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The socio-ecological legacies of centuries-old charcoal making practices in a mountain forest of the northern Pyrenees

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ABSTRACT

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

1. Introduction

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

Among key analytical approaches developed in the field of historical

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

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

A better knowledge of forest management history and woodland changes induced by charcoal making necessarily requires an in-depth understanding of the resulting practices (logging, species and wood caliber selection, etc.) and their temporalities (seasonality, cutting rotation, etc.). Available data mainly rely on ethnographic observation (Acovitsioti-Hameau, 2001; Hanus, 2007; Burri, 2008; Burri et al., 2010), modern scholarly treatises (e.g. Biringuccio, 1556; Della Fratta Montalbano, 1678; Duhamel Du Monceau, 1761; Bellenghi, 1816; Marié de L'Isle, 1835; Malepeyre, 1836; Valerius, 1851; Percy, 1864; Svedelius et al., 1875; Dromart, 1880), and/or experimental approaches (Poggi and Métailié, 1998; Fregni and Maccaferri, 2010; Paradis-Grenouillet, 2012). However, the only way to develop an understanding of local practices and, more broadly, to learn how people worked before modern times, is to study CK remains. In this perspective, wood scientists are developing dendrometric and dendrochronological tools to accurately reconstruct the entire technical operational sequence of charcoal production, from wood selection and removal to silviculture management and the charring process (Ludemann and Nelle, 2002; Strachan et al., 2013; Raab et al., 2015; Dupin, 2018; Paradis-Grenouillet et al., 2018a, 2018b; Fouédjeu et al., 2021).

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

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

2. Materials and methods

2.1. The survey area

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

2.2. Archaeological survey, CK selection and sampling strategy

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

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

Because most CKs exhibited a thick layer of charcoal (ranging from 20 to 120 cm thick) mixed with a very black and homogeneous soil, generally without any stratigraphy, stepwise sampling was carried out using a soil auger, every 20 cm in depth from the first horizon (A) to the ochre sterile and continuous mineral layer as is detailed in Py-Saragaglia et al. (2017). Samples for each 20 cm layer from all sampling points carried out on the same terrace (at least six per CK) work together and form the so-called "charcoal layer" (CL). A total of 57 CLs were analyzed (Fig. 1).

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

2.3. Analysis of the charcoal dataset

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

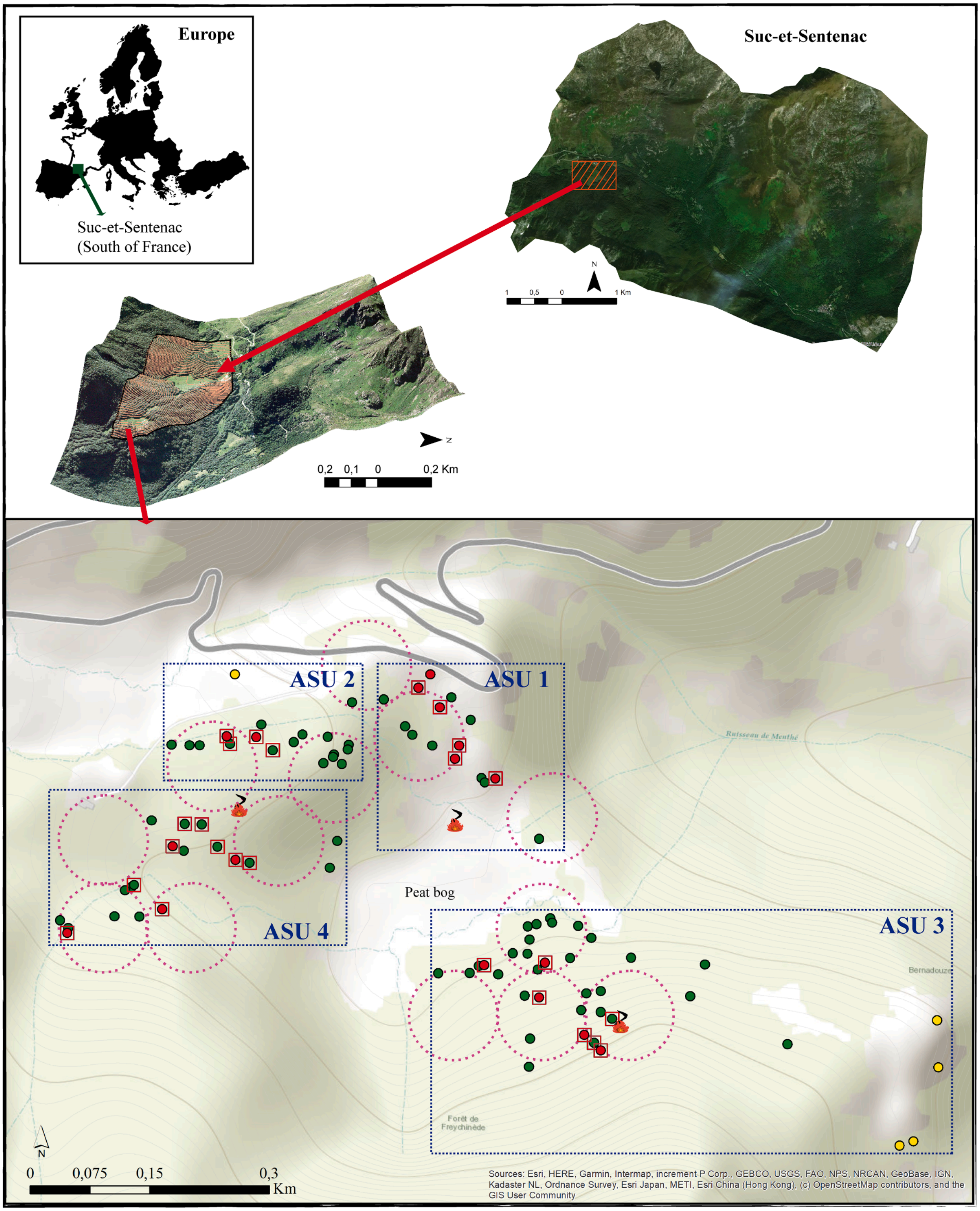

Fig. 1. Sampling design of the Bernadouze forest green points represent the totality of recorded and sampled CKs (n = 80); red points, CKs (n = 17) dated by C14; red squares, CKs with dendro-anthracological analysis (n = 25); red circles, IBP plots (n = 13); “fires” represent pedoanthracological pits (n = 3); yellow points represent pastoral sites (n = 5) . (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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

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

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

In order to reconstruct harvested wood diameters, we applied the

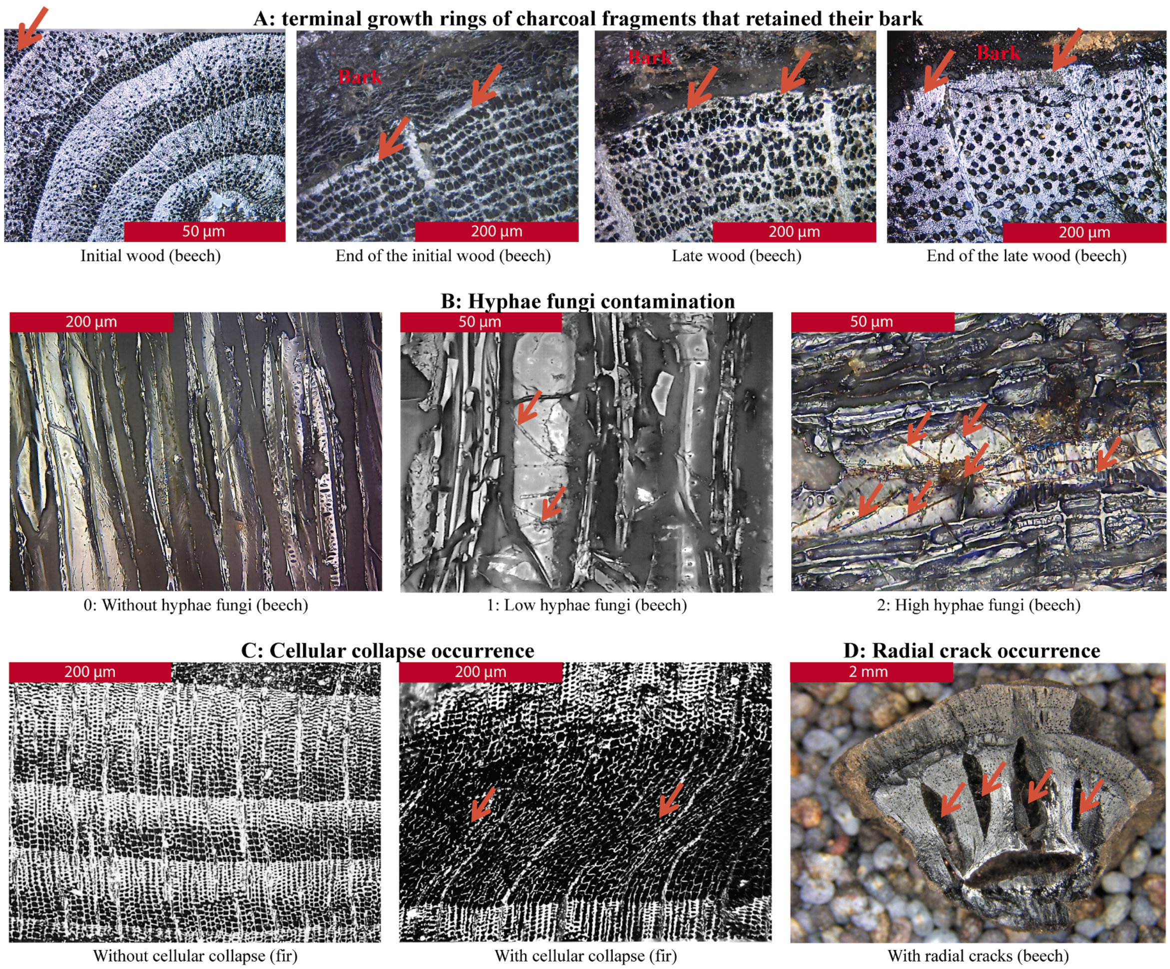

Fig. 2. Photos illustrating: terminal growth rings of charcoal fragments that retained their bark (A), hyphae fungi contamination (B), cellular collapse (C), and radial cracks (D).

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

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

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

DI = (nb “Cont.1” x 1 + nb “Cont.2” x 2 + nb “Cont.3” x 3)/nb total.

2.4. *Assessment of current stand capacity to host biodiversity*

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

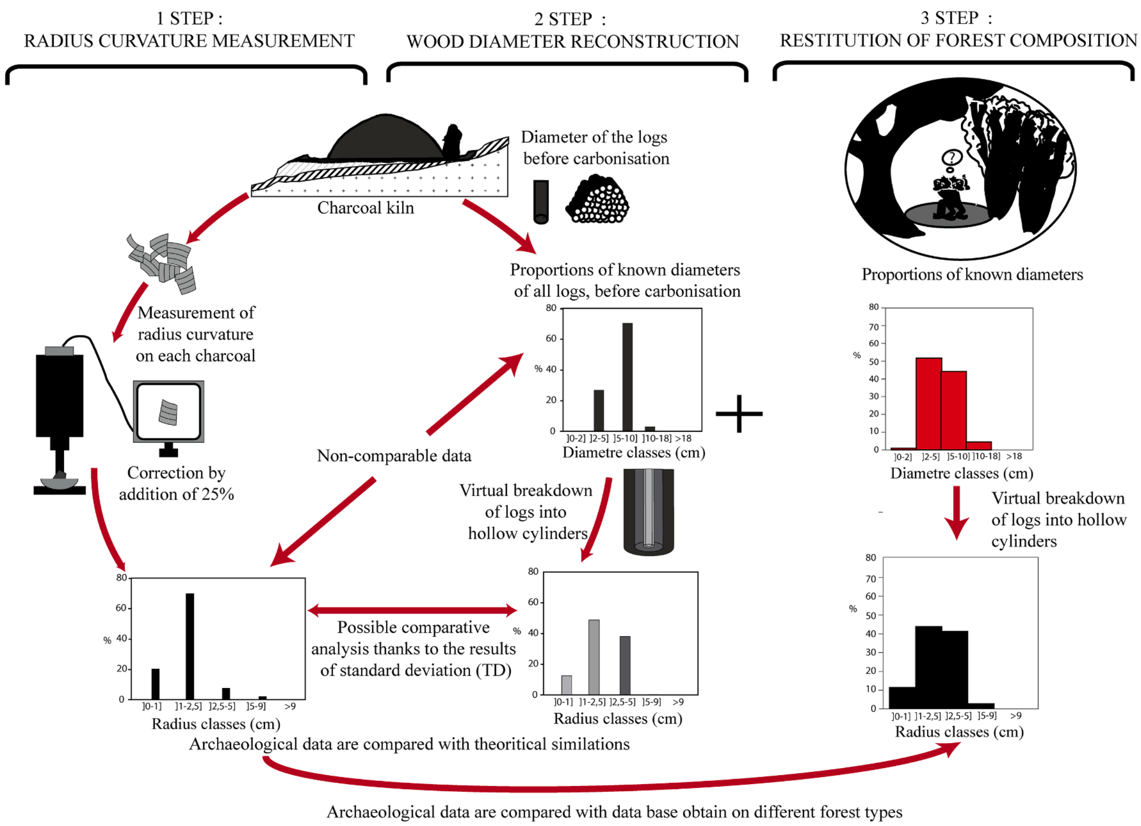

Fig. 3. Illustration of the three steps required to find wood diameter (Paradis-Grenouillet et al., 2015, modified).

3. Results

3.1. Chronology of charcoal making activity

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

3.2. Wood selection for charcoal production

3.2.1. Selected tree species and seasonality of logging

We identified two main species (Figs. 5 and 6): beech (n = 5605) and fir (n = 1438). We also identified 19 other tree taxa with relative frequencies below 1% (Figs. 5 and 7): (i) pioneer taxa, i.e. legume family (Fabaceae), birch (*Betula*), willow (*Salix*), grey alder (*Alnus incana* L.), alder (*Alnus*), juniper (*Juniperus*), (ii) post-pioneer taxa, i.e. wild cherry (*Prunus*), scots/mountain pine (*Pinus*), evergreen and deciduous oak (*Quercus*), apple sub-family (Rosaceae, Maloideae), mountain ash (*Rosaceae, Maloideae* cf. *Sorbus*), hazel (*Corylus*), ash (*Fraxinus*), rose (*Rosa*), elm (*Ulmus*) wild cherry (*Prunus*), scots/mountain pine (*Pinus*), evergreen and deciduous oak (*Quercus*), apple sub-family (*Rosaceae, Maloideae*), mountain ash (Rosaceae, Maloideae cf. *Sorbus*), hazel (*Corylus*), ash (*Fraxinus*), rose (*Rosa*), elm (*Ulmus*), and, (iii) shade-tolerant tree taxa (so-called "dryads"), i.e holly (*Ilex aquifolium* L.), common yew (*Taxus baccata* L.) and fir/juniper (*Abies alba/Juniperus*). When similar anthracological (tree taxa proportions) and dendro-anthracological (diameters) spectra were recorded from several CLs of the same CK, they were combined in a single CL (e.g. CKs 4, 14, 17, 18, 19, 31, 34, 74).

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

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

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

Data from 41 CLs out of the total of 43 CLs for beech, and from all CLs

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

Sample name	Laboratory code	Age 14C BP	Cal BC-AD 2 σ = 95,4%
Ck 4 [0-40cm]	Poz-73024	65 ± 30	1693-1918
Ck 74 [40-60cm]	Lyon-14958 (SacA-53114)	80± 30	1691-1921
Ck 14 [0-40cm]	Lyon-14950 (SacA-53106)	130 ± 30	1675-1942
Ck 63 [20-40cm]	Lyon-14957 (SacA-53113)	140 ± 30	1672-1944
Ck 29 [20-40cm]	Lyon-14953 (SacA-53109)	140 ± 30	1672-1944
Ck17 [0-20cm]	Lyon-14951 (SacA-53107)	185 ± 30	1653-Present
Ck 19 [40-80cm]	Poz-73023	255 ± 30	1520-1800
Ck 1 [20-40cm]	Poz-73022	270 ± 30	1510-1798
Ck 79 [40-80cm]	Beta-480930	320 ± 30	1484-1644
Ck 34 [0-40cm]	Lyon-14954 (SacA-53110)	330 ± 30	1480-1640
Ck 7 [40-60cm]	Lyon-14949 (SacA-53105)	365 ± 30	1453-1635
Ck 6 [20-40cm]	Poz-77095	375 ± 30	1450-1632
Ck 17 [60-100cm]	Lyon-14952 (SacA-53108)	390 ± 30	1442-1631
Ck 11 [0-20cm]	Poz-73025	525 ± 30	1327-1442
Ck 27 [20-40cm]	Poz-97774	560 ± 30	1312-1428
Ck 49 [20-40cm]	Lyon-14955 (SacA-53111)	615± 30	1299-1401
Ck 62 [20-40cm]	Lyon-14956 (SacA-53112)	1110 ± 30	882-1015
Ck 8 [20-40cm]	Poz- 109082	1120 ± 30	774-995

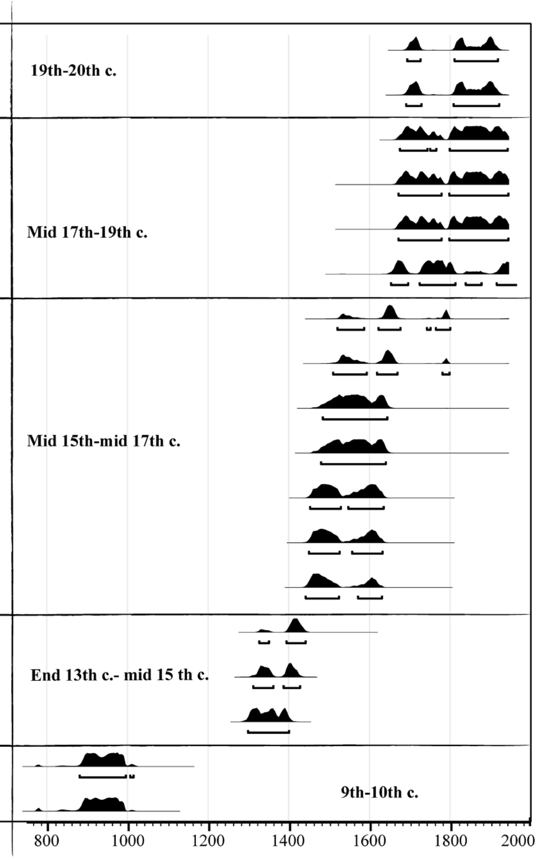

Fig. 4. Plot of radiocarbon dates for charcoal kilns in the Bernadouze forest distributed into five historical periods. Data were calibrated with OxCal v4.4.4 Bronk Ramsey (2021); r:5 Atmospheric data from Reimer et al. (2020).

for fir highlight good correlation (TD between 20% and 40%), sometimes very good (TD < 20%), with simulated data (Appendix 4, Figs. 2 and 3).

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

The minimum number of rings was counted on 5534 beech charcoal samples and 1436 fir samples (Fig. 6; Appendix 3). We observed the predominance of charcoal with 1 to 5 tree rings preserved: 55.9% for beech and 66.1% for fir. Charcoal with 6–15 rings represented 37.1% for beech and 25.6% for fir. In addition, a few 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 beech and 1.3% of fir.

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

3.2.3. *State of wood before carbonization*

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

Globally, for both taxa (Fig. 6), we observed 25 CLs of beech and 13 CLs of fir with low decay (0.1 < DI ≤ 0.5). We also observed moderate decay (0.5 < DI < 1) in 30 beech CLs and 16 fir CLs and very high decay (DI ≥ 1) in 6 CLs for beech and 12 for fir. Finally, very low decay (DI ≤ 0.1) was observed in 1CL for beech and 5 CLs for fir (Appendix 4, Fig. 4A,B).

In the same corpus, we identified RCs on 1421 beech charcoal pieces and 156 on fir charcoal pieces. A total of 5466 charcoal have no RC. The mean RC/cm^2 per CLs ranges from 0 to 13.6 for beech charcoal and from 0 to 53.1 for fir. Results show the use of seasoned wood in 53 CLs and green wood in 1CL for beech (Appendix 4, 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).

3.3. *Current stand capacity to host biodiversity*

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

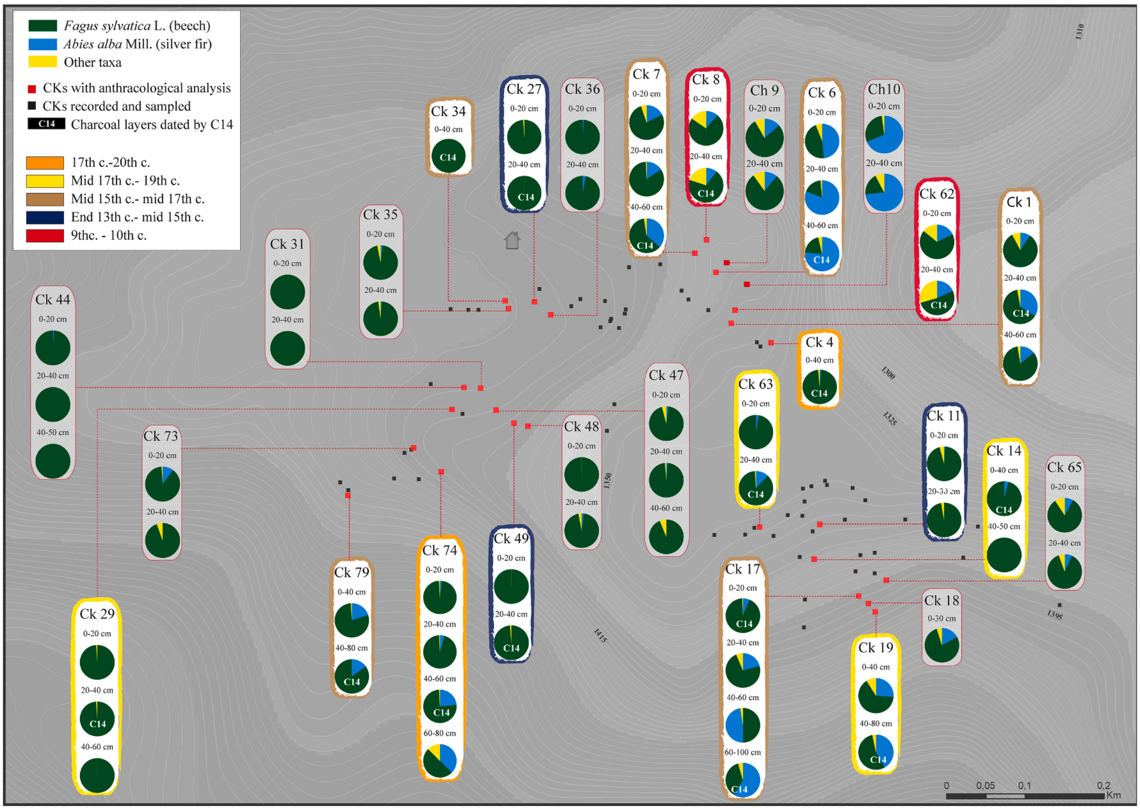

Fig. 5. Results of charcoal analysis by charcoal kilns (CKs) and by charcoal layers (CLs) in the Bernadouze forest.

4. Discussion

4.1. *General trends in the historical charcoal manufacturing practices at Bernadouze*

4.1.1. *Mono- or multi-species CKs depend on wood availability and economic strategies*

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

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

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

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

4.1.2. *The use of well-calibrated pieces of woods harvested between the end of the growing season and vegetative recovery*

Our results highlight the preferential use of small-caliber wood (2–5 cm in diameter) for beech, and medium (5–10 cm) and large-caliber wood (15 cm) for fir (Fig. 6), as already evidenced in other areas (Nelle, 2002; Deforce et al., 2013; Paradis-Grenouillet et al., 2015; Dupin, 2018; Máliš et al., 2021). This use is in line with the recommendation given in some historical treatises, i.e. the best charcoal was made with small and medium caliber wood (+/−5 to 10 cm in diameter) (Duhamel Du Monceau, 1761, 9; Marié de L'Isle, 1835; Malepeyre, 1836, 128). Moreover, the mixing of small (less than 5 cm) and large woods allows a more homogeneous carbonization and avoids wood pile collapse, and small branches or twigs are also used to fill gaps left between large pieces of wood (e.g. Dromart, 1880; Lugli and Pracchia,

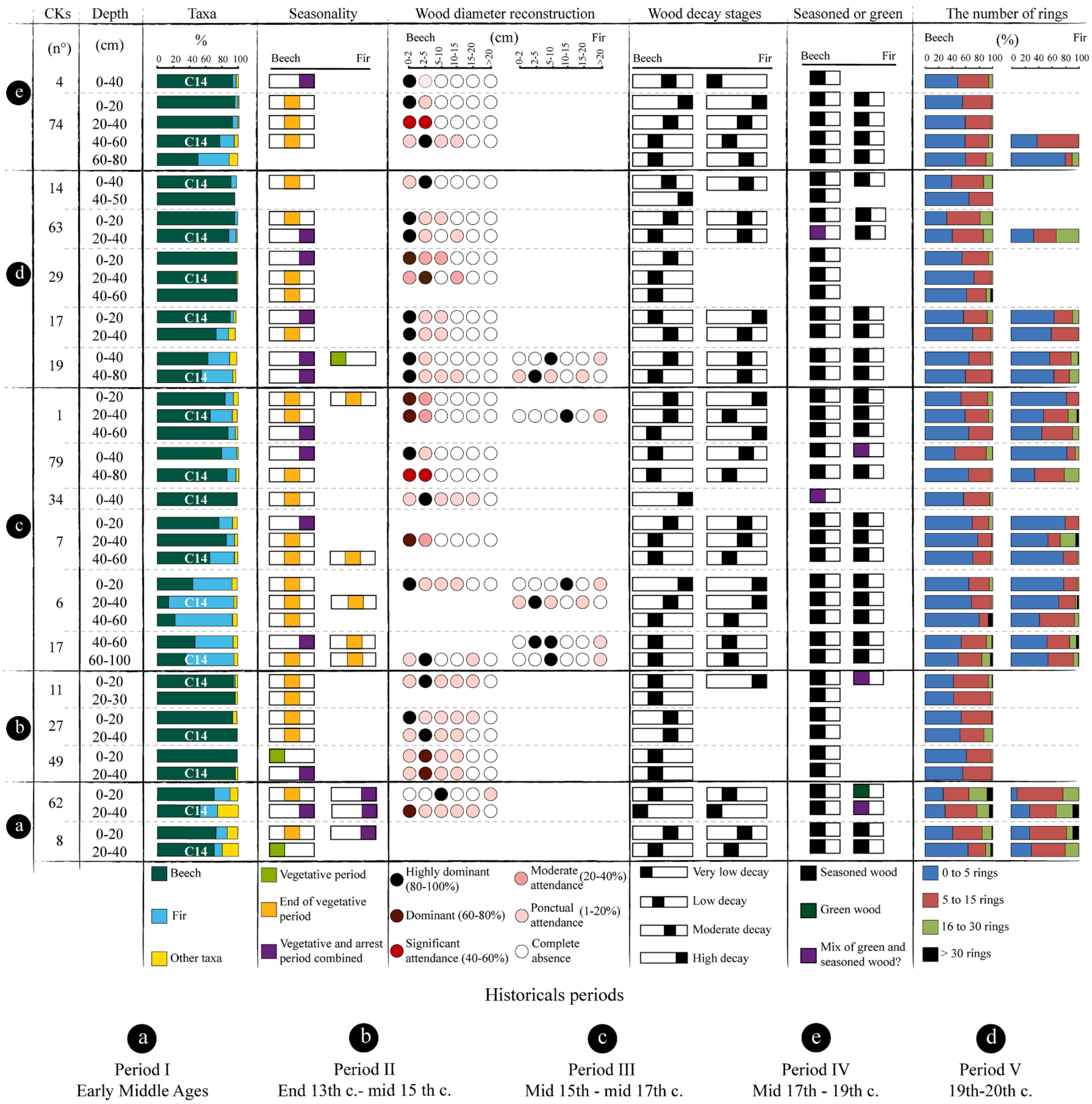

Fig. 6. Chronological representation of radiocarbon dated charcoal kilns (CKs). The oldest CKs are at the bottom and the most recent at the top. All data concerning the taxa found through anthracological analysis have been represented, including data on harvest seasonality, wood diameter reconstruction,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

1995; Bond, 2007; Burri, 2008). Another common practice consisted in splitting some of the largest wood items before carbonization to facilitate their charring (Malepeyre, 1836, 128; Valerius, 1851, 222). To conclude, we cannot absolutely exclude the possibility that this was practiced at Bernadouze, insofar as the presence of large wood in the CKs was recorded.

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

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

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

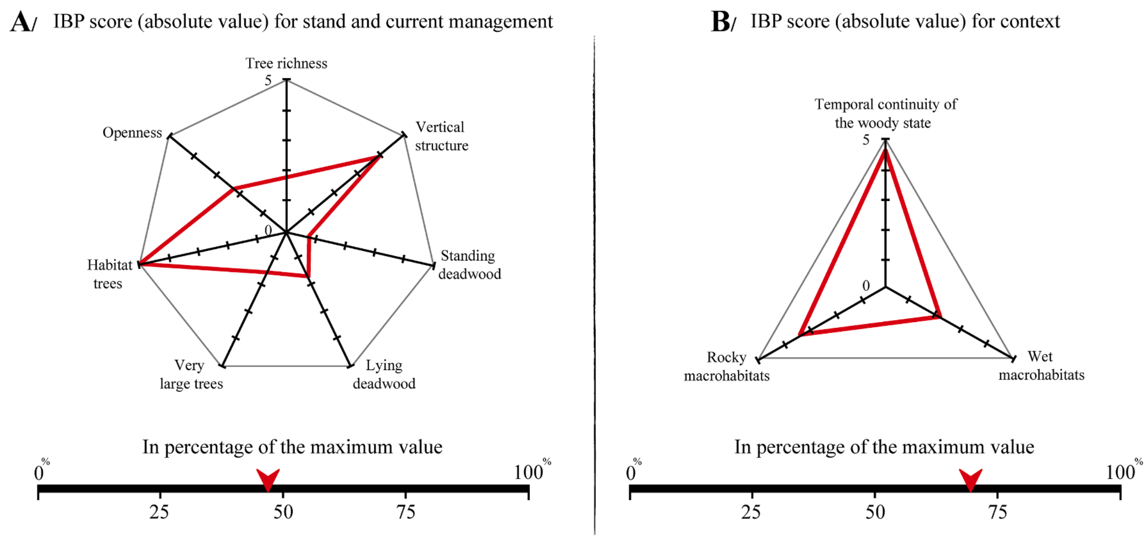

Fig. 7. IBP results (in %): A) related to the seven factors describing current stand; B) Related to the three factors describing context.

quality charcoal (Duhamel Du Monceau, 1761, 10; Malepeyre, 1836, 113; Percy, 1864, 208–209; Svedelius et al., 1875, 35–36).

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

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

4.2. Some insights about silvicultural practices over time

Charcoal results show that charcoal production started in the 9th-10th c. in a mixed beech-fir forest and ended in the first half of the 20th c. in a mono-specific beech woodland with very few occurrences of fir. They suggest that the Bernadouze forest was managed, from the 9th-10th to the mid-17th c., as a beech coppice with fir standards leading to a multi-level forest. In Europe, at least from the late Middle Ages onwards, coppicing was the most common silviculture treatment for broadleaved species to produce fuel (Peterken, 1993; Unrau et al., 2018). But, among the wide range of possible operating systems (e.g. simple coppice, coppice selection system, pollarding, etc.), it is still difficult to accurately characterize past coppice treatment from charcoal alone because of the lack of charcoal diameter references from these different kinds of beech coppices.

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

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

In Bernadouze, the minimum harvesting age for beech ranges from 6 to 15 years (37.1%) and 16 to 30 years (6.1%) (Fig. 6). Possible coppice rotation would range from 6 to 30 years, with a dominance of wood harvested between 6 and 15 years. The over-representation of 1–5 years-old charcoal may result from fragmentation accentuated by (i) the scraping and cleaning of the terrace by charcoal burners before each carbonization, (ii) taphonomic processes in soils, and (iii) the archaeological sampling and sieving (Chrzavzez, 2013; Blondel et al., 2018; Fouédjeu et al., 2021).

There is little documentation of former beech coppicing rotation in Ariège. During the 19th c., cutting cycles ranged from 15 to 18 years, according to Forest managers and Mines engineers (Cantelaube, 2005, 215). Currently, for coppice selection systems, undergrowth cutting rotation is commonly estimated at 6 to 12 years (total cycle of 36 years) in the western Italian Alps and the Apennines, and 10 to 15 years in the Pyrenees (total cycle c. 30 years) (Salvador, 1930; Coppini and Hermanin, 2007; Nocentini, 2009; Nicolescu et al., 2018). Such variability depends on (i) the target diameter and product (fuel wood, charcoal, poles), and (ii) the capacity for coppice regeneration, which varies according to species and site conditions (Buckley and Mills, 2015).

Regarding the seasonality of harvesting, our results are in line with previous research which demonstrated that shoot growth and coppice production are optimized when shoots are cut between late winter and early spring, which corresponds to the best season for its growth (Nicolescu et al., 2018).

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

4.3. The long-term legacy of historical human practices

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

Forest ancientness refers to the duration of uninterrupted wood cover, independent of the past and current management practices that may have changed forest features (Dupouey et al., 2002). Forest ancientness impacts communities for several taxa, in particular those species with weak recolonization capacity such as vascular plants (Hermy et al., 1999), lichens (Rose, 1993), ground beetles (Assmann, 1999) and ectomycorrhizal fungi (Diedhiou et al., 2009).

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

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

At Bernadouze, regular and short-rotation logging, intended to remove all the shoots that have reached the target size, has not favoured the presence of dead trees (standing and on the ground), very large timber, and old trees (the oldest trees are 130–160 years old, as shown in (Fouédjeu et al., 2021). Today, a large part of the forest is managed according to group-selection from former stumps, except for five plots where there is still old and stunted coppice. However, given the geographical position (northern central Pyrenees) and the stationary conditions (north-facing mountain level, soil types), the potential habitat is a mixed forest of deciduous and coniferous trees dominated by beech, silver fir and yew (Bardat et al., 2004; http://www.euforgen.org/species/). This potential mixed forest would be host to a variety of secondary species (pioneer and post-pioneer species such as alder, European mountain ash, ash tree, willow etc.), more or less localized at particular stations (rock outcrops, wetlands with waterlogged soil) or openings associated with natural and/or anthropogenic disturbances (clearings, edges, and other areas with a well-developed herb layer composed of flowering plants, etc.). The loss of tree-species diversity provides a much lower hosting capacity because biodiversity associated with deciduous and coniferous trees do not fully overlap (e.g. Bouget et al., 2019). It can be assumed that, although secondary species are always scattered or spatially localized in natural beech-dominated forests (e.g. Commarmot et al., 2005), their extreme rarity at Bernadouze confers a decrease of hosting capacity, since most pioneer and post-pioneer species have partly gender-specific corteges (e.g. Ryvarden and Melo, 2014; Bouget et al., 2019). Moreover, these secondary species are crucial for the silvigenetic cycle and for biodiversity, because they provide deadwood and dendromicrohabitats during the phases of the cycle when these attributes, provided by dryads, are scarce (Larrieu et al., 2014a). The absence of very large trees and the scarcity of deadwood also restrict the forest's hosting capacity. However, fairly high density and diversity of TreMs were observed, which is favourable to biodiversity as these structures host a wide range of taxa (Larrieu et al., 2018). This finding could be partly tied to the increased density of trunk-based cavities induced by the conversion of former stump coppices into high forest (Gouix, 2011).

4.3.2. Ensuring collective memory and cultural heritage

Ancientness contributes significantly to the patrimonialization of a forest. According to oral testimonies recorded in the CNRS documentary film "*Haut-Vicdessos, une vallée et des hommes*", this heritage value has a significant socio-cultural and collective dimension (https://www.youtube.com/watch?v=LjXtsRTaACk). It might have contributed to reinforcing the feeling of belonging to a social group that shares an attachment to a forest which they inherited from medieval common rights granted to the population by their lords. Despite the nationalization of the forest and the erosion of common rights during the 19th c., this attachment is still present today. Indeed the last, large group-selection harvest, carried out in 2016, sparked considerable public outcry among the local population. From the perspective of their historical depth and their impact on forest cover, charcoal-making platforms are a key component - beside pastoral remains - of the heritage value of the Bernadouze forest. Such vernacular heritage reflects the close relationship between society and forests. Today, it is immediately necessary to compile the living memory of the native inhabitants of the valley, in order (i) to better understand the importance of the place in the attachment of the local populations to the Bernadouze forest (Sebastien, 2020) and (ii) to pass it down to future generations through educational and cultural activities that capture the millennial history of this forest (e.g. discovery trails etc.). To be successful, these activities must include forest managers, scientists and inhabitants. In Europe and France, ancient forests are estimated to represent between 30 and 50% of the total forest area (Cateau et al., 2015; Bergès and Dupouey, 2017).

It is urgent to conserve them (Jacquemin et al., 2014; Bergès and Dupouey, 2020). In order to offset the regular harvesting that has taken place over the centuries, and which has profoundly modified the natural cycles of the Bernadouze forest, managers have to consider these legacies as they implement management strategy. This management should also promote biocultural issues.

5. Conclusion and recommendations for the Bernadouze forest

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

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

In order to reverse the effects of past practices and increase the forest's biodiversity hosting capacity, we recommend: (i) conserving all firs and secondary tree-species already present and increasing the density of the latter by creating gaps large enough to be suitable for saplings of pioneers, (ii) setting aside areas to reach high degrees of maturity at a local level, (iii) re-introducing yew in areas at a distance from pasture (potential conflict with pastoral uses must be considered), making it possible to recover a degree of naturalness at the site in the long term, (iv) increasing deadwood components (e.g. by leaving the crowns of felled trees on the ground and avoiding regular harvesting of scattered fallen trees) and conserving a high density of habitat-trees to increase saproxylic resources significantly (most tree-related microhabitats contain decaying wood).

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

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

Credit authorship statement

Léonel Fouédjeu: Field investigation, Laboratory data acquisition, Data analysis methodology, Data analysis, Writing, editing. **Sandrine Paradis-Grenouillet:** Supervision, Data analysis methodology, Data analysis, Writing, editing. **Laurent Larrieu:** Supervision, Field investigation, Data analysis, Writing, editing. **Mélanie Saulnier:** Supervision, Field investigation, Writing, editing. **Sylvain Burri:** Supervision, Field investigation, Writing, editing. **Vanessa Py-Saragaglia:** Supervision, Field investigation, Data analysis methodology, Writing, editing.

Declaration of Competing Interest

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

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Appendix A. Supplementary material

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