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Title: High resolution reconstruction of modern charcoal production kilns: an integrated approach combining dendrochronology, micromorphology and anthracology in the French Pyrenees

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Abstract

Numerous charcoal kiln remains can still be found throughout the world, evidencing wood harvesting related to former industries. These remains represent effective sources and tools for studying (i) pre-industrial pressures on forest resources and (ii) past strategies related to woodland management. However, radiocarbon dating (AMS), which is the main tool to reconstruct the chronology of past charcoal manufacturing activity, doesn't provide sufficiently accurate dating, especially for the post-1650 period, due to the broad probability range of the dates resulting from wiggles in the calibration curve. In order to overcome the radiocarbon dating limitation and therefore refine the chronology of modern charcoal manufacturing, this paper proposes to apply an integrated approach combining archaeology, micromorphology, anthracology and dendrochronology. To characterise the archaeological record of a target charcoal kiln terrace from the "Forêt de Bernadouze", located in a historical iron production valley of the Northern Pyrenees, we combined classical stratigraphic analysis with a micromorphological study. The results highlight the multiperiod nature of the terrace, i.e. a palimpsest of multiple charcoal production episodes, revealing two major phases marked by an abandonment period between them. Subsequently, we constructed a beech charcoal-ring (n=49) chronology cross-dated with the new "Forêt de Bernadouze" reference chronology from freshly felled, living beech trees (n=24) to obtain the annual resolution of charcoal ring formation. Based on the new reconstructed master chronology covering the 1879-2016 period, we were able to calibrate the charcoal-ring chronology for the 1881-1941 period. Consequently, we (i) dated the charcoal production activity performed on the target terrace during the 1924-1942 period and (ii) identified a shift in the rate of use of the terrace, from one-off to high-intensive use. This study also provides new insights regarding (i) the particular nature of the archaeological record and (ii) the operating and timing of past charcoal-making practices in connection with silvicultural treatments.

Keywords: ancient charcoal production, anthracology, micromorphology, dendrochronology, Northern Pyrenees, modern radiocarbon plateau

Introduction

Worldwide, many Charcoal Kiln (CK) terrace or platform remains still exist in present day open landscapes (fields and meadows), forests and even supra-forest areas above the current timberline, providing evidence of the wide distribution of the practice of charcoal production in the past (Hart et al., 2008; Ludemann, 2010; Dupin et al., 2017; Benatti et al., 2018; de Oliveira and Scheel-Ybert, 2018; Durand et al., 2018; Patzlaff et al., 2018). Indeed, charcoal was and in some locations still is a crafting resource used as fuel for ironmaking and smelting of other metals. Studying of the spatial distribution and chronology of former CK terraces (Raab et al., 2015; Deforce et al., 2020), as well as their taxonomic composition (Davasse, 2000; Rouaud, 2013; Dupin et al., 2017) or diameter of charred woods (Ludemann and Nelle, 2002; Knapp et al., 2015; Paradis-Grenouillet et al., 2015; Tolksdorf et al., 2015), has already provided crucial insights into the history of pre-industrial charcoal production and its associated forest management systems (silvicultural treatments), as well as enabling the characterisation of their legacy in current landscapes (Samojlik et al., 2013; Schmidt et al., 2016; Pescini et al., 2018). In addition, approaches combining historical, archaeological and ethnographic data have also enabled assessment of the art of burning charcoal, and especially its technical operational sequence (*chaîne opératoire*) and its seasonality (Burri, 2008; 2018; Paradis-Grenouillet et al., 2018).

However, in the northern hemisphere, the study of CK remains, which testify to a major development of charcoal manufacturing in the last centuries, i.e. between the seventeenth and nineteenth century (Davasse, 2000; Allée et al., 2010; Ludemann, 2010; Strachan et al., 2013; Raab et al., 2015; Dupin et al., 2017; Karimi Moayed et al., 2020) always faces the major issue that is the weak accuracy of dating obtained since the 1650s (Davasse, 2000; Strachan et al., 2013; Py-Saragaglia et al., 2017; Deforce et al., 2020; Karimi Moayed et al., 2020). Poor accuracy leads to strong wiggles in the calibration curve creating a "radiocarbon plateau", which are aggravated first by the "De vries effect", i.e. high-frequency preindustrial secular variations in 14C activity and secondly, by the "Suess-effect", i.e. the dilution of atmospheric 14C levels resulting from the widespread burning of fossil fuels since the beginning of the 1900s (coal, gas, oil) (De Vries, 1958; 1959; Stuiver, 1961; Tans et al., 1979).

New experiments are increasingly implemented to refine the chronology of modern charcoal production. Optically Stimulated Luminescence (OSL) method, for example, has been recently successfully applied to refine the dating of modern CKs in Belgium (Karimi Moayed et al., 2020). Other testing approaches are based on dendrochronological analysis applied on remaining charcoals from CKs (Nelle, 2002; Strachan, 2011; Strachan et al., 2013; Raab et al., 2015). Dendrochronological study requires charcoal pieces that preserve a sufficient number of rings (i.e.>30) to enable robust cross-dating (Backmeroff and Di Pasquale, 2001; Pichler et al., 2010; 2013). However, even the largest pieces found in CKs often preserve a low number of annual growth rings, because of charcoal fragmentation during carbonisation and the post-depositional processes. In order to increase the length of ring chronologies, it is therefore necessary to sample a higher number of charcoal fragments (Blondel et al., 2018). Moreover, the progress of formation of terminal tree-ring (early wood, late wood) on charcoal fragments that kept their bark is also highly valuable to identify the felling season and thus reconstruct the seasonality of wood harvesting practices (Py-Saragaglia et al., 2017; Fouédjeu et al., 2019).

Micromorphology is often used to characterise depositional history of archaeological sites (Béguier et al., 2011; Nicosia and Stoops, 2017) but has been very rarely applied to the study of CK sites (Hirsch et al., 2017; Raab et al., 2017). Micromorphological analysis can provide valuable and complementary information about CK terrace by characterising their micro-stratigraphy. Such analyses may highlight different phases of reuse, which are often difficult to detect by standard archaeological and anthracological methods. Indeed, it is difficult to clearly identify reuse phases of a terrace stratigraphically (the stratigraphic succession of charcoal-rich levels and levels of surrounding sediment leaching following periods of long abandonment) although several historical sources (Duhamel Du Monceau, 1761; Marié de L'Isle, 1835) and ethnographic surveys testify to such sequences (Battesti, 1992; Lugli and Pracchia, 1995; Montanari et al., 2000; Scipioni, 2002). CK reuse is driven by constraints that are both topographic, i.e. the low availability of flat areas in mountainous landscape that leads to the reuse of existing sites, and technical, i.e the mixture of charcoals and earth originating from previous CK burning is considered to be better to cover the kilns than newly excavated soil (Poggi and Métailié, 1998; Burri, 2008). The terrace was usually cleaned before each use and, then, the removed soil was recycled to cover the new wood pile, leading to the mixture of old and new charcoals during each carbonisation. Despite complex reuse processes, the terrace stratigraphy (also termed the charcoal platform soil profile) is often visually homogeneous (forming a continuous black layer) with thickness usually varying between 5 to 30 cm, and sometimes up to 80-100 cm (Bonhôte et al., 2002; Dupin et al., 2017). In France, only Gebhardt (2007) was interested in stratigraphic analysis based on a micromorphological approach until more recent applications by Dupin et al. (2019). Dupin et al. (2019) highlighted that stratified CKs usually result from an occasional use of the terrace while CKs characterised by a "homogeneous" profile are usually linked to periods of repeated intensive charcoal production.

This methodological paper aims to evaluate the relevance of an interdisciplinary approach combining archaeological, micromorphological and dendrochronological analyses in order to better-assess the chronology of modern charcoal production. More specifically, our objectives are to detect and date, firstly, potential different phases of charcoal production, i.e. several years of CK uses, and secondly, within these phases, the different episodes, i.e. a single or several burnings within a short period of time. Consequently, we decided to apply this original approach on an identified CK exploited with certainty during the last century (in the 1900s). This CK is located in the Northern Pyrenean beech forest known as "Forêt de Bernadouze", within the Vicdessos steel valley, where charcoal production is well-documented by previous historical ecology studies (Izard, 1989; Py-Saragaglia et al., 2018; Saulnier et al., 2019). The importance of working with a recently exploited CK terrasse is justified by the need (i) to compare oral testimony with the results of this study and validate them, (ii) to obtain charcoal fragments whose ring chronologies can be cross-dated with a reference chronology based on living beech trees. Micromorphological analysis has been applied to detect whether the CK terrace has been reused for several years or even decades. In addition, dendrochronological analysis has been applied on charcoal fragments in order to accurately date the CK use phases. In order to cross-date the master charcoal ring width chronology, we first construct a robust chronology for living beech trees in the "Forêt de Bernadouze", considering that no beech chronology was currently available for the Vicdessos valley or its surrounding area. Subsequently, we analysed terminal growth rings of charcoal fragments that retained their bark, in order to identify the felling season and assess CK intensity of use. Beyond these strictly methodological aspects, this study raises other issues related to charcoal making practices, i.e. the ways of using a terrace and associated fuel wood logging rhythms, and their impacts on the stratigraphy of the terrace and on silvicultural practices (coppice and rotation).

2. Material and methods

2.1. Study area

The study area is located on the northern slope of the Pyrenees, in the high valley of Vicdessos (administrative department of Ariège), on ancient limestone rocks between 1300 to 1450 m a.s.l (Fig.1) (see Saulnier et al. (2019) for more details). The woody vegetation (Bernadouze catchment area) is mainly composed of *Fagus sylvatica* L. (beech) with a minor component of *Abies alba* type (fir) localized mainly above 1500 m a.s.l. Three types of stands are currently dominant: (i) a high beech forest (derived from the conversion of former coppices), (ii) an old fast-growing coppice, and (iii) a line of stunted coppice around the Bernadouze peat bog.

In the 46ha investigated area of the site, 80 former CK terraces were found, which were geolocated and integrated in a GIS database and sampled for analysis (Fig.1). Combination of anthracological study of 28 of them with soil charcoal analysis (pedoanthracology) and historical data provided a reconstruction of the forest composition, structure, humans uses and system of management from the late Bronze Age to contemporary times (Py-Saragaglia et al., 2018; Saulnier et al., 2019).

According to oral testimony, we identified one of the last used CK terraces (57°09'.51''N and 61°90'.45''E) dated from at least the late 1930s (Fig.1). This CK terrace was located within the current high beech forest on a relatively flat area (approx. 5% slope), at the edge of the Bernadouze peat bog (called in the past "Freychinède"; Jalut et al., 1982), on a topographic terrace in direct proximity to a limestone outcrop almost completely covered with mosses. Around this CK we located 4 other CKs during archaeological field survey including only one with a radiocarbon date in the mid 17th-20th c. (Lyon-14957 -SacA-53113-, 140 ± 30 BP, 1669-1945 (95.4%) Cal AD with a high probability in the 1669-1891 period (79.9%)) (Fig. 1).

Sampled living beech trees were mainly located in the northwestern part of the woods along an altitudinal transect between 1345 and 1410 m a.s.l. (Fig.1). The two sampling areas were located in the heart of the current high forest separated from each other by a poorly accessible escarpment area and a small forest corridor mainly composed of young silver fir trees (20-30 years old) associated with a few other broadleaf trees.

2.2. Sampling strategies

2.2.1. Archaeological survey and charcoal sampling

CK terrace was cleaned of its litter (leaves and plant debris) to define its extent. A surface of 16 m², including most of the CK surface, was divided into 16 squares of 1 x 1m. For this experimental study, a 4 m long and 1 m wide survey trench was dug from west to east, across the centre of the terrace, in the northern part of the grid. The CK fill was then gradually stripped layer by layer (Stratigraphic Unit, SU) until the ochre mineral layer was reached. In charcoal-rich layers, at least one 10-litre bucket of sediment (= one sample) was collected in each square (4 in total). In total, 10 samples (100 litre of sediment) were collected during the investigation (Fig.2). Finally, the northern stratigraphic profile of the trench was described and drawn (Table 1, Fig.3).

2.2.2 Micromorphological sampling

Directly on the stratigraphic profile, oriented sediment columns were sampled at 2 points:

(i) A a continuous column here referred to as “Bern1” was collected at the west end of the survey trench (square 4) (Fig. 3 a, b);

(ii) A second column was taken in the east half of the profile, close to the middle of the CK fill (square 2), (Fig.3 a,c). This column, referred to as “Bern 2-3”, was divided into 2 segments because it was not possible to remove another continuous column from its soft sediments.

The sampling of both columns required digging into the ochre mineral layer on which the archaeological survey had stopped, to a depth of 10 cm.

2.2.3 Dendrochronological sampling

We took advantage of a forest logging managed by the National Forests Office (ONF) to carry out sampling of living beech. In the autumn 2016, 64 discs were extracted by lumberjacks directly from the stumps of freshly felled trees. Every sampled stump was geolocated (Fig.1). Sampled stumps were selected according to their estimated age (i.e selection of oldest/largest trees), their type (high beech trees) and their location in the forest.

2.3 Laboratory Analysis

2.3.1 Anthracological analysis

The sampled sediments were wet-sieved with a 4 mm mesh sieve and then dried in the shade. Charcoal fragments were identified using a reflected light optical microscope (Leica DM4 M) with magnifications of 100 to 1000 according to the three anatomical planes of wood (transverse, tangential and radial). All charcoal fragments were identified at the level species, genus, family or sub-family (Schweingruber, 1978; Vernet, 2001). The transverse sections were carefully cut (see below) and set aside for measuring ring width in a second step. In addition, when bark was preserved, its position in the last ring was recorded.

2.3.2. Micromorphological analysis

After drying and resin impregnation of the columns, a total of 5 large thin sections were carried out in PACEA laboratory (CNRS-Univ. Bordeaux). The thin sections were visually observed to distinguish their general characteristics and scanned to obtain digital images for meso-scale observation (Haaland et al., 2019).

At the microscopic scale, we used a Zeiss Axio Imager A2m microscope allowing observations in transmitted light (TL), Plane Polarised Light (PPL), Cross Polarised Light (XPL), and Oblique Incident Light (OIL) at magnification x25 - x500. The OIL observations were made using additional Zeiss gooseneck fibre optic illumination. The microphotographs were taken using a Zeiss Axiocam ICc5 digital camera controlled by Zeiss Axiovision software. The descriptive terminology follows Stoops (2003) and the interpretative framework is based on Stoops et al. (2010).

2.3.3. Dendrochronological analysis

2.3.3.1. Wood and charcoal sample preparation

The transverse surface of the living tree discs was prepared by fine sanding to grit size of 600 using an electric sander to magnify tree ring features. Then discs were divided into several pieces to facilitate measurement.

While some authors have suggested that charcoal fragments with at least 50-60 rings are more suitable for conducting a dendrochronological analysis (Kuniholm, 2016; Blondel et al., 2018), other studies have already successfully constructed robust chronologies using charcoal fragments with 30 rings (Backmeroff and Di Pasquale, 2001; Pichler et al., 2010; 2013). Consequently, we selected fragments preserving at least 30 rings to maximise sample size while also enabling obtaining robust measurements.

To facilitate charcoal-growth-ring measurement, the sampled pieces were simply broken by hand or with a cutting tool, i.e. a scalpel, to obtain good cross-sections. This method is particularly suitable for hard charcoal pieces (Pichler et al., 2013).

2.3.3.2. Tree-ring measurement

For both living tree and charcoal samples, we applied a visual cross-dating method to assign to each ring a year of formation (Stokes and Smiley, 1996). Tree rings were then measured with an accuracy of 0.01 mm using the LINTAB™ measuring table combined with TSAPWIN™ Scientific software (Rinn, 2003). Two to three radii (elementary series) were measured per sample. This technique provides a more representative individual average of tree growth (Bourquin-Mignot and Girardclos, 2001).

Cross-dating of series (based on the identification of characteristic years such as narrow rings) was conducted in order to detect the presence of false rings or missing rings during measurement (Latte et al., 2012) that could reduce the common signal of all the samples. Visual checks and crossdating were conducted using CDendro 7.8.1 to support the validation or rejection of potential adjustments to measurements. The accuracy of the cross-dating was evaluated by calculating the cross-correlation values between series. We considered a cross-correlation value of 0.5 as the threshold to decide to keep or exclude a series from the dataset.

The best correlated series were then averaged in order to produce a master chronology for (1) living tree and (2) charcoal. Finally, master chronologies from both the living tree and charcoal were detrended using a cubic fixed spline in order to remove the effects of age, competition and local specific conditions. This method is well-adapted to trees growing in closed- canopy forest and/or in frequently disturbed forests (competition, fire, etc.) (Lambert et al., 2010; Cook and Kairiukstis, 2013). The detrended chronology from charcoal fragments was then cross-dated with the detrended chronology of the Forêt de Bernadouze (felled trees) in order to propose a date for the operation of the CK.

In order to increase the number of charcoal fragments that kept the bark, which are mandatory to effectively assess charcoal making practices (seasonality of felling), we subsequently calculated new cross-correlation values between the master chronology of charcoals and part of the previous, excluded charcoal fragments. For this additional analysis, we set the new acceptable correlation value at 0.4. The new selected charcoal dataset was only used to study charcoal making practices and these additional fragments were not added to the master chronology.

3. Results

3.1. Archeological evidence and charcoal features

The black circular area corresponding to the location of the last CK(s) built on the terrace measured 5 m in diameter (Fig. 2). The area formed a slight basin-shaped depression which was filled with organic matter and charcoal-rich black earth up to a maximum depth of 35 cm within the trench survey. We distinguished six stratigraphic units (SUs) (Table 1; Fig. 3).

In total, we selected 303 charcoal fragments with 104 fragments extracted from the SU 2 and 199 from the SU 3. All these charcoal fragments were identified as beech (*Fagus sylvatica* L.). Among the 94 fragments that had preserved their bark, the state of progress in the terminal ring formation varied with 42 fragments exhibiting a terminal ring with final wood, 9 fragments exhibiting a terminal ring with only the early wood, and 3 fragments exhibiting a terminal ring at the end of the early wood. The minimum diameter measurement with the calliper shows diameters raging between 0.8 and 3.6 cm after correction (systematic addition of +25% to compensate for shrinkage losses during charring (Paradis-Grenouillet, 2012).

3.2. Microstratigraphic features

Sample Bern 1 was processed into 3 thin sections covering about 35 cm in sequence. The succession of 7 facies (Bern1_a-g) (Fig.4) were distinguished. Sample Bern2-3 allowed the realization of two thin sections, covering a sequence of about 28 cm, in which 4 facies (Bern2-3_a-d) were distinguished (Fig.5).

The description and the observation of facies both macroscopically (color, coarse constituents, etc.) and microscopically (fine constituents, pedofeatures, microstructure, etc.) highlighted important similarities between Bern 1 and Bern 2-3. We were able to synthesize these observations as 5 micro-facies types (MFT) (Fig.6).

The detailed micromorphological description of Bern1 and Bern2-3 is presented in Table 1 of the Supplementary material (Table S1)

MFT_A (e,g. Bern2-3_a)

This MFT corresponds to a forest soil deep mineral horizon formed by the alteration of underlying dolomitic marlstone formation and, to a lesser extent, input from the erosion of the surroundings metamorphic and crystalline formations (Trenet, 1997). These sediments were excavated to create the depression in which subsequent CK burning episodes took place.

MFT_B (e.g. Bern1_a, Bern1_c, Bern2-3_c)

This MFT_B is formed by rounded aggregates of material similar to the local sediment that may correspond to colluvial input into the depression. These materials are regularly affected by biopedological agents (e.g. soil mesofauna, roots) (Kooistra and Pulleman, 2010; Bertran et al., 2017), leading to blending with combustion residues from over- and underlying deposits.

MFT_C (e.g. Bern1_b, Bern1_d, Bern1_f, Bern2-3_b, Bern2-3_d)

Most of the CK terrace depression fill is related to MFT_C, which was formed by a mix of mineral and organic residues related to charcoal making, including charcoal and redeposited oxidized soil aggregates. Soil mesofauna and root action disturbance were important and sometimes complemented by climatic processes such as freeze/thaw cycles (Vliet-Lanoë, 2010), all of which led to mixing and homogenization of what were likely originally differentiated deposits.

MFT_D (e.g. Bern1_e, Bern2-3_c)

This MFT is mainly characterised by in-situ thermally altered deposits, corresponding to original kiln surfaces. These deposits may correspond to mainly mineral material such as those of MFT_B (Bern2-3_c) or those formed of previous combustion residues such as MFT_C (Bern1_e).

MFT_E (e.g. Bern1_g)

The summit of the terrace depression fills a humic horizon, with mostly organic constituents and virtually no mineral content. Organic constituents are regularly altered and fragmented.

3.3. Felled trees master chronology

The mean age of felled trees was 145 years, with a maximum of 162 years and a minimum of 89 (Supplementary material, Table S1). The ring widths varied from 0 (missing rings) to 31 mm, with a mean of 10 mm.

We used the 24 best cross-dated individual chronologies to build the master chronology of the Forêt de Bernadouze, resulting in a master chronology 137 years long, covering the 1879-2016 period. The average correlation between all individual series was 0.6 and the average Student's t-test value is 11.9. The square correlation matrix highlights the very good synchronization of the individuals (Fig. 8a).

Our chronology was compared with two other beech chronologies from the Pyrenees: the Iraty forest chronology (Bourquin-Mignot and Girardclos, 2001) and the Baish Aran (Cavin and Jump, 2017). Correlation with the Iraty forest chronology (located about 200 km as the crow flies on the same slope of the French Pyrenees), was very strong with a Student t-test around 6.85, and a mean correlation of 0.48. It was weaker with the Baish Aran chronology located on a southern slope in the Spanish Pyrenees (53 km as the crow flies) with values of 3.6 for the Student's t-test and of 0.33 for the mean correlation (Fig.7).

3.4. Charcoal kiln master chronology

In total, 104 charcoal fragments from SU 2 and 199 from SU 3 were measured. The mean length of individual charcoal chronologies was 31, with a maximum of 66 years and a minimum of 6 (Supplementary material, Table S2). The charcoal ring widths varied between 0 (missing rings) and 25 mm, with a mean of about 4 mm.

Only 167 fragments presented at least 30 rings i.e 55.1% of total. The analysis and comparison of these series allowed the selection of 49 individuals (20 from SU 2 and 29 from SU 3) exhibiting very high cross-correlations for constructing a master chronology of 65 years. The average correlation between individual series was 0.6 and the average Student's t-test was 7.1. The square correlation matrix showed the good quality of cross-dating of these series (Fig.8b). Using the master chronology (felled trees) of the "Forêt de Bernadouze", we were able to cross-date the CK master chronology for the 1878-1942 period, but we preferred to keep only the 1881-1941 period, for which the accuracy of the cross-dating is higher, with a Student t-test value of 10.4 and a mean correlation of 0.7 (Fig.9).

Using the charcoal master chronology, we were able to cross-date 33 additional charcoal fragments that were first excluded. These 33 new samples enabled us to obtain more charcoal fragments with bark. On the 82 total accepted fragments, 16 had retained the bark. Based on this dataset, 8 different felling years between 1924 and 1942 were obtained with certainty (Fig.10a,b).

4. Discussion

4.1. Characterisation of the CK record

The combination of archaeological and micromorphological observations allowed us to better characterise (i) the CK fill, i.e. the archaeological record used to reconstruct past charcoal production and related woodland harvesting, (ii) the relative chronology of charcoal deposits. The two approaches also highlight some of the taphonomic processes that have affected the CK infilling and evidence the multiperiod nature of the CK use.

The CK terrace was established on the local regolith observed in MFT_A (SU 6). This MFT corresponds to a forest soil deep mineral horizon formed by the alteration of the underlying dolomitic marlstone and, to a lesser extent, by input from the erosion of the surroundings metamorphic and crystalline formations (Trenet, 1997). Subsequent deposits (MFT_ B to E, SU 5, 4, 3, 2) recorded a succession of phases related to the use, maintenance and abandonment of the CK.

Phases of actual use of the CK are best exemplified by in-situ thermally altered sedimentary deposits (MFT_D) and reworked charcoal fragments, corresponding to surfaces on which the kiln was set and operated. Similar, but reworked, oxidized materials are also observed in other MFTs and suggest that in several instances these surfaces were disturbed. Indeed most of the CK depression fill is formed by a mix of redeposited mineral and organic residues related to charcoal production (MFT_C, SU 3 and 2). This result was expected considering that most of the produced charcoal was usually recovered and the terrace cleaned after the long process of charring (Battesti, 1992; Izard, 1992; Lugli and Pracchia, 1995; Montanari et al., 2000; Raab et al., 2017). Therefore, it is difficult to accurately evaluate the number of clearance and reuse phases, partly because of their own destructive nature, but also because their remains include decaying organic material in a biopedologicaly active environment and subject to bioturbation by soil mesofauna and root action (Kooistra and Pulleman, 2010; Bertran et al., 2017) sometimes complemented by climatic processes such as freeze/thaw cycles (Vliet-Lanoë, 2010). Thus, this combination of anthropogenic (practices) and taphonomic factors led to a mixing and homogenization of originally differentiated deposits and the macroscopic appearance of the fill as a homogeneous black layer.

Based on micromorphological results, the depression infill displays obvious microstratigraphic succession, notably because of the intercalation of MFT_B with MFT C. On the margins of the CK, a succession of layers can be observed that indicate this sequence, whereas in the center the deposits are much more homogeneous. MFT_B is formed by rounded aggregates of material similar to the local sediment that may correspond to colluvial input into the depression related to wall collapse, potentially favoured by weathering (Langohr, 2000). This assumption is verified both at the edge of the structure, with material additions characteristic of CK edge collapse backfill, and in the centre of the CK where a similar deposit is present. Those materials are also regularly affected by biopedological agents leading to blending with combustion residues from over- and underlying deposits. This pattern implies, therefore, a potential mixing of charcoal fragments from different charcoal production episodes in SUs 2 and 3. Lastly, the summit of the depression fill corresponds to a humic horizon (MFT_E, SU 2), which represents the development of forest soil (Gerasimova and Lebedeva-Verba, 2010) after the last episode of the CK use.

Overall, a succession of different episodes of charcoal production is detected through microstratigraphy where it was otherwise undetectable by macroscopic observation. Some are observable through the presence of in-situ thermally altered sediment (MFT_D), but others are only evidenced through their reworked residues (MFT_C). The infilling of the depression by unaltered sediments points to abandonment phases indicating discontinuous charcoal production activities. This kind of multiperiod use was expected for this type of structure and activity (Dupin et al., 2019), but the assessment of the different types of activities conducted and their precise chronology remains a challenging endeavor because of their destructive nature and their taphonomic context (Raab et al., 2017).

The anthracological remains in such a structure are very abundant, but their state of preservation and location are clearly affected by charcoal production practices (e.g. raking out of charcoal, cleaning, reuse of burnt charcoal-rich earth) and also bioturbation and weathering processes (e.g. soil mesofauna, root action, frost cycles).

Consequently, these charcoal remains are often subject to further fragmentation (Elmer et al., 2015) and subsequent vertical and lateral displacement. As a result, charcoal fragments sampled from SUs 2 and 3 likely represent a palimpsest of several different charcoal production phases carried out on the terrace (MFT_C).

4.2. Accuracy of the CK master chronology

The statistical report for the chronology of Bernadouze's CK has a Student's t-test value of 10.4 and a mean correlation of 0.7. Comparison with similar studies (Supplementary material, Table S3) shows that results of our cross-datation are in the range of those obtained in previous studies (Student's t-test ranging between 3.7 and 12.2 and mean correlation between 0.6 and 0.7), which highlights the high robustness of the chronology of Bernadouze's CK. Indeed, in France, the experimental study conducted by Blondel et al. (2018) on the site of Saint-Paulien (Haute-Loire) gave a 67-year chronology built using 4 charcoal fragments and validated with 7 regional chronologies with Student's t-test values ranging between 3.7 and 5.5. In the Schwaz/Brixlegg region (Tyrol, Austria), charcoal fragments from the mine of Mauk E allowed the construction of a 149-year master chronology, based on 133 charcoal samples, which was cross-dated with two regional chronologies, giving Student's t-test values of 4.5 and 5 (Pichler et al., 2013). In Patagonia (Argentina), 3 charcoal fragments from the archaeological site of Cerro Pintado give a 50-year chronology with a mean correlation of 0.6 with a regional chronology (Fermé and Villalba, 2011). In the USA, the 72 charcoal samples from the CKs of Old Greenwood and Gray's Crossing (Truckee, California) allowed the reconstruction of a 122-year master chronology that was cross-dated with one regional chronology giving a Student's t-test value of 9.3 and mean correlation of 0.6. In Mt Hope (Central Nevada), a floating chronology of 100 years based on 12 samples was cross-dated with a local chronology giving a Student's t-test value of 10.6 and a mean correlation of 0.7. Finally, in Central Nevada, the 202-year floating chronology constructed based on 41 charcoal samples from the Cortez site was cross-dated with a Student's t-test value of 12.2 and a mean correlation of 0.6 (Strachan et al., 2013).

We are aware that the high Student's t-test and mean correlation values we obtained may be influenced by the short length of both the individual charcoal chronologies, for which we got a maximum length of 66 years, and the master chronology, 61 years. However, the master chronology length is comparable to the length of the chronologies of Saint Paulien and Cerro Pintado, which were constructed with less than 5 samples. In addition, the CK charcoal master chronology has been cross-dated (contrary to some others except those of the USA) with a local living tree chronology built using beech trees growing on the same site. The high correlation values resulting from the cross-dating (charcoal vs living tree chronologies) allow us to confirm the hypothesis according to which, in the context of charcoal production, burnt wood is almost always collected close to the site of charcoal production. On the other hand, some samples showed strong correlation with very similar growth patterns suggesting an ecologically identical supply location (Blanc-Garidel and Wicha, 2019) or a common tree origin (Pichler et al., 2013).

Moreover, we used only charcoal which retained at least 30 rings to build the master chronology, although other studies suggested using charcoal fragments with at least 50 rings (Kuniholm, 2016; Blondel et al., 2018). The silvicultural treatment implemented in the "Forêt de Bernadouze" was the "coppice selection system" (*taillis fureté* in French), which was considered as the best suited for European beech (Salvador, 1930; Nicolescu et al., 2018). This system consists of cutting on each stump only shoots that have reached a target diameter, which the age determines the rotation. In the Forêt de Bernadouze, before 1892, the total cycle of cut rotation was probably ca. 50 years (maximum age reached by trees) including several felling cycles probably fixed to ca. 15 years. From 1920, the total cycle of ca. 48 years included three rotations of 16 years. Consequently, the age reached by shoots used for charcoal making was in theory about 10-16 years old minimum and about ca. 48-50 years old maximum.

4.3. High-temporal chronological reconstruction of charcoal production activity on the target CK terrace

4.3.1. A non-intensive initial phase of charcoal making

The deeper MFT_C was observed in Bern 1_b and Bern 2-3_b layers and confirmed an early charcoal making phase on the terrace. The substratum was excavated by charcoal burners to make a flat area, slightly curved, and accommodate a wood pile of about 5 meters in diameter. This size corresponds with the average diameter of the CKs detected in the Forêt de Bernadouze with 5.1 x 4.7 meters in diameter, and elsewhere in the mountains of the northern Pyrenees (Bonhôte et al., 2002). According to Bonhôte (1998, Annex 2, pp 220-223), in mountain areas this diameter could correspond to CKs consuming up to 15 to 20 "steres" (cubic metres) of wood. The construction technique of the type of kiln used in the Pyrenees is less well known than those found in other regions such as Liguria or Portugal (Poggi and Métailié, 1998). In the studied CK, the remains of this former episode were thoroughly scraped, thus there is very little evidence with which to reconstruct the process. However, it is not possible to conclude if this phase involved a single episode of the use of the terrace (only one CK) or different successive uses. In the Mediterranean region, several charcoal making episodes (up to five successive events) can take place on the same CK in a single year (Battesti, 1992). It is possible, therefore, that this first phase of exploitation probably hosted several episodes in a short period of time. However, there are no historical records from the Pyrenean area to support this hypothesis.

No charcoal was collected and studied from the Bern1_b and Bern2-3_b layers corresponding to SU 5 and the deepest part of MFT_C. Therefore it is not possible to date precisely this first charcoal production event. Based on our knowledge of the charcoal production chronology in the "Forêt de Bernadouze", we hypothesise that this former phase is potentially attested to elsewhere in this area. In addition, it may be only a few years or decades ahead of the next. Indeed, two CKs were radiocarbon dated at the same time i.e. between the end of 19 th and the beginning of the 20th c. with a high probability of dating from the 1811-1926 period (71.5% of probability) (Poz-73024, 65 ± 30 BP, 1691-1921 (95.4%) Cal AD and Lyon-14958 (SacA-53114), 80± 30 BP, 1690-1926 (95.4%) Cal AD)). The anthracological study of these two CKs also showed a taxonomic composition similar to the target CK discussed. While one CK was composed almost exclusively of beech (97.4%) with some trace of fir (1.5%), the other CK composition indicated the combined use of beech (75.5%) and fir (23.6%). It could therefore be envisaged that this first charcoal making event can be dated to the early 20th c. Historical documentation indicates that wood harvesting operations were conducted on a 16-year rotation and were characterised by 8 biennial cuts (Chassinat, 1892; Rochebrunel, 1920). The rotation set between 1906 and 1921 could therefore correspond to the initial phase of charcoal production recorded in the CK.

The MFT_B, observed both at the edge (Bern1_c) and in the middle of the terrace (Bern2-3_c) and corresponding to SUs 3 and 4, contained inputs of eroded sediment from the edge of the CK terrace. This partial filling of the terrace, attributed to the collapse of the edges, suggests an abandonment phase. However, the duration of this phase of abandonment, which probably ranged from one to several years remains difficult to accurately date. In mountain areas, the duration of the infilling process depends mainly on the instability of the environment (i.e erosion, landslides, often accentuated by acute slopes) and on the combined effects of climatic and edaphic factors (Izard, 1999; Langohr, 2000).

Dupin et al. (2019) showed that the reuse of a CK, without a long period of interruption, generally results in a homogeneous stratigraphy where abandonment markers are completely removed by cleaning. This evidence suggests that a more or less prolonged interruption in the use of a CK may result in the creation of an abandonment layer interspersed between the charcoal sequences. This hypothesis presents the best fit with the evidence collected from the present study. Comparable observations on other CKs have been interpreted as an indication of abandonment and multiperiod use of the terrace (Dubois et al., 1996; Izard, 1999; Montanari et al., 2000; Nelle, 2003; Gebhardt, 2007; Rouaud, 2013; Raab et al., 2017).

Repeated combustion on one site can lead to relative sterility of the soil, which can take several decades to recover (Acovitsioti-Hameau, 2001b; Carrari et al., 2017) and lead to its abandonment. The abandonment also may be directly related to the management of the surrounding forest resource. The CK remains represent material evidence for the management of a reduced surface area of the forest (called "parcel management" by Fabre and Gervet

(1992). Availability of wood fuel is not infinite, and this forces the temporary abandonment of a "parcel" for the time coppice/woodland takes to regenerate (Battesti, 1992). This refers to the notion of the logging district, based on a rotation of cutting cycles (Acovitsioti-Hameau, 1995), in theory 8, 10, 12 or 15 years, which is a forest management method very often used in montane areas (Duhamel Du Monceau, 1761; Salvador, 1930) and also very well suited with charcoal production in order to ensure the sustainability of fuel resources.

The partial preservation of the filling layer also suggests that when the terrace was reoccupied for a new episode of charcoal making, (i) the charcoal burner did not consider it necessary to clean-up and dig-up the flat area, or (ii) the layer of sediment filling the pit was so thick that it was not completely removed. Indeed, when preparing the terrace for a new burning, the charcoal maker would start by thoroughly cleaning the terrace. Due to its quality (fine, smooth and not very porous), this mixture of earth and charcoals was collected in order to cover the new wood pile, allowing a better insulation from the air (Battesti, 1992; Musset, 2000; Acovitsioti-Hameau, 2001a; Hanus, 2018; Rouaud and Allée, 2018). The reuse of abandoned terraces is often advised by modern technical treatises as well as by former and current charcoal burners because of specific soil properties (see the overall review in Krebs et al., 2017, Table 2). Indeed, charcoal production on an old terrace allows better control of pyrolysis and thus, increases charcoal productivity by up to 10% (Larcher, 1986).

4.3.2 The second phase of use of the CK terrace

Overlapping SUs 3 and 2, the MFT_C (observed in Bern 2-3_d and from Bern1_d to Bern1_f) suggested a new phase of charcoal production. In the center of the terrace (Bern2-3_d), the micromorphological analysis of oxidized sediment highlighted several CK uses, which appeared more regular and intense than in the previous phase as suggested by the high concentration of charcoal fragments (Dupin et al., 2017; 2019). The successive episodes of use led to significant mixing of the materials remaining inside the CK. Individual chronologies from two fragments collected in SU 3 (squares 1 and 2) suggested a restart date of activity in 1924 (Fig. 10 a,b). According to historical documentation, this date also corresponds to the phase of rotation of logging operations between 1922 and 1937, characterised by biennial cuts (Rochebrunel, 1920). Based on our results, we therefore assume that the first charcoal harvesting was carried out in 1924. In 1937, a third 16-year rotation from 1938 to 1953 was approved (Noiriel, 1965). Following the activity restart, several charcoal making episodes were identified based on individual chronologies of charcoal remains in the early 1930s. Two other individual chronologies constructed from a charcoal fragment extracted from SU 3 in square 1 and from another fragment extracted from SU 3 in square 2 provided two additional probable cutting dates in 1931 and 1932 respectively. Although no dates were obtained between 1924 and 1931, the absence of markers indicating the abandonment of the terrace suggests that the charcoal production was probably continuous and intensive (Dupin et al., 2019). It is also highly likely that charcoal fragments from this period were completely removed during the systematic preparation of the CK to allow renewed use by the charcoal burner. In any case, three new dates provided by the individual chronologies of three other charcoal specimens extracted from SU 3 in squares 2 and 4 point to date a new event in 1935. This event may be linked to the intensification of charcoal production as revealed by micromorphology in this facies. Subsequently, three separate charcoal chronologies from SU 2 (2 charcoals) and SU3 (1 charcoal) (squares 2 and 3) provided three additional dating points in 1939. From 1939 onwards, the new dates obtained became annual: 2 charcoal fragments extracted from SU 2 and 1 fragment from SU 3 dated to 1940 (squares 2 and 4), 2 fragments from SU 3 dated to 1941 (squares 1 and 4) and finally 1 fragment collected in SU 3 (square 2) dated to 1942. These three consecutive dates characterise several successive, very brief and closely spaced, charcoal making episodes located at the transition from SU 3 to 2 (Fig.10 a,b). For this period, historical documents confirm that at least three cuts occurred mainly between 1941 and 1942 (Noiriel, 1965). In addition, the presence of reworked, heterogeneous materials, mixing weathered sediments and charcoal fragments, at the top of the CK terrace fill testifies to the occurrence of one or more charcoal making operations. The lumpy microstructure, abundant earthworm droppings and the traces of root action in this part of the facies, are characteristic of the homogenization of this deposit. Once filled in, the terrace appears to have been permanently abandoned since pedogenesis resumed in the form of the establishment of a humus horizon (MFT_E, Bern1_g). The CK was definitively abandoned in 1942 (Fig.10 a,b). Finally, the chronology demonstrates that the CK stratigraphy was totally mixed since both the most recent and the oldest charcoal making episodes were found in SU3, while the intermediate episodes were evidenced in SU2. This result is consistent with the CK complex history reconstructed through micromorphological analysis.

4.3.3 Some insights about charcoal burner practices and seasonality

The formation progress of the terminal ring provided new information about the seasonality of harvesting practices for supplying wood. Our results suggested that trees felling usually occurred at the end of the growing season, i.e. in autumn. Previous archeological works already highlighted that fuelwood harvesting for charcoal making was generally done from late autumn until the first sap rises at the end of winter (Montanari et al., 2000; Fouédjeu et al., 2019). The period from late winter up to early spring (before the beginning of growing season) is also considered to be the best time to cut coppices for new shoot growth (Nicolescu et al., 2018). As the felled wood was rarely charred green, it was first stacked in the forest for a few months (Bond, 2007), providing a partially dry wood that was easier to burn. Thereafter, wood was charred, very often as early as the following spring, i.e. in the same year of felling or at the latest at the beginning of the following year (Duhamel Du Monceau, 1761; Percy, 1864; Py-Saragaglia et al., 2018). According to local modern and contemporary historical records charcoal burning season in the mountains of Ariège lasted generally from September, sometimes late August, to June or some cases to July, with a short stop during the months of January and February (Bonhôte, 1998, annex 2, 220-223). In addition, the log calibre reconstruction of charcoal fragments highlights that charcoal burners used mainly very small-calibre wood (0.8 to 3.6 cm), i.e. shoots with their terminal twigs, confirming that wood fuel came from coppice harvesting (Py-Saragaglia et al., 2018).

Various charcoal fragments lacked terminal rings; these 66 charcoals designate *terminus post quem* dates. However, even though we were unable to date accurately their felling dates, these fragments may highlight one or more additional phases/episodes of charcoal making and/or the continuity of practices on the CK terrace. Indeed, we cannot completely exclude the possibility that the last dated rings correspond to the felling of the shoot. In fact, it is not unusual in an archaeological context for excavation, sampling or sieving to increase the risk of charcoal fragmentation and bark detachment (bark cells are already poorly resistant to carbonisation) (Blondel et al., 2018). But in the absence of sapwood which is not visible on beech wood, it is impossible to validate that the last dated ring corresponds to the date of felling.

Conclusion

This paper (i) highlighted, through the implementation of an original and integrated approach, the complexity of the CK tool, archive and chronology of charcoal making practices, and (ii) provided new insights about the successive phases of use and abandonment of an ancient CK terrace. By combining micromorphology and dendrochronology, we have also been able to characterise the rate of terrace reuse at high temporal resolution. Micromorphological analysis highlighted the multiperiod nature of the CK use. The dendrochronological study of charcoal fragments allows us to overcome the radiocarbon dating (AMS) limitation by improving the accuracy of CK use dates to an annual resolution. Our study reveals (i) a regular and repetitive use of the CK terrace and (ii) its operation over a very specific period of time. We therefore highlighted two major phases of charcoal production interspersed with a phase of abandonment resulting from the need for (to allow) the beech coppices to grow and to regenerate. The first phase has only been evidenced by the microstratigraphy analysis but cannot be dated due to the lack of charcoal fragments. The second phase was precisely dated between 1924-1942 and was characterised by an intensification of the felling cuts from 1939 onwards becoming annual.

Our study highlighted the relevance of an integrated approach to better characterise the long-term variation in intensity of charcoal production and of its pressure on local woodland. All results underline the need to develop such integrated approaches for the study of post-1650 CKs in order to refine the chronology of charcoal burner practices and better understand their impact on forest ecosystems. Locally, the construction of the "Forêt de Bernadouze" master chronology has provided a new dendrochronological reference for beech on the northern slope of the Pyrenees and highlights the need to build new reference sets, at least for the dominant species (beech, fir, oak, pine). As emphasized by Deforce and Haneca (2015), the comparison of charcoal growth patterns with those derived from current forest management models (coppice, coppice with standard, selection coppice system, high forest, etc.) may facilitate the reconstruction of past woodland management practices.

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List and legends of tables and figures:

Tables

Table 1: Synthesis and description of stratigraphic units (SU)

Figures

Figure 1: The Forêt de Bernadouze represented with sampling points of charcoals kilns (CK). Green squares represent four CKs near to CK target and red square CKs dated by radiocarbon between 19th and 20th c. White points represent the totality of 64 dendrochronological samples. White circles, the 46 dendrochronological samples analysed for this study. The red star represents the CK selected for the micromorphological and dendrochronological study.

Figure 2: Protocol illustrating excavation and sampling of the CK. (a) White dotted circle shows the CK boundary after removal of litter. Grid with 1 x 1 m squares. Sampling of a bucket of 10 litres of sediment per tiles and SU. (b) Excavation of a quarter of the CK.

Figure 3: (a): North section of the trench. (b) and (c). Detail of the western and the central part of the section after an additional 10 cm, discovery of a fifth SU and the localization of micromorphological samples. (d): Schematic survey of the trench.

Figure 4: Scans and microphotography of Bern1 sample. (A) Scan of the indurated sample with schematic organization of micro-facies (a to g). (B, C and D) Scans of the three thin-sections. (E) Bern1_a: main coarse mineral materials; (red arrow: phlogopite; yellow arrows: dolomite) surrounded by carbonated clay-silt. (F) Bern1_b: centimetric charcoal surrounded by a mix of mineral and organic materials. (G) Bern1_b: heterogeneous constituents and organization with both unaltered aggregates (yellow arrow), oxidized aggregates (red arrow) and carbonaceous material (blue arrow). (H) Bern1_c: integration of combustion residues-rich material as mesofauna faecal pellets (yellow arrows) and a large rounded aggregate of unaltered sediment (red arrow). (I) Bern1_d: aggregate of oxidized sediment in secondary position within a heterogeneous matrix including abundant combustion residues and biological features. (J) Bern1_g: Topsoil organic layer with abundant leaf fragments (red arrows).

Figure 5: Scans and microphotography of samples Bern2 (A, C) and 3 (B, D). (A, B) Scan of the indurated samples (A: Bern3, B: Bern2) with schematic organization of micro-facies (a to d). (C, D) Scans of the two thin-sections. (E) Bern2-3_a: channel infilling including fragmented charcoal. (F) Bern2-3_b: aggregates, mostly of biological origin, made of combustion residues rich heterogeneous material (red arrow) or of mineral components similar to the local regolith. (G) Bern2-3_c: Oxidized upper part of the micro-facies. (H) Bern2-3_b: General organization and microstructure with mixture of aggregates enriched in combustion residue (red arrow) and others similar to the surrounding regolith (yellow arrow).

Figure 6: A synthesis of the organization of the identified MFTs in samples (images from resin-indurated blocs cut, wetted and taken on a flatbed scanner)

Figure 7: Comparison of the master chronology of the Forêt de Bernadouze (red) with the chronologies of the Iraty Forest (green, French Basque Country) and Baish Aran (blue, Spanish Pyrenees). The table at the foot of the figure indicates the main statistical results of the cross-dating processes.

Figure 8: Correlation matrix illustrating the very good synchronization of live trees (a) and charcoal (b). Black color indicates the quality of correlation.

Figure 9: Interdating charcoal chronology with live wood chronology. The table at the bottom indicates the main statistical results of the cross-dating processes.

Figure 10: Diagram of the 82 dated charcoal series presented as horizontal bars. Stars represent the number of the stratigraphic units (SU) from which the charcoal fragments come. Fragments without bark are indicated in green and fragments with bark in red. Blue points indicate the last ring produced by the tree only on charcoal with bark and yellow vertical lines indicate dates of felling. (b): Time course of use of the terrace illustrating the trend of charcoal production on the CK. Green color represents charcoal without bark and red color charcoal with bark. We can see an intensification from 1939.

Supplementary material

Table S1: Detailed micromorphological description of the five soil thin sections

Table S2: Description of individual and master chronologies built on felled trees and charcoal fragments

Table S3: Synthesis of the different charcoal-based chronologies used to compare the new Bernadouze charcoal chronology

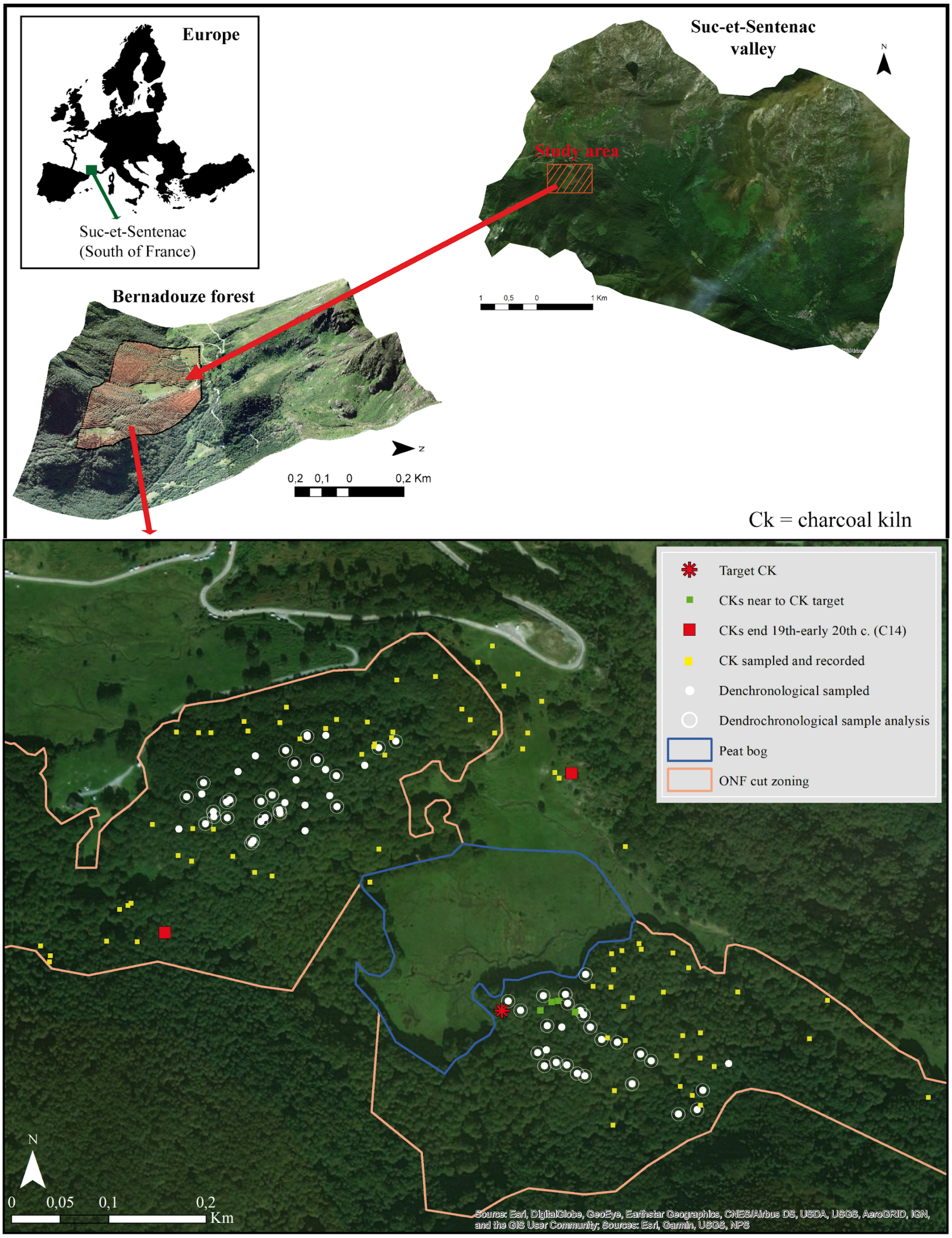

Europe
Suc-et-Sentenac
(South of France)
Suc-et-Sentenac
valley
Study area
Bernadouze forest
0,2 0,1 0 0,2 Km
Ck = charcoal kiln
Target CK
CKs near to CK target
CKs end 19th-early 20th c. (C14)
CK sampled and recorded
Denchronological sampled
Dendrochronological sample analysis
Peat bog
ONF cut zoning
N
0 0,05 0,1 0,2
Km
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community; Sources: Esri, Garmin, USGS, NPS

Figure 1

Figure 2

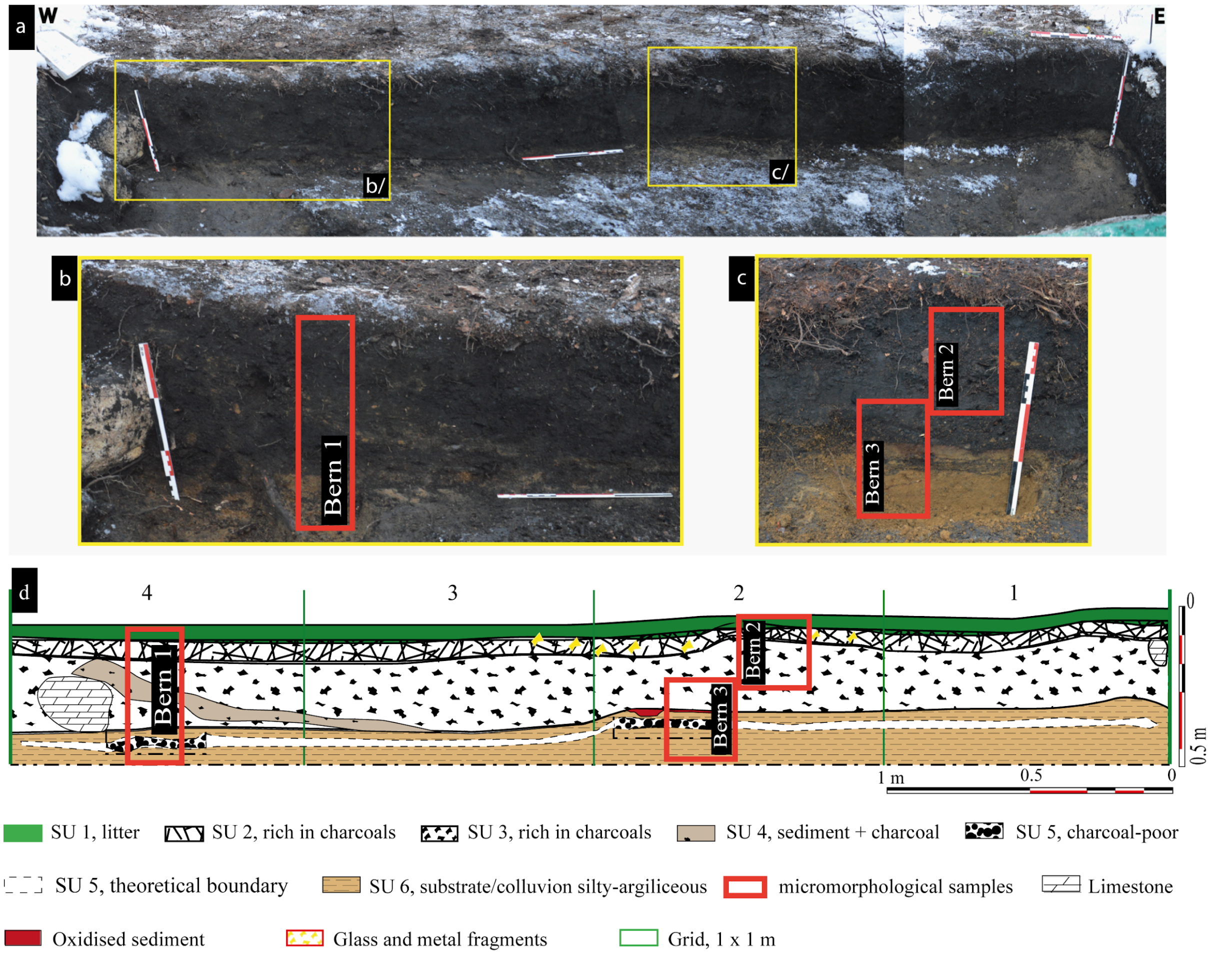

a
W
E
b/
c/
b
Bern 1
c
Bern 2
Bern 3
d
4
3
2
1
Bern 1
Bern 2
Bern 3
0
0.5 m
1 m
0.5
0
SU 1, litter
SU 2, rich in charcoals
SU 3, rich in charcoals
SU 4, sediment + charcoal
SU 5, charcoal-poor
SU 5, theoretical boundary
SU 6, substrate/colluvion silty-argiliceous
micromorphological samples
Limestone
Oxidised sediment
Glass and metal fragments
Grid, 1 x 1 m

Figure 3

Bern1

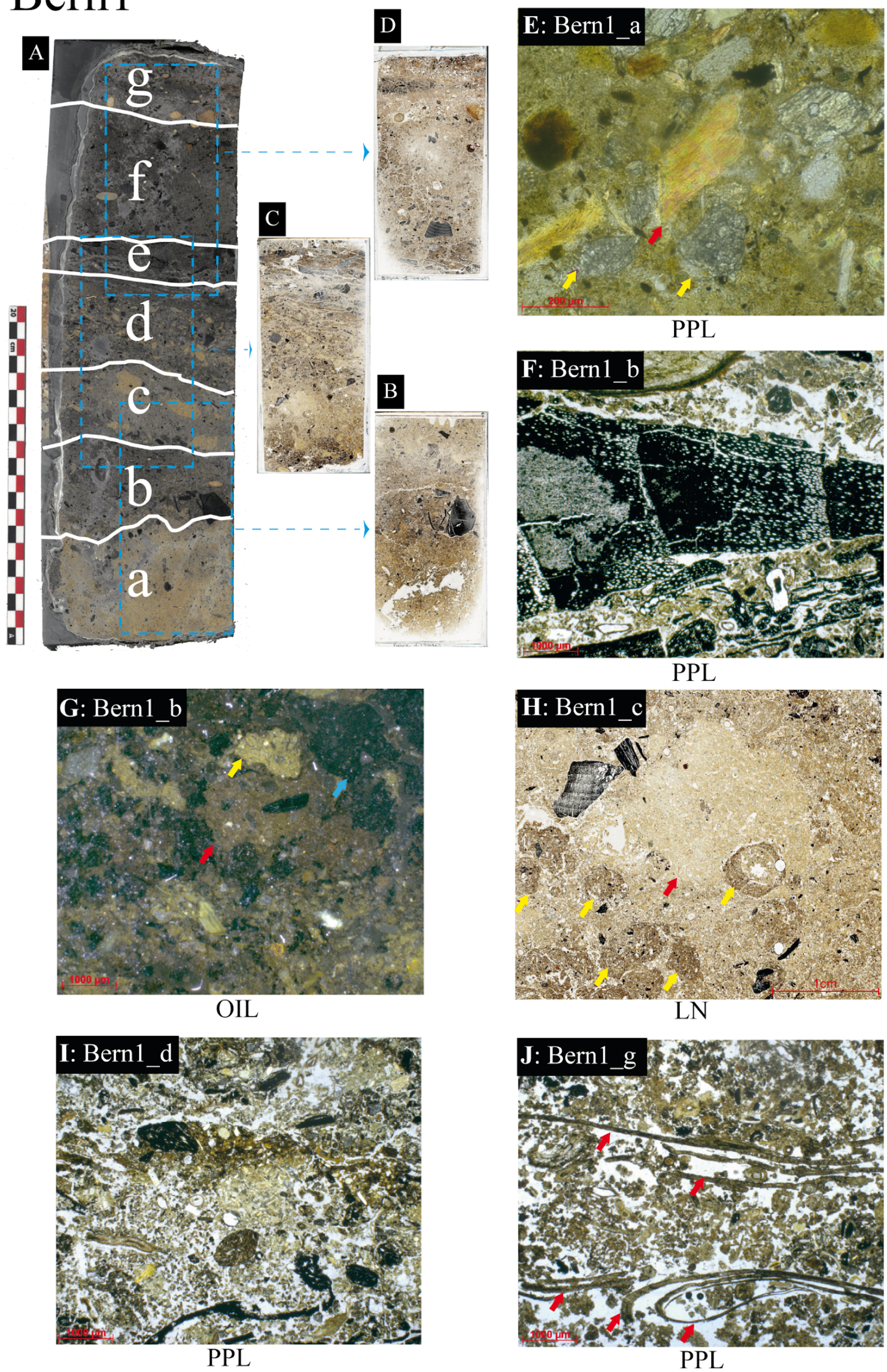
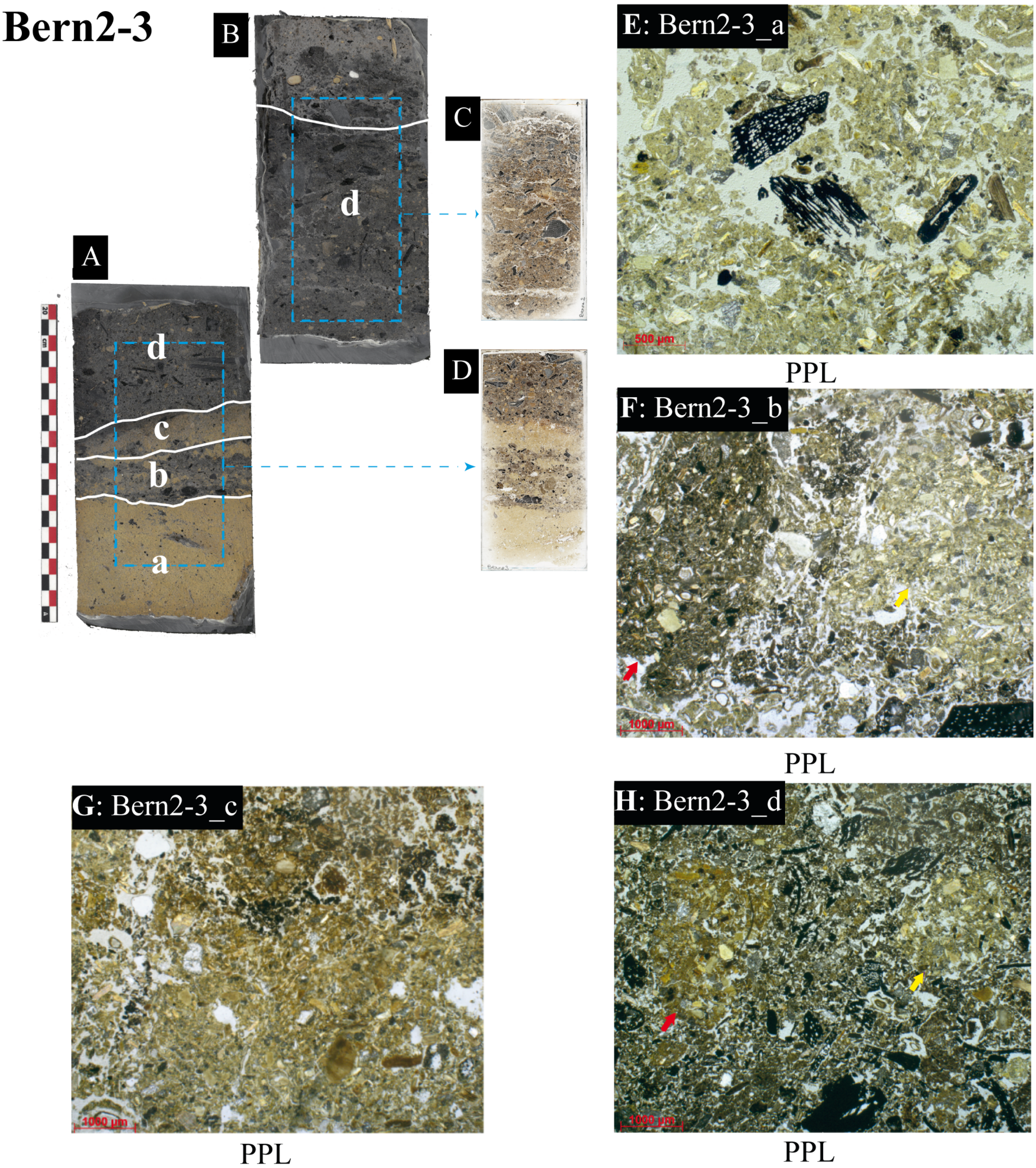


Figure 4



Bern2-3
A
B
C
D
d
c
b
a
E: Bern2-3_a
500 µm
PPL
F: Bern2-3_b
1000 µm
PPL
G: Bern2-3_c
1000 µm
PPL
H: Bern2-3_d
1000 µm
PPL

Figure 5

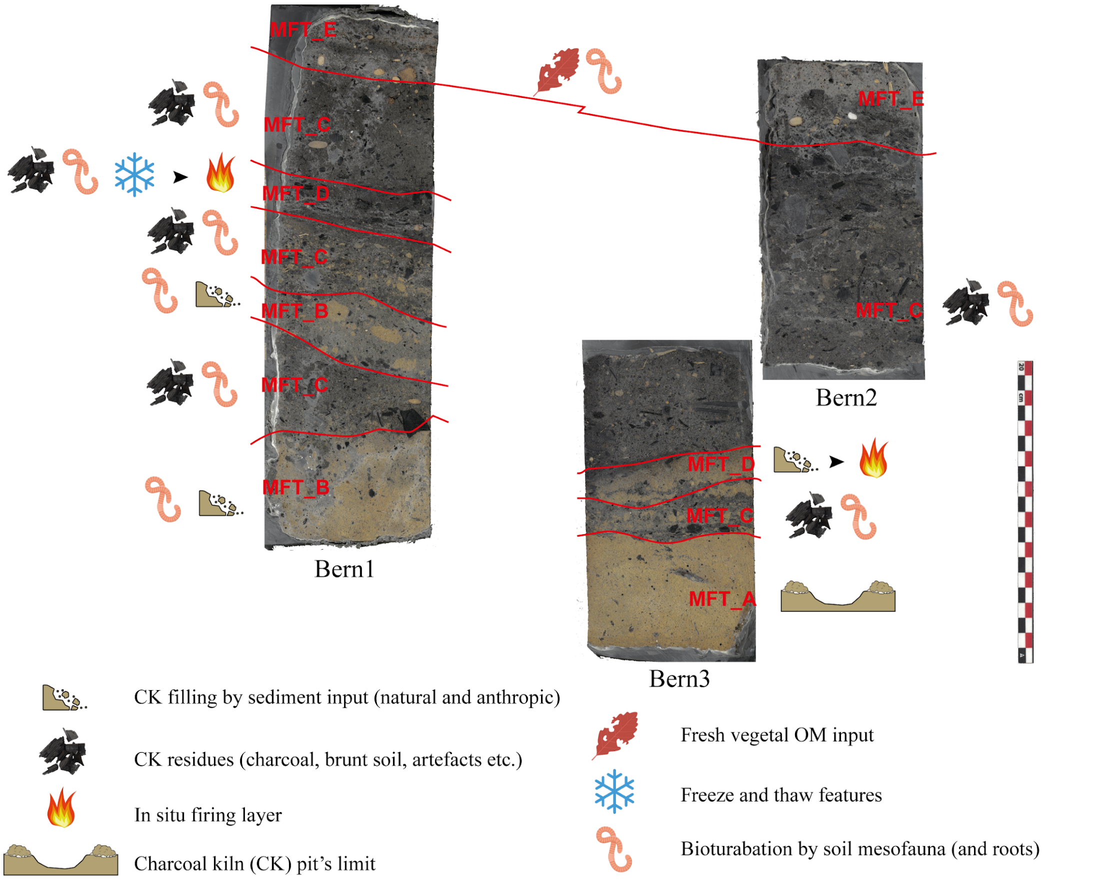
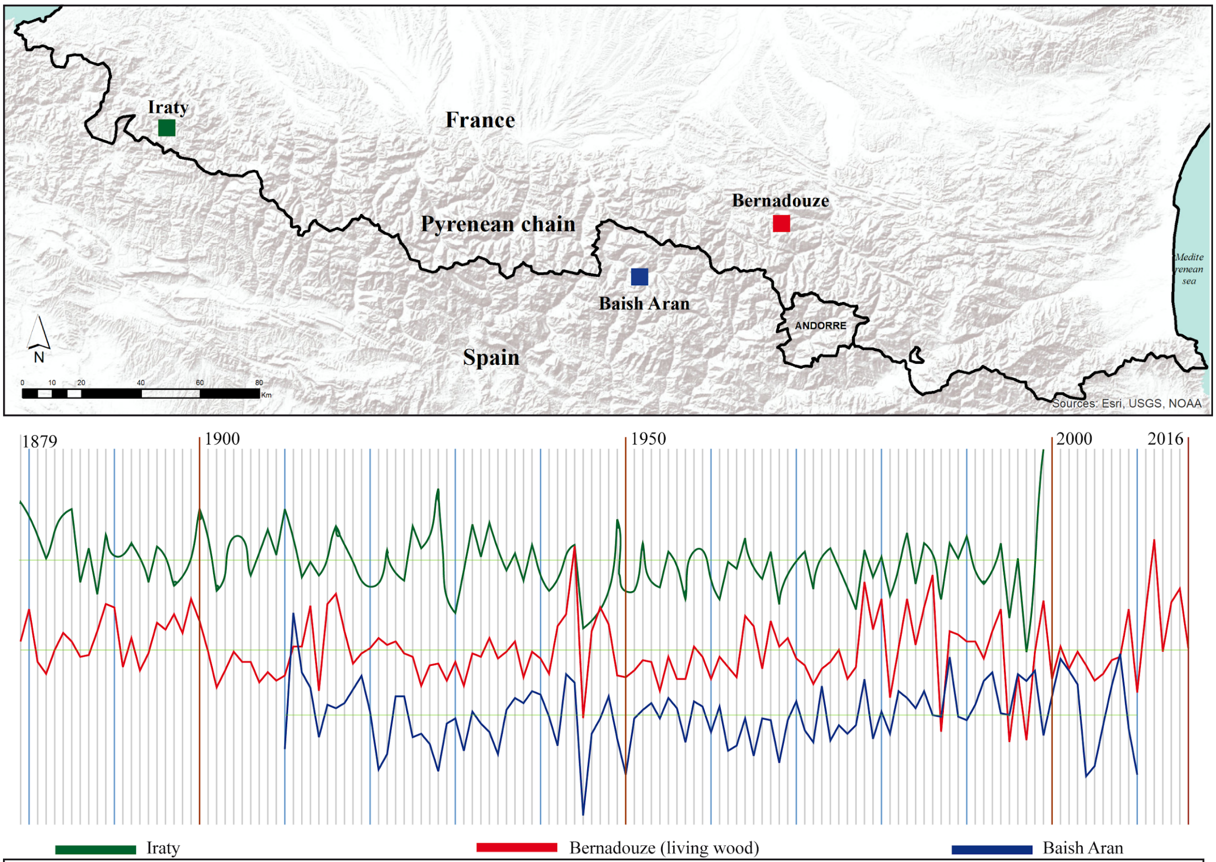

MFT_E
MFT_C
MFT_D
MFT_C
MFT_B
MFT_C
MFT_B
Bern1
MFT_E
MFT_C
Bern2
MFT_D
MFT_C
MFT_A
Bern3
CK filling by sediment input (natural and anthropic)
CK residues (charcoal, brunt soil, artefacts etc.)
In situ firing layer
Charcoal kiln (CK) pit's limit
Fresh vegetal OM input
Freeze and thaw features
Bioturabation by soil mesofauna (and roots)

Figure 6



	Test Student	Mean correlation	Overlap	Source
Iraty (Pays Basque, France)	6.85	0.48	120	Bourquin-Mignot and Girardclos, 2001
Baish Aran (Spain)	3.6	0.33	100	Cavin and Jump, 2017

Figure 7

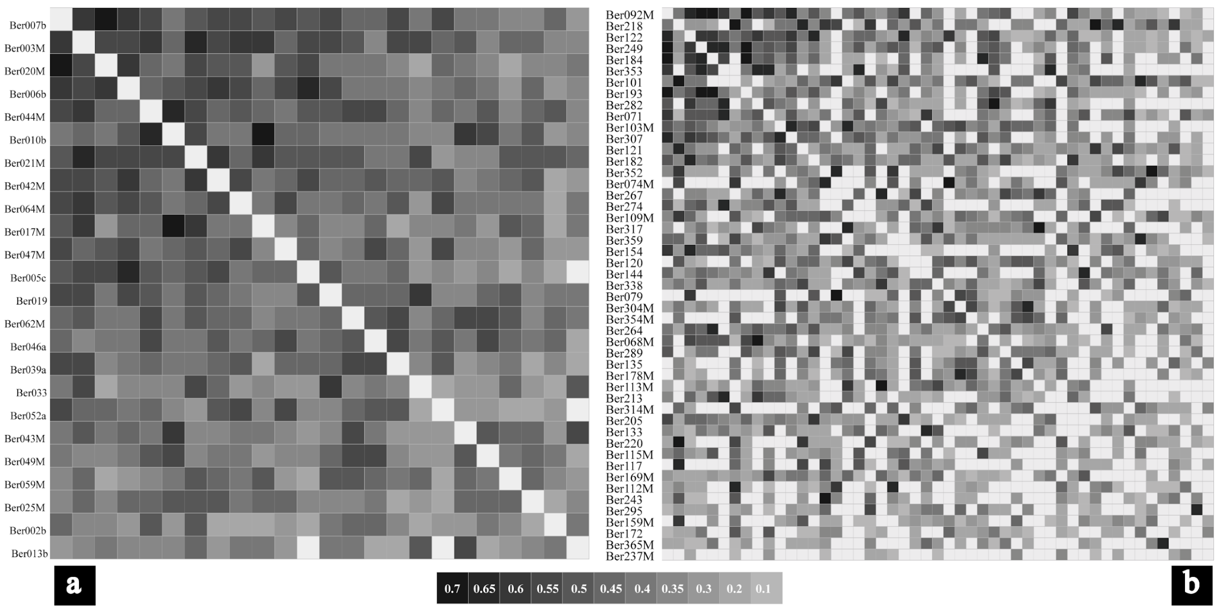


Figure 8

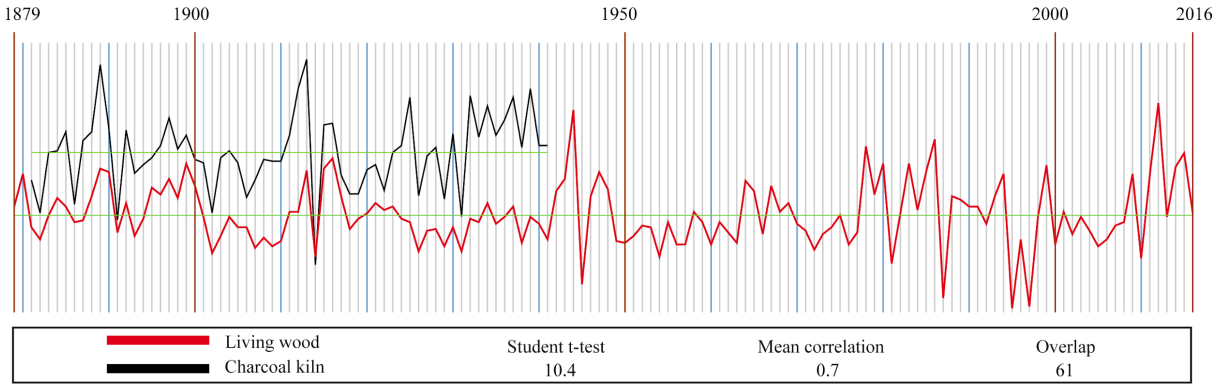

1879
1900
1950
2000
2016
Living wood
Charcoal kiln
Student t-test
10.4
Mean correlation
0.7
Overlap
61

Figure 9

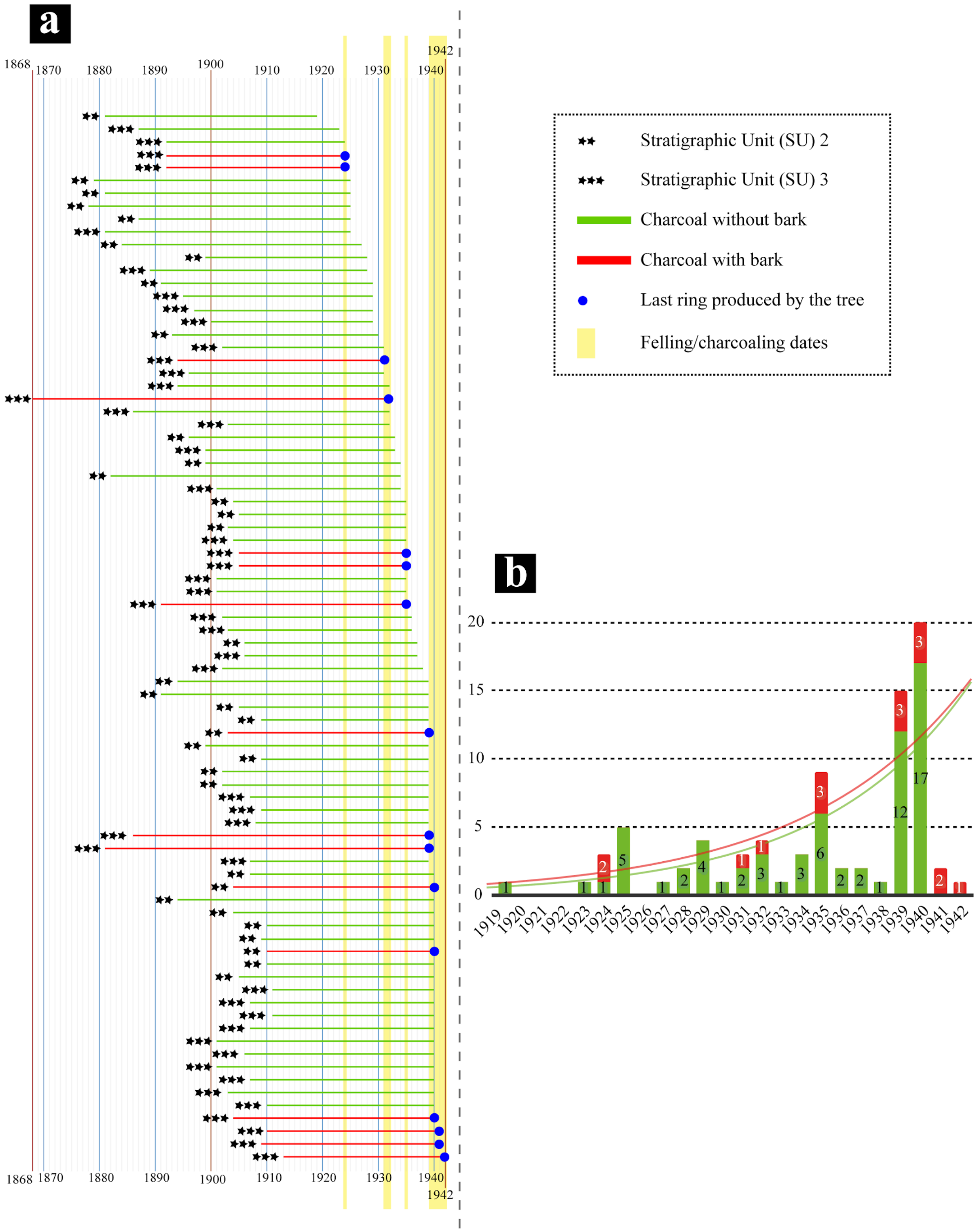


Figure 10

SU	Depth (cm)	Description of the SUs

1	0 -10	Litter mixed with humus, very poor in charcoals.
2	10-20	Part of the carbonaceous layer characterised by a significant presence of charcoals. Very black, loose and shallow layer. This layer is located on a very compact surface (top of the SU 3). This SU featured several glass fragments, a cutlery set and tin cans
3	20-35	Part of the carbonaceous layer, highly homogeneous, thick and very rich in charcoals. This SU is located directly on the mineral layer. It contains small, powdery rocks in some sections and some rare glass fragments.
4	5-12	This SU presents a mix of sediment and charcoals (low density) inserted in the SU 3 at the western edge of the section. Charcoals in this SU have not been studied (Fig. 3D).
5	2-3	This very fine SU, detected only at the micromorphological thin section, is intercalated in the mineral soil. It has very low charcoal content and was not sampled and studied by dendrochronology (Fig. 3B-C- D).
6	35-45	Substrate without charcoal, silty-clays colluvium (Fig. 3C, D)

Table 1: Synthesis and description of stratigraphic units (SU)

Sample	Facies	Description	SU
Bern 1	Bern1_g	Organic material in various states of degradation. Microstructure very loose with well-separated crumbs.	2
Bern 1	Bern1_f	Mineral materials including frequent fragments of charcoal. Their microstructure is essentially friable, with small, well-separated aggregates. The more massive and larger aggregates seem to correspond essentially to earthworm pellets. Fecal pellets of various sizes (earthworms, enchytraeidae) and fresh root tissues are observed.	2
Bern 1	Bern1_e	Charcoals (from a few µm to several centimetres) are abundant. The microstructure evolves vertically from a relatively porous and friable assemblage (microstructure of separate crumbs) to a more massive top. The presence of channels their filling with faecal pellets and frequent fresh root tissue indicate marked biological activity.	3
Bern 1	Bern1_d	The limit is clear, but irregular with Bern1_c. The microstructure and constituents are similar to those of Bern1_b. The presence of charcoals and micro-charcoals is significant and aggregates of oxidized sediments are occasionally observed. The biological features frequently intersect these usual elements of superficial horizons affected by successive freeze/thaw cycles.	3
Bern 1	Bern1_c	The contact is clear with underlying facies and mineral materials are similar to those of Bern1_a. Frequent charcoals and microcharcoals (less than in Bern1_b however) are present in the porosity. Moreover, aggregates of materials similar to those Bern1_b as well as centimetric and sub-rounded aggregates of yellow silty-clay are observed.	3 and 4
Bern 1	Bern1_b	The contact with Bern1_a is diffuse. The materials are similar to those of Bern1_a, with, however, a markedly higher proportion of organic constituents, notably millimeter- to centimeter-sized charcoal. Aggregates of oxidised sediments are also observed. The biological activity is materialized by numerous fillings formed by faecal pellets and root tissues.	5
Bern 1	Bern1_a	Reworked material with a crumby/granular microstructure and rounded aggregates. Mixed with combustion residues (burned sediments, charcoal) through biological activity (mesofauna channels, roots).	6
Bern 2-	Bern2-3_d	Heterogeneous mixture of materials: local sediments, sometines rubefied,	2

3		abundant charcoal. Significant bioturbation including channels and associated dejections. Root tissues are also frequently observed.	and 3
Bern 2-3	Bern2-3_c	The contact with the underlying facies is diffuse. Organization is characterised by the accumulation of more or less rounded centimetric aggregates. Biological features are always present, notably through the integration of combustion residues in the faecal pellets filling the porosity and root tissues.	3
Bern 2-3	Bern2-3_b	The constituents are heterogeneous but enriched in charcoals and microcharcoals and brown to greyish in PPL. Crumby and micro aggregated microstructure. The traces of biological activity are abundant, whether in the form of channels, root tissues in the porosity or faecal pellets attributable to soil mesofauna.	5
Bern 2-3	Bern2-3_a	Massive carbonated clay-silt with dolomite and tremolite sands. Few biological features, few organic constituents.	6

Table S1: Detailed micromorphological description of the five soil thin sections

Material types	Individual chronology characteristics									Master chronologies				
	Number of elementary series			Length			Ring width (mm)			Number of individual chronologies	Length	Ring width (mm)		
	min	max	mean	min	max	mean	min	max	mean			min	max	mean
wood	1	4	2.72	89	162	145.34	0	30.9	9.97	24	137	0	24	10
charcoal	1	3	1.25	6	66	31.18	0	24.8	3.6	49	60	0	22	4

Table S2: Description of individual and master chronologies built on felled trees and charcoals

	Chronology	Species	Student t-test	Mean Corr	Overlap	Authors / Source
Bernadouze	Bernadouze	Beech	10.4	0.7	61	Fouedjeu et al.
Mine E Mauk	EACC	Cembro pine	4.5	N/A	149	Nicolussi et al. (2009)
	TA_Mag1i	Fir	5.0	N/A	105	Billamboz and Neyses (1999)
St Paulien	Bourgogne.Classic.Beta	Oak	5.5	0.4	115	LCE University UBFC
	ClassicOaks-Cor	Oak	4.6	0.4	115	LCE University UBFC
	NEF3	Oak	4.2	0.4	115	Dendronet
	Lorraine.Classic4	Oak	4.1	0.3	115	Dendronet
	Auvergne.Classic	Oak	3.9	0.3	115	LCE University UBFC
	Franche-Comté/ Classic.beta	Oak	3.9	0.3	115	LCE University UBFC
	Belgium-GR	Oak	3.7	0.4	115	University ULG
Cero Pintado	Austrocedrus chilensis	Chilean cedar	N/A	0.6	50	Villalba and Veblen (1997)
Old Greenwood and Gray's Crossing	Truckee, California	yellow pines	9.3	0.6	122	Strachan et al. (2013)

Mt. Hope	Central Nevada	Single-leaf Pinyon	10.6	0.7	100	Biondi and Strachan (2009)
Cortez			12.2	0.6	202	

Table S3: Synthesis of the different charcoal-based chronologies used to compare the new Bernadouze charcoal chronology