carbonization (Gebhardt, 2007; Dupin et al., 2019; Fouédjeu et
286 al., 2021). The vertical and lateral displacement of remaining charcoal pieces may mix charcoal from the
287 alternating charring of monospecific wood piles. In addition to this taphonomic consideration, mixing was
288 generally discouraged by scholars and forest engineers (Duhamel Du Monceau, 1761, 8; Valerius, 1851, 202).

289 However, the mixing of hardwood and softwood could occur when the amount of either wood species was
290 insufficient to make up a whole CK (Valerius, 1851, 224). For example, in Central Pyrenees (Ariège, Aude),
291 charcoal burners used a mix of beech with oak, hazelnut, or a weak proportion of fir ($\frac{1}{5}$ or less) during the 18th
292 and 19th c. (Lapassat, 1983; Fruhauf, 1990; Bonhôte, 1998, 220-223). Because of this practice, the possibility
293 that fir and beech were charred together in the same CK at Bernadouze cannot be excluded, but in highly
294 different proportions probably due to local wood availability and/or economic strategies.

295 In addition to the species, several other factors may affect the quality of charcoal produced: wood pile
296 construction, caliber, age of wood pieces, tree growth pattern, moisture content, decay stage, etc. (Biringuccio,
297 1556, 84; Duhamel Du Monceau, 1761, 9-10; Percy, 1864, 201; Svedelius et al., 1875, 24).

298 3.1.2. The use of well-calibrated pieces of woods harvested between the end of the growing season and
299 vegetative recovery

300 Our results highlight the preferential use of small-caliber wood (2 to 5 cm in diameter) for beech, and medium
301 (5 to 10 cm) and large-caliber wood (15 cm) for fir (Fig. 6), as already evidenced in other areas (Nelle, 2002;
302 Deforce et al., 2013; Paradis-Grenouillet et al., 2015; Dupin, 2018; Máliš et al., 2021). This use is in line with
303 the recommendation given in some historical treatises, i.e. the best charcoal was made with small and medium
304 caliber wood (+/- 5 to 10 cm in diameter) (Duhamel Du Monceau, 1761, 9; Marié de L'Isle, 1835, 110;
305 Malepeyre, 1836, 128). Moreover, the mixing of small (less than 5 cm) and large woods allows a more
306 homogeneous carbonization and avoids wood pile collapse, and small branches or twigs are also used to fill
307 gaps left between large pieces of wood (e.g. Dromart, 1880; Lugli and Pracchia, 1995; Bond, 2007; Burri,
308 2008). Another common practice consisted in splitting some of the largest wood items before carbonization to
309 facilitate their charring (Malepeyre, 1836, 128; Valerius, 1851, 222). To conclude, we cannot absolutely exclude
310 the possibility that this was practiced at Bernadouze, insofar as the presence of large wood in the CKs was
311 recorded.

312 The relative frequency of charcoal pieces that kept bark was low, probably resulting from both carbonization
313 and taphonomic (fragmentation) processes. But 64% of these charcoal fragments revealed that, from the end of
314 13th c. to the 20th c., fuelwood for charcoal production was harvested between the end of the growing season
315 (i.e. autumn yellowing of deciduous tree leaves) and vegetative recovery (leaf appearance), as already
316 demonstrated by many anthracological and ethnoarchaeological studies (Montanari et al., 2002; Bond, 2007;
317 Glais, 2007, 6; Py-Saraglia et al., 2017). This globally corresponds to the recommendations in 18th and 19th
318 c. technical treatises i.e from the fall until the first sap rises at the end of winter (Duhamel Du Monceau, 1761, 9;
319 Bellenghi, 1816, 43; Marié de L'Isle, 1835, 269; Valerius, 1851, 204; Percy, 1864, 208; Svedelius et al., 1875,
320 35-36).

321 3.1.3. Wood moderately seasoned before the burning season to obtain quality charcoal

322 In Bernadouze, charcoal burners mainly used seasoned wood, implying a seasoning phase just after cutting. In
323 the same way, the Decay Index (DI) shows that 81.9% of the wood was weakly to moderately decayed,
324 suggesting that most charred wood was felled healthy and then decayed during a seasoning period. An
325 experimental study has highlighted that contamination by wood-rotting fungi usually lasts two years after tree
326 death and occurs only during the warmer months, i.e. the short summertime, in mountain areas (Théry-Parisot,
327 2001, 51; Py et al., 2015). Considering the low contamination levels, the seasoning period is estimated to be less
328 than one year. Our interpretation is in line with almost all contemporary scholarly treatises reporting a seasoning
329 period lasting from 2 to 12 months, even if a few treatises suggested, if necessary, the possibility of charring
330 green wood (Della Fratta Montalbano, 1678). The length of seasoning depends on the cutting season, weather,
331 and wood diameter (e.g. Biringuccio, 1556, 85; Duhamel Du Monceau, 1761, 10; Bellenghi, 1816, 43;
332 Malepeyre, 1836, 113), but must not be too long in order to obtain moderately seasoned wood to ensure good
333 quality charcoal (Duhamel Du Monceau, 1761, 10; Malepeyre, 1836, 113; Percy, 1864, 208-209; Svedelius et
334 al., 1875, 35-36).

335 Around a fifth of the charcoal (18.1%) was heavily altered, implying that some rotten wood was charred. This
336 practice is not in line with scholarly treatises, which advise against the use of rotten wood which degrade both
337 charcoal productivity and quality (Valerius, 1851, 222; Percy, 1864, 209). Nevertheless, carbonization of dead
338 wood was sometimes recommended to recycle forestry waste (Bellenghi, 1816, 43). In this sense, a 1302 law
339 regulating charcoal production in Vicdessos required charcoal burners to use dry and dead trees before cutting
340 living ones (Verna, 2001, 72, 82).

341 After seasoning, wood was very often charred as early as the following spring and continued until the first
342 snows, as has been demonstrated for another Pyrenean valley (Bonhôte, 1998, 220-223; Py-Saragaglia et al.,
343 2017) and prescribed in the historical treatises (Duhamel Du Monceau, 1761, 10; Malepeyre, 1836, 128;
344 Valerius, 1851, 222). Such a claim has been made for other regions in Western Europe (e.g. Burri, 2012, 214-
345 224; Hanus, 2018).

346 3.2. Some insights about silvicultural practices over time

347 Charcoal results show that charcoal production started in the 9th-10th c. in a mixed beech-fir forest and ended in
348 the first half of the 20th c. in a mono-specific beech woodland with very few occurrences of fir. They suggest
349 that the Bernadouze forest was managed, from the 9th-10th to the mid-17th c., as a beech coppice with fir

350 standards leading to a multi-level forest. In Europe, at least from the late Middle Ages onwards, coppicing was
351 the most common silviculture treatment for broadleaved species to produce fuel (Peterken, 1993; Unrau et al.,
352 2018). But, among the wide range of possible operating systems (e.g. simple coppice, coppice selection system,
353 pollarding, etc.), it is still difficult to accurately characterize past coppice treatment from charcoal alone because
354 of the lack of charcoal diameter references from these different kinds of beech coppices.

355 Reports from the Forest Administration mention beech coppice in 1669, 1807, and 1860, without specifying the
356 type of coppice forest. At Bernadouze, the first explicit mention of a selection coppice system dates from 1892
357 (Chassinat, 1892), but we do not know when this system was implemented exactly. We hypothesize that the
358 implementation of this system was consecutive to a strong harvesting of fir, occurring during the mid-15th-mid-
359 17th c., resulting in poor fir regeneration and its progressive rarefaction in the overstory. With fir trees providing
360 the shade which favors the growth of beech shoots, the coppice selection system and selective cuttings were
361 technical solutions to respond to the increasing demand for charcoal from the mid-17th c. Moreover, the
362 exposure to multiple cutting cycles could have led to the increasing shoot production per resprouting stump, but
363 it also reduces shoot diameter. This hypothesis is supported by evolving diameters of beech charcoal, from a
364 mix including large diameters from the 9th-10th c. to the mid 15th c., to the almost exclusive use of small
365 diameters mixed with some medium diameters from the mid 15th-mid 17th c. (Fig. 6).

366 From the end of the 19th c., thinning, which consisted in removing undesirable individuals from the main stool
367 as well as standing deadwood and decaying stems, was prescribed by forest managers to improve productivity in
368 the Bernadouze forest (Chassinat, 1892; Rochebrunel, 1920; Noiriel, 1965). Thinning consisted in removing
369 undesirable individuals from the main stool - such as defective works, poorly or over abundantly stemmed
370 growth - as well as standing deadwood and decaying stems. Therefore, the partly altered charcoal found in the
371 CKs could reflect from the recycling of this management technique's byproducts. While iron production-related
372 demand gradually ceased in the 19th c. (Cantelaube, 2005, 693-734), harvesting for local needs (e.g. blacksmith
373 shops) continued. Due to socio-economic changes in the 20th c., degraded beech coppice trees were gradually
374 converted to high forest using cleaning-cuts and selective thinning (Rochebrunel, 1920; Noiriel, 1965).

375 In Bernadouze, the minimum harvesting age for beech ranges from 6 to 15 years (37.1%) and 16 to 30 years
376 (6.1%) (Fig. 6). Possible coppice rotation would range from 6 to 30 years, with a dominance of wood harvested
377 between 6 and 15 years. The over-representation of 1-5 years-old charcoal may result from fragmentation
378 accentuated by (i) the scraping and cleaning of the terrace by charcoal burners before each carbonization, (ii)

379 taphonomic processes in soils, and (iii) the archaeological sampling and sieving (Chrzavzez, 2013; Blondel et
380 al., 2018; Fouédjeu et al., 2021).

381 There is little documentation of former beech coppicing rotation in Ariège. During the 19th c., cutting cycles
382 ranged from 15 to 18 years, according to Forest managers and Mines engineers (Cantelaube, 2005, 215).
383 Currently, for coppice selection systems, undergrowth cutting rotation is commonly estimated at 6 to 12 years
384 (total cycle of 36 years) in the western Italian Alps and the Apennines, and 10 to 15 years in the Pyrenees (total
385 cycle c. 30 years) (Salvador, 1930; Coppini and Hermanin, 2007; Nocentini, 2009; Nicolescu et al., 2018). Such
386 variability depends on (i) the target diameter and product (fuel wood, charcoal, poles), and (ii) the capacity for
387 coppice regeneration, which varies according to species and site conditions (Buckley and Mills, 2015).
388 Regarding the seasonality of harvesting, our results are in line with previous research which demonstrated that
389 shoot growth and coppice production are optimized when shoots are cut between late winter and early spring,
390 which corresponds to the best season for its growth (Nicolescu et al., 2018).

391 Regarding fir, 25.6% of charcoal is between 6-15 years and 6.8% is between 16-30 years old (Fig. 6). This does
392 not match the expected age for standards because their rotation length is generally at least twice as long as that
393 of coppices (Burley et al., 2004). According to Huffel (1926, 68), fir trees could be harvested from 40 years of
394 age onwards. In the Eastern Pyrenees, the mid-17th c. Forest Law set the age of exploitability of the fir trees
395 scattered in beech woodlands from 80 to 100 years (Fruhauf, 1980, 31; Bartoli, 2011, 141-142). Because of the
396 difficulty of hauling fir timber due to topography and the lack of buoyant watercourses, 20th c. forest engineers
397 recommended exploiting trees of about 45-50 cm in diameter at breast height (Salvador, 1930). When fir trees
398 had reached the target diameter, they were harvested and only the best logs were transported to sawmills, while
399 the crowns, tops, branches and slash could be recycled for charcoal production (Bonhôte and Fruhauf, 1990b).
400 Despite fragmentation bias (which limits the number of tree rings retained), charcoal age results may reflect the
401 use of such forestry waste.

402 3.3. The long- term legacy of historical human practices

403 3.3.1. An ancient but immature forest, with weak tree-species diversity and hosting capacity

404 Forest ancientness refers to the duration of uninterrupted wood cover, independent of the past and current
405 management practices that may have changed forest features (Dupouey et al., 2002). Forest ancientness impacts
406 communities for several taxa, in particular those species with weak recolonization capacity such as vascular

407 plants (Hermy et al., 1999), lichens (Rose, 1993), ground beetles (Assmann, 1999) and ectomycorrhizal fungi
408 (Diedhiou et al., 2009).

409 Ancientness is usually evaluated by comparing current forest maps to older maps (Cateau et al., 2015). In
410 France, the *Etat-Major* maps, established when forest cover was at its lowest in the mid-19th c., are considered
411 to be the most accurate of available maps. On this map, our study area is represented with forest cover. The
412 assessment of ancientness for longer periods is exceedingly difficult, due to the absence of continuous historical
413 records. However, our results combined with a previous soil charcoal study provide evidence of continuous
414 forest cover from the Middle-Late Bronze Age to the modern period, through the absence of identified charcoal
415 from heathland species as well as the scarcity of pioneer species (Saulnier et al., 2019). Until the Carolingian
416 period (610-722 AD), the forest hosted the three main European mountain dryads: beech, fir and yew (Saulnier
417 et al. 2019). Then, the combined or successive effects of charcoal production and agro-sylvo-pastoral activities
418 led to the progressive shift of forest composition: the disappearance of yew, the rarefaction of fir, and the
419 favorisation of the more competitive beech eliminating post-pioneer light-demanding species in modern times
420 (Py-Saraglia et al., 2018; Saulnier et al., 2019).

421 Forest maturity refers to the state of biological development of the trees within a stand (age diameter and
422 development stage of the oldest and largest trees), and also to the quantity and diversity of dead wood and tree-
423 related microhabitats (TreMs) (Cateau et al., 2015). Deadwood and TreMs are pivotal resources for many forest-
424 dwelling taxa (Stokland et al., 2012; Larrieu et al., 2018). Very large trees provide the entire range of TreMs
425 (Larrieu et al., 2014b) including e.g. perched deadwood, a particularly important resource for saproxylic beetles
426 (Bouget et al., 2011) that increases their functional diversity (Gossner et al., 2013). Maturity is heavily driven by
427 past and present forest management. To display maturity attributes similar to a near-natural forest, the forest
428 must not have been subject to harvest for several decades (Bouget et al., 2014; Paillet et al., 2015). When
429 management is based on coppicing, more than 70 years of being set-aside are needed to recover both the amount
430 and diversity of deadwood and TreMs significantly larger than those observed after harvest (Larrieu et al., 2017;
431 2019b).

432 At Bernadouze, regular and short-rotation logging, intended to remove all the shoots that have reached the target
433 size, has not favoured the presence of dead trees (standing and on the ground), very large timber, and old trees
434 (the oldest trees are 130-160 years old, as shown in Fouédjeu et al., 2021). Today, a large part of the forest is
435 managed according to group-selection from former stumps, except for five plots where there is still old and

436 stunted coppice. However, given the geographical position (northern central Pyrenees) and the stationary
437 conditions (north-facing mountain level, soil types), the potential habitat is a mixed forest of deciduous and
438 coniferous trees dominated by beech, silver fir and yew (Bardat et al., 2004; <http://www.euforgen.org/species/>).
439 This potential mixed forest would be host to a variety of secondary species (pioneer and post-pioneer species
440 such as alder, European mountain ash, ash tree, willow etc.), more or less localized at particular stations (rock
441 outcrops, wetlands with waterlogged soil) or openings associated with natural and/or anthropogenic disturbances
442 (clearings, edges, and other areas with a well-developed herb layer composed of flowering plants, etc.). The loss
443 of tree-species diversity provides a much lower hosting capacity because biodiversity associated with deciduous
444 and coniferous trees do not fully overlap (e.g. Bouget et al., 2019). It can be assumed that, although secondary
445 species are always scattered or spatially localized in natural beech-dominated forests (e.g. Commarmot et al.,
446 2005), their extreme rarity at Bernadouze confers a decrease of hosting capacity, since most pioneer and post-
447 pioneer species have partly gender-specific corteges (e.g. Ryvardeen and Melo, 2014; Bouget et al., 2019).
448 Moreover, these secondary species are crucial for the silvigenetic cycle and for biodiversity, because they
449 provide deadwood and dendromicrohabitats during the phases of the cycle when these attributes, provided by
450 dryads, are scarce (Larrieu et al., 2014a). The absence of very large trees and the scarcity of deadwood also
451 restrict the forest's hosting capacity. However, fairly high density and diversity of TreMs were observed, which
452 is favourable to biodiversity as these structures host a wide range of taxa (Larrieu et al., 2018). This finding
453 could be partly tied to the increased density of trunk-based cavities induced by the conversion of former stump
454 coppices into high forest (Gouix, 2011).

455 3.3.2. Ensuring collective memory and cultural heritage

456 Ancientness contributes significantly to the patrimonialization of a forest. According to oral testimonies
457 recorded in the CNRS documentary film "*Haut-Videssos, une vallée et des hommes*", this heritage value has a
458 significant socio-cultural and collective dimension (<https://www.youtube.com/watch?v=LjXtsRTaACK>). It
459 might have contributed to reinforcing the feeling of belonging to a social group that shares an attachment to a
460 forest which they inherited from medieval common rights granted to the population by their lords. Despite the
461 nationalization of the forest and the erosion of common rights during the 19th c., this attachment is still present
462 today. Indeed the last, large group-selection harvest, carried out in 2016, sparked considerable public outcry
463 among the local population. From the perspective of their historical depth and their impact on forest cover,
464 charcoal-making platforms are a key component - beside pastoral remains - of the heritage value of the

465 Bernadouze forest. Such vernacular heritage reflects the close relationship between society and forests. Today, it
466 is immediately necessary to compile the living memory of the native inhabitants of the valley, in order (i) to
467 better understand the importance of the place in the attachment of the local populations to the Bernadouze forest
468 (Sebastien, 2020) and (ii) to pass it down to future generations through educational and cultural activities that
469 capture the millennial history of this forest (e.g. discovery trails etc.). To be successful, these activities must
470 include forest managers, scientists and inhabitants. In Europe and France, ancient forests are estimated to
471 represent between 30-50% of the total forest area (Cateau et al., 2015; Bergès and Dupouey, 2017). It is urgent
472 to conserve them (Jacquemin et al., 2014; Bergès and Dupouey, 2020). In order to offset the regular harvesting
473 that has taken place over the centuries, and which has profoundly modified the natural cycles of the Bernadouze
474 forest, managers have to consider these legacies as they implement management strategy. This management
475 should also promote biocultural issues.

476 4. Conclusion and recommendations for the Bernadouze forest

477 Our interdisciplinary approach has allowed an accurate characterization of centuries-old charcoal-making
478 practices, integrating the methods of collecting wood and managing the forest, which are essential for a better
479 understanding of the legacy effects of these practices on current landscapes.

480 We highlighted how sustainable charcoal making practices emerged and took root from the end of the 13th to
481 the 15th centuries without significant change. Starting in the Modern era (mid-15th-mid-17th c), socio-economic
482 strategies heavily contributed to the forest homogenization processes through the conversion of coppice-with-
483 standards (leading to the rarefaction of silver fir) into a beech coppice selection system. Finally, the shift from
484 historical coppicing systems to beech high forest during the 20th c. led to the rejuvenation of stands, inducing a
485 reduction in the biodiversity hosting capacity of the forest. The continuous removal of dead wood, in these
486 successive management strategies, has likely contributed in great part to biodiversity loss, specifically in
487 saproxylic species.

488 In order to reverse the effects of past practices and increase the forest's biodiversity hosting capacity, we
489 recommend : (i) conserving all firs and secondary tree-species already present and increasing the density of the
490 latter by creating gaps large enough to be suitable for saplings of pioneers, (ii) setting aside areas to reach high
491 degrees of maturity at a local level, (iii) re-introducing yew in areas at a distance from pasture (potential conflict
492 with pastoral uses must be considered), making it possible to recover a degree of naturalness at the site in the

493 long term, (iv) increasing deadwood components (e.g. by leaving the crowns of felled trees on the ground and
494 avoiding regular harvesting of scattered fallen trees) and conserving a high density of habitat-trees to increase
495 saproxylic resources significantly (most tree-related microhabitats contain decaying wood).

496 Aged coppices, which result from the extension of rotation cycles after the suspension of charcoal production,
497 provide interesting ecological niches due to their heterogeneous structure and to the presence of dead wood.
498 These coppices require adapted silviculture practices to maintain these characteristics and their associated
499 ecological niches (Nicolescu et al., 2018).

500 From a scientific perspective, it is now necessary to renew research by considering the complexity of the
501 multiple uses of the forest over time. To do so, other drivers must be investigated, such as pastoralism, timber
502 production, and hunting, to understand their combined effect on forest ecosystems and on the shaping of the
503 landscape. Finally, we suggest using this case study for scientific mediation related to the multi-secular relations
504 between bloomeries and the dynamics of Pyrenean mountain forests.

505 Credit authorship statement

506 **Léonel Fouédjeu:** Field investigation, Laboratory data acquisition, Data analysis methodology, Data analysis,
507 Writing, editing. **Sandrine Paradis-Grenouillet:** Supervision, Data analysis methodology, Data analysis,
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510 Writing, editing. **Vanessa Py-Saragaglia:** Supervision, Field investigation, Data analysis methodology,
511 Writing, editing.

512

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