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Title:

Long-term Forest Evolution and Woodland Uses in an Ancient Charcoal-production Forest of the French Eastern Pyrenees: an Interdisciplinary Approach with High Spatio-temporal Resolution

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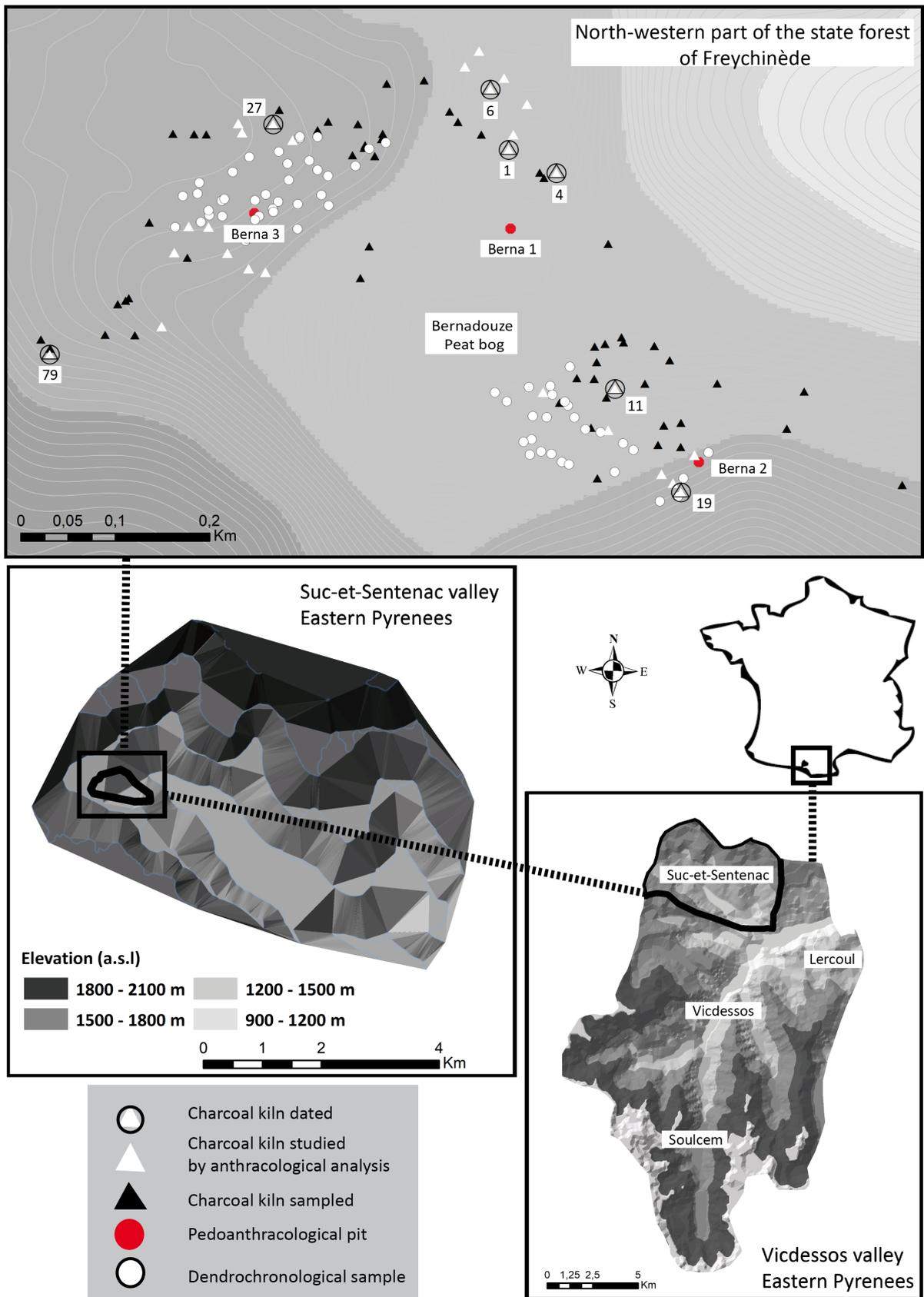


Figure 1. Study area national location and at the scale of the Vicdessos and Suc-et-Sentenac valleys and mapping of -1- charcoal kiln sites (dated by radiocarbon analysis and studied by anthracological analysis -circled white triangle-, studied by anthracological analysis only - white triangle- and sampled by auger coring but unanalysed

-black triangle-), -2- pedoanthracological pits, -3- trees sampled for dendrochronological references -circled white circle- ©L. Fouédjeu Fomou, 2018.

Introduction

This study characterizes the long-term history at a local level of an ancient ‘charcoal-production forest’ located in the high Vicdessos valley in the eastern French Pyrenees. We are interested in knowing its history and the evolution of human practices that have shaped it throughout time. The forest is in the north-western part of the state forest of Freychinède in the high valley of Suc-et-Sentenac (Fig. 10-1). It is within a managed biological reserve created in 1983 which primarily aims to ensure the biodiversity conservation of a large peatbog called Bernadouze and the complex of peat bogs, mountain lakes, woodland and open landscapes that surrounds it.

The public value the area, but mistakenly regard it as highly natural. It is used for seasonal grazing by farmers from the commune of Suc-et-Sentenac which helps maintain open areas near the peat bog. The forest is managed by the National Forests Office, which has prescribed a group-selection harvest in a buffer zone of 90 ha. Other activities are restricted or prohibited.

The part of the forest studied is around the Bernadouze peat bog between 1350 and 1600 m asl (Fig. 1). It has a north and north-west exposition on slopes with varying degrees of steepness. The soils of the watershed have a chalky origin. According to the bioclimatic model this is within the montane beech-fir forest zone, but fir (*Abies alba* Mill.) is currently very restricted. There are few individuals at the upper margin of the beech stand (*Fagus sylvatica* L.) around 1650-1700 m asl, in an ecotone situation. A very localised stand of conifers with pines (*Pinus uncinata* Mill. ex. Mirb.) and fir occupies scarps at the higher part of the southern-eastern woodland cover. A small plantation also exists of young trees (30 years) mixed with deciduous species in a forest aisle corresponding to an avalanche corridor. However, overall the natural regeneration of fir in beech woodland is scarce.

The forest is almost exclusively dominated by beech, which constitutes a large part of the current forest cover in the High Ariège and Vicdessos valley (40% of the forested surface in 1990, according to the National Forest Inventory). In the Bernadouze forest, beech wood exists in three different forms: (i) high forest, from the conversion of former coppices, dominated by 130-150 year old trees; (ii) tall-growing coppices of old trees from a coppice selection method (i.e. stump sprouts are of different ages) located in the north-western part of the forest; (iii) a strip around the peat bog of tall-grown coppices that have been browsed in the past. Thus, this forest shows the main characteristics of northern slope beech forests of the eastern Pyrenees that have been exploited in the past for charcoal production (DAVASSE, 2000).

These forests, more or less modified by human activity, survived because of the past management of coppice systems, mainly to supply iron works. Evidence of iron metallurgy in archaeological data comes from the end of Late Antiquity within the Lercoul massif in the north-eastern part of the Vicdessos valley not far from the Rancié (Sem) mines (Fig. 1) (DUBOIS, 2000). No archaeological data revealing steelmaking activities during the early medieval period has, as yet, been discovered but archaeologists and historians assume such continuity (DUBOIS, 1996; VERNA, 2001). This is supported by texts from the late 13th c. and mainly from the early 14th c. with the introduction of the *mouline* technology. This sort of hydraulic forge including a low shaft furnace (direct reduction) was spread along the waterways on the left bank of the Ariège, as in Vicdessos, between the beginning of the 14th and the 15th c. This required more fuel than the previous hand-forging process, and so strongly increased the pressure on

forest cover. Historians propose that this resulted in the introduction of more restrictive forestry practices and the prohibition of access to certain forests such as oak or fir woodlands.

Geographers and palaeoecologists have demonstrated that fir was disadvantaged because it does not have the capacity to regrow from stumps as beech does. Therefore, the beech wood culture based on coppice systems was implemented until recently to ensure the constant renewal of fuel wood resources (DAVASSE, GALOP, 1990; DAVASSE, 2006). Nevertheless, the stages of this process in terms of their impact on pre-existing forest ecosystems, their changes and spatial dynamics at a local scale, are still poorly documented from the medieval period to the first half of the 17th c. when the Catalan forge process arose (CANTELAUBE, 2009). The texts are relatively silent on this topic and archaeological remains dating back to the early medieval period studied from this perspective are scarce. There is no charcoal kiln site prior the mid-15th c. detected in Vicdessos by DAVASSE, 2000, although at least ten were found within the Lercoul forest (DUBOIS, MÉTAILIÉ, 2001). This study of charcoal kilns showed that beech dominated until the medieval period and it was replaced by fir from the 14th c.

At the regional scale, palynological data has shown that mountain forests were largely dominated by fir before ca. 2500-2300 BC. Beech expansion after this period was associated firstly with climate cooling and secondly with the development of agro-pastoral and steel-making activities (KENLA, JALUT, 1979; JALUT ET AL., 1982; REILLE, 1993; GALOP, JALUT, 1994). However, fir was still in the woodlands of the high Soulcem valley (Fig. 1), which was logged for charcoal making during the 16th c. and later elsewhere (DAVASSE, 2000). The fir-beech relations related to human activities were complex and processes observed in different valleys cannot be generalised. The confidence intervals for radiocarbon dates are too high to follow what could be rapid changes. In addition, the actual charcoal-making practices and how they evolved are largely undescribed before the mid-18th c. when steel-makers sought to perfect traditional methods (BONHÔTE ET AL., 2002; CANTELAUBE, 2009).

In our study area, the use of new multi-proxy analyses of sedimentary sequences for the late Holocene palaeoenvironmental reconstruction at very high temporal resolution is not possible because the Bernadouze peat bog was exploited in the past for peat production. Consequently, to overcome these limits, we used an interdisciplinary approach, mobilising archaeological investigations and new methodologies based on charcoal analysis from charcoal kiln sites and soils. Initial results and interpretation of this on-going research look at: (i) the reconstruction of the pre-charcoal-making forest evolution, (ii) the characterisation of a conjunction of different human practices and uses over time.

An Interdisciplinary and Suitable Methodology for a Local-Scale High-Resolution Study

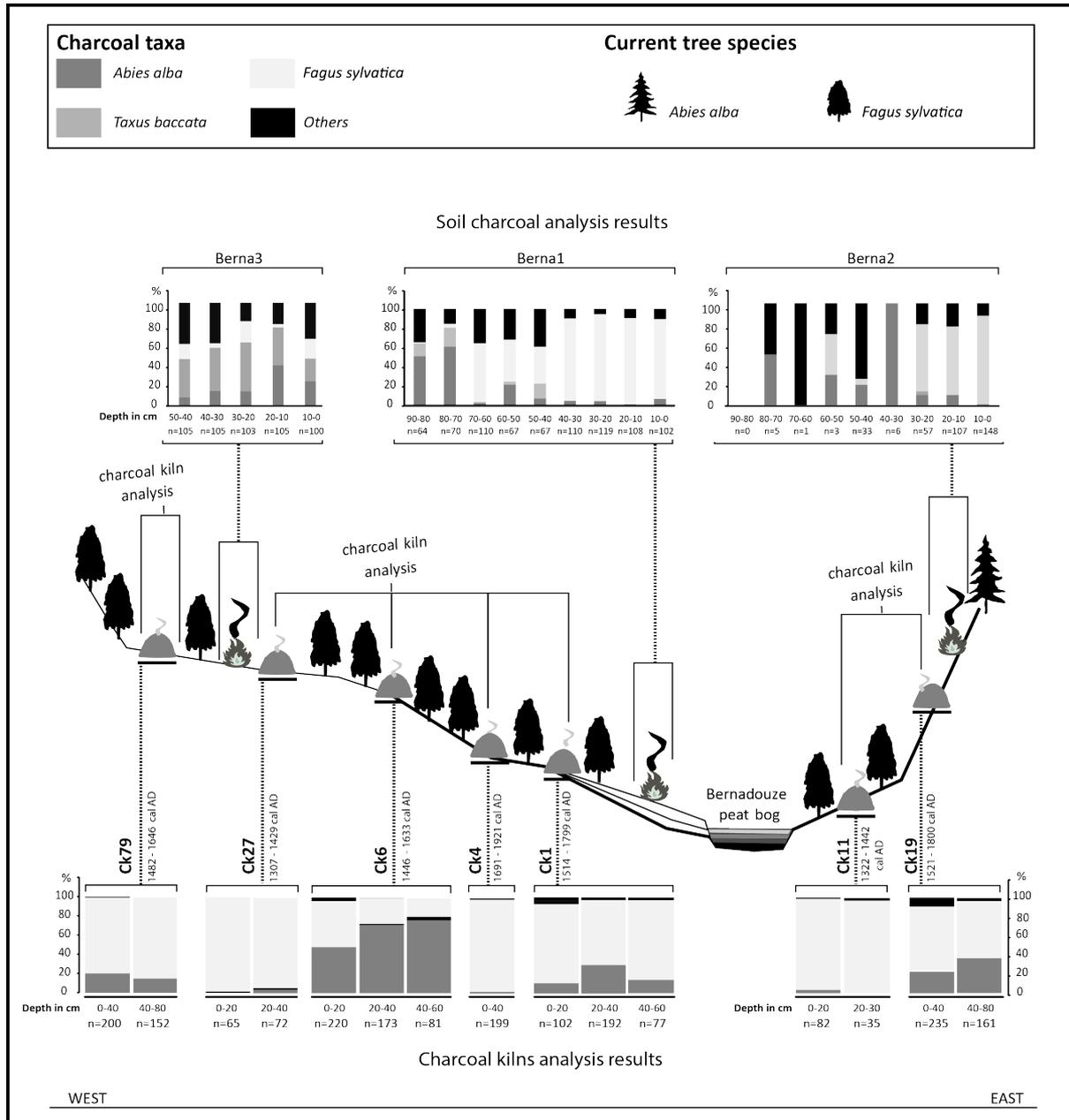


Figure 2. In the central part of the figure: representation of sampling protocol for soil charcoal analysis (3 pits: Berna 1, 2 and 3) on a north-west/south-east transect and location of dated charcoal kilns (CK 79, 27, 6, 4, 1, 11 and 19) on it; in the lower part, percentage anthracological spectra (cumulative histograms) of dated charcoal kilns; in the top part, mass of charcoals by layer in milligrams per kg of dry soil per identified taxa (called specific anthracomass) for the three pits ©R. Cunill, L. Fouédjeu Fomou, M. Saulnier, 2018.

Archaeology of Charcoal Kiln Terraces: Systematic Survey and Charcoal Sampling

Forestry archives of the 17th, 18th and 19th c. used for eco-historical inquiries ([DAVASSE, 2000](#)) did not give the precise location of charcoal kiln sites. However mid-seventeenth century documents indicate that the upper section of the basin was devoted to charcoal-making and that six forges existed around the main basin (a total of twelve forges was estimated ca. 1650, [DAVASSE, 2006](#)). The writings of the 18th c. relate charcoal-making restrictions in certain woodlands and a complete prohibition throughout the territory in 1740. During the 19th c., five forges were mainly supplied by charcoal sourced outside of Vicdessos ([BONHÔTE, CANTELAUBE, 1989](#)).

Forested areas that have supplied charcoal-making production can be investigated through archaeological techniques, but the exhaustive study (planimetric excavation) of individual or a few charcoal kiln terraces provides limited information ([DAVASSE, 2000](#)). Thus we have chosen to do a systematic field survey throughout the forest massif over an area comprising around 30 ha (Fig. 1, 2). Within the study zone particular attention was given to black soils with charcoals on the surface, stream banks, flat surfaces, suspicious terraces on steep slopes and margins of both past and recent paths. This large-scale field approach aimed to detect a maximum number of charcoal kiln sites.

All features were geolocated with a differential GPS, measured, described and systematically sampled using a soil auger, by steps of 20 cm in depth. This sampling method, already tested in the Pyrenees ([PY-SARAGAGLIA ET AL., 2017](#)), makes it easier to collect charcoal throughout the entire kilns' charred sediments and provides a high-resolution view, both spatial and temporal, of the past charcoal-burning activity. For this study, at least six sampling points are taken per terrace to obtain a sufficient number of charcoal pieces for dendro-anthracological analysis. Charred sediments were sieved with water using a column of 4 and 2 mm sieves and then dried out in direct sunlight. Here, only charcoal retained in the 4 mm mesh was studied. The analysis of 50 to 60 charcoal fragments per sampling layer is sufficient to obtain a reliable representation of the composition of the past-harvested forest ([DAVASSE 2000](#); [PY-SARAGAGLIA, 2017](#)) but more are necessary to make create a picture of the initial diameter of the wood used ([FOUÉDJEU ET AL., 2017](#)).

Dendro-anthracological Analysis of Charcoal Remains: Reconstruction of Forest Dynamic and Human Practices

The dendro-anthracological approach followed the methodology developed by [PARADIS-GRENOUILLET, 2012](#) and was based on the 1990s pioneering work focused on the reconstruction of initial wood diameter from charcoal ([DUFRAISSE, 2002](#); [NELLE, 2002](#); [MARGUERIE, HUNOT 2007](#)). It consists of measuring the radius curvature - i. e. the distance between the last ring visible on the charcoal transverse plane and the pith - of about 50 charcoal fragments from the same species per sampling layer. Initially we have measured about 30 fragments for each species (*Abies alba* and *Fagus sylvatica*) at which point the diameter class proportions were beginning to stabilise. Additional measurements are on-going. Measurements were performed using trigonometry in an isosceles triangle with the AnthracoloJ software developed by [PARADIS-GRENOUILLET ET AL., 2010](#). This method applied to charcoal making contexts allows us to explore issues relating to historic forest dynamics and management practices ([PARADIS-GRENOUILLET ET AL., 2015](#)).

In parallel with this approach and the conventional identification methods ([CHABAL ET AL., 1999](#)), we have made a systematic quantification of anatomical deformations -radial cracks, cellular collapses, reaction wood, vitrification patches- and fungal infestation traces (charred hyphae) as in [PY-SARAGAGLIA ET AL., 2017](#). This can provide information about the physiological and phenological state of the wood before the carbonisation process ([MARGUERIE, HUNOT 2007](#); [THÉRY-PARISOT, 2001](#); [THÉRY-PARISOT, HENRY, 2012](#); [HENRY, THÉRY-PARISOT, 2014](#)). Moreover, when bark was preserved, we have registered its position in the last growth ring: for example early wood, transition between early and late wood, late wood, end of the late wood. All these observations make it possible to characterise more fully the forest management, supply practices and charcoal burners uses and their seasonality.

Improving the Chronological High-Resolution of Environmental Changes: Radiocarbon Dating and Application of the Dendrochronology Method on Larger Charcoal Remains

The radiocarbon dating of charcoal is very useful to establish a chronology for forest evolution. The method is based on comparing the measurement of the residual ¹⁴C content in organic matter with the modern activity of carbon ([OBERLIN, 2005](#)). It makes it possible to determine the time elapsed (number of years) from the death of the organism (tree, branch, root), and then to go back to its death date (death of cells -for charcoal without bark- or tree death or part of it). Mass spectrometry by accelerator (AMS) was preferred over the liquid scintillation method. The AMS method is now faster and offers important advantages, especially the possible dating with 1 milligram of carbon or less which is required for soil charcoals.

The BP dates were calibrated using the OxCal computer software Oxford Radiocarbon Accelerator Unit, version 4.2 ([REIMER ET AL., 2013](#)). Only calibrations with a 95% confidence level are used (Fig. 3). Calibration allows us to convert the date range (statistical ranges about 80-100 to 200 years) in real years and provides probability peaks. Uncertainties still exist, especially with the radiocarbon plateaus, but we aimed to increase the chronological resolution of dated events using dendrochronological method. This consists of cross-dating tree-ring chronologies which are constructed using living and fossil woods (from peat bog and barns) and larger charcoals from charcoal kiln sites (Fig. 4). This method has been validated in experimental ([BLONDEL ET AL., 2018](#)), archaeological and natural contexts ([BROSSIER, POIRIER, 2018](#)). We aimed to detect synchronous charcoal kilns and in the best cases specify the date of wood cutting with an annual resolution and even its season.

The implementation of this dendrochronological approach required the construction of a local reference chronology for beech. We took advantage of a forest cut carried out in autumn 2016 by the ONF foresters, to sample beech slices on the cut trees which were distributed throughout the Bernadouze forest (Fig. 1). The slices to be sampled were selected on the one hand according to the estimated age of the trees in order to obtain the longest possible chronologies and on the other hand according to the position of the trees in order to avoid edge effects. In the laboratory, all slices were smoothed by sanding with progressively finer grades of sandpaper, to an optimum surface resolution that allowed the annual rings to be easily recognized under magnification.

All of the individual ring-widths were measured to an accuracy of 0.01 mm ([RINNTECH[®], 2010a](#)) and cross-dated using TSAPwin scientific programs ([RINNTECH[®], 2010b](#)). Cross-dating was accomplished by matching patterns of wide and narrow rings between cores from the same tree, and between trees from

the same area. The average chronologies obtained on each tree slice are then themselves averaged to obtain a standard reference chronology for the Bernadouze forest.

Beech charcoal fragments from charcoal kiln with a minimum of 30 measurable rings were selected for dendrochronological measurements. The chronologies constructed from charcoals will in future be compared to the Bernadouze reference chronology using the cross-dating method. In another project the chronologies based on timbers from wood barns will also be constructed (V. Labbas, post-doctoral research fellowships Chaire IDEX GRAGSON). Other information will come from sedimentary archives (peat, lake) made by M. R. Coughlan within the framework of the Human-Environment Observatory Haut-Vicdessos. The results of this combined approach will be presented in the future.

Based on Oxcal v4.3.2 Bronk Ramsey (2017); r:5 IntCal13 atmospheric curve (Reimer et al. 2013)

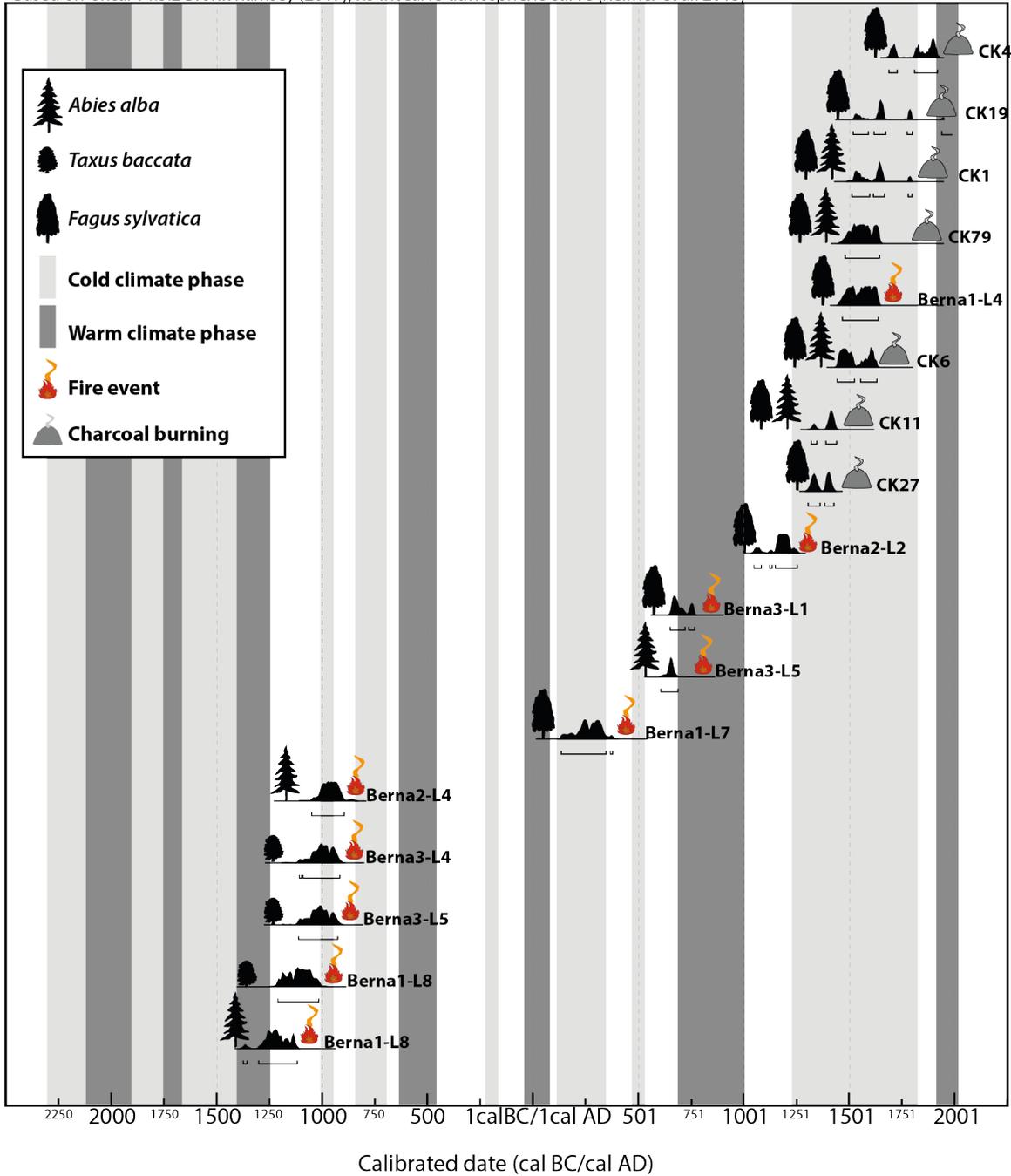


Figure 3. Probability distributions of ^{14}C dates from soil charcoal (fire event) and charcoal kiln sites from the Bernadouze area. Black plots show possible ages with 95.4% probability (calibrated date cal BC/cal AD). Tree drawings symbolize the species dated (*Abies alba*, *Taxus baccata*, *Fagus sylvatica*); cold and warm climate phases according to *TINNER ET AL. 2003* are represented ©Vanessa Py-Saragaglia, 2018 according to Oxcal v4.3.2. Bronk Ramsey (2017); r:5 Int Cal 13 atmospheric curve (Reimer et al., 2013).

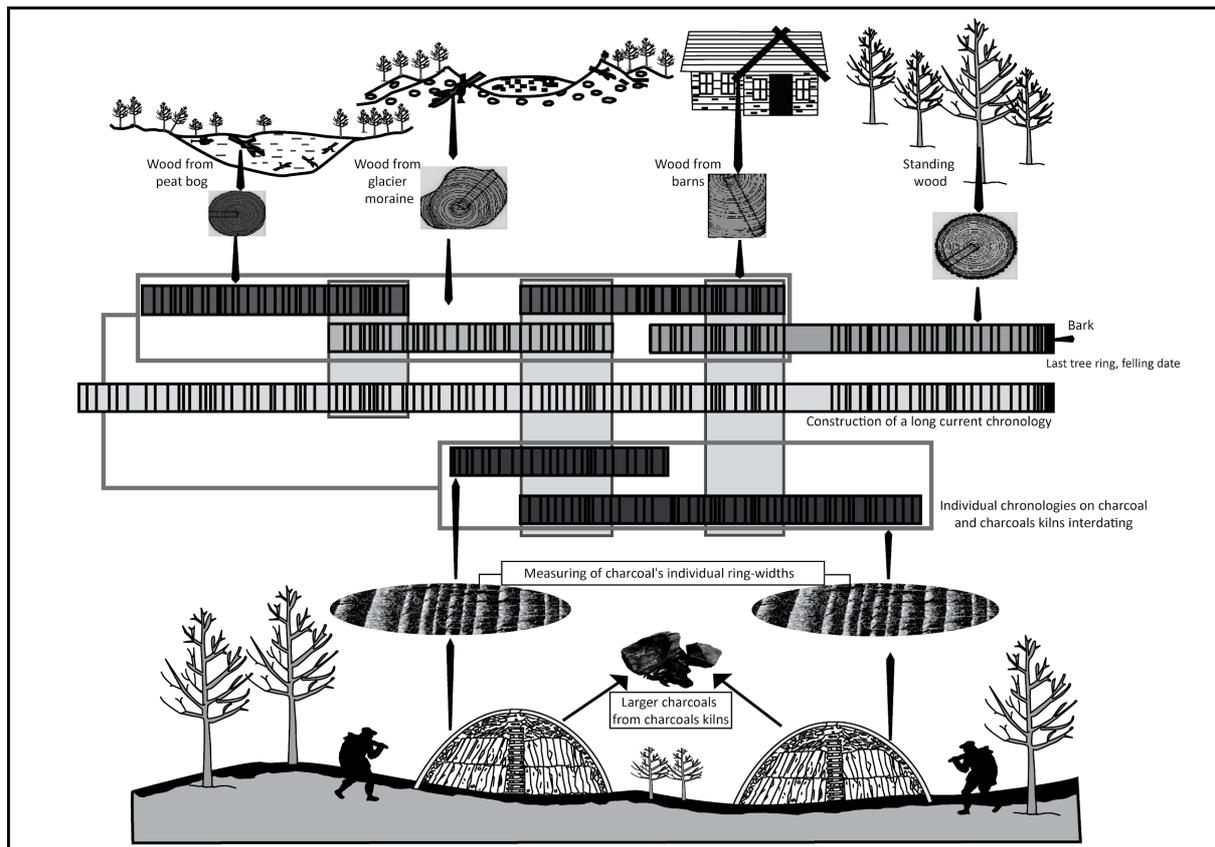


Figure 4. Dendrochronological protocol elaborated for dating charcoal kiln sites with higher chronological resolution than with radiocarbon dating ©M. Saulnier and L. Fouédjeu Fomou, 2018.

2.4. Combined Study of Charcoals from Soils

Soil charcoal analysis or pedo-anthracology allows us to reconstruct past woody vegetation change during the Holocene (THINON, 1978; 1992). Charcoal fragments isolated from soil firstly confirm the presence of past woody vegetation within the sampled area and secondly, their microscopic analysis allows us to identify the taxa involved. Their ^{14}C dating makes it possible to estimate their age. Thus, the information from the last few centuries provided by the charcoal kilns study can be supplemented by the last millennia information from the soil charcoal analysis (Fig. 2).

The edaphic origin of charcoals is independent of human selection and so provides a high reliability in terms of the spatial variation between valleys. The soil presence being the only requirement, the method can be applied widely on terrestrial environments. Then it is thus particularly relevant in areas where sedimentary archives are not present and/or preserved as in the Bernadouze peat bog, because of its past cutting. Here, the aim of the pedo-anthracological multi-sampling strategy was to obtain high spatial resolution analysis within a valley (Fig. 1, 2).

Three sampling areas were defined (Berna 1, 2 and 3). Two of them (Berna 2 and 3) were located inside the beech woodland and with the other in the pasture area nearby the peat bog (Berna 1) (Fig. 1, 2). The contamination of soils by charcoal from charcoal-making activity seems highly improbable in Berna 2, because it is situated at in the uppermost part of the charcoal production area within the south-east part of the forest. In Berna 3 contamination from charcoal kilns seem improbable or limited because it is located in a relatively steep gradient of the opposite side of the northernmost charcoal making areas.

Berna 1 is located in a pedo-sedimentary context, at the foot of a small alluvial cone. As a result, it is assumed that natural and/or anthropogenic fire activities from both northern and north-western slopes have been recorded there.

Soil samples were extracted by digging pits revealing complete soil profiles presented by SAULNIER ET AL., submitted. The depth of the pits varied from 100 to 170 cm. 5 litres of soil were sampled in the different visible soil layers. Dried soils were wet-sieved through 4, 2 and 0.8 mm sieve meshes. When it was possible a minimum of 50 charcoal fragments from each mesh size of each layer was randomly chosen for taxonomic identification using the method presented by CUNILL ET AL., 2015. 10 charcoal fragments possessing sufficient mass (4 mg) were dated by AMS radiocarbon dating in both Beta Analytic (Miami, Florida, USA) and Poznan Radiocarbon Laboratories (Poznan, Poland).

Results and Discussion

Main Forest Changes from the Bronze Age to the Early Modern Period

Our charcoal analysis did not allow the detection of evidence of charred wood remains from the first half of the Holocene. The regional vegetation evolution during this period is documented by palynological studies carried out some time ago in the Bernadouze peat bog called improperly Freychinède (JALUT ET AL., 1988; 1992; REILLE, 1993; REILLE, LOWE, 1993 synthesised by SAULNIER ET AL., submitted). They highlighted the arrival and expansion phases of the main forest species since the beginning of the post-glacial period at ca. 10 422 BC. The fir pollen curve started at ca. 6136 BC and its optimum was dated from ca. 4304 BC (JALUT ET AL., 1982). The start of beech expansion is dated 2990 BC i.e. between the Late Neolithic to the beginning of the Early Bronze Age. Our combined study of charcoals from soils and charcoal kiln sites allows us to reconstruct at very high spatio-temporal resolution the Bernadouze woody vegetation evolution from the Bronze Age to the early modern period (Fig. 2). This provides new insights into the chronology of local vegetation changes from both Middle and Late Bronze Age to the 17th c. AD (Fig. 2, 3).

During the Middle and Late Bronze Age, the structure and composition of the Bernadouze forest was quite similar to the sub-natural mountain fir (-beech) forest for the north slope of Ariège Pyrenees. It was mainly composed by two natural “*dryades*” (The *dryades* are shade-loving tree species at least during the juvenile stage. There are four *dryade* species in the European flora: *Fagus*, *Abies*, *Taxus* and *Picea*): fir, largely dominant, probably associated with beech, poorly represented in pit levels, below. The significant presence of a third *dryade* - the yew (*Taxus baccata* L.) - indicates a more complex structure that we can see currently in Pyrenean old-growth forest. The yew is currently rare within the dominant vegetation storey but still present particularly on calcareous substrates (it may be also on rich and acid ones). The significant presence of this species, which not reaching the canopy but participating at the dominant vegetation storey, could provide evidence of a dense and structured forest with centuries-old trees (SAULNIER ET AL., submitted). Soil charcoal analysis implies therefore the existence of an old-growth fir-dominated forest around 1300-900 BC, i.e. until more recently than assumed from palynological data. This may also indicate that there was more waterlogged soils than currently because fir is very tolerant of these soil conditions, which might be limiting for other species as beech.

After this period, the forest vegetation began to change with both fir and yew decreasing and beech expanding. This suggests the opening of gaps in the canopy (exceeding 500 m², see WALTER, 2002;

DIACI, 2002) which are rapidly colonised by beech. In the Gallo-Roman-Late Antiquity and Carolingian periods, the forest appearance was clearly different from the Bronze Age. It was dominated by beech associated with fir, the latter being very much more restricted. At the same time, a higher level of canopy openness is evidenced by the higher occurrence of deciduous species in Berna 1 (layer 7). Fir stands were located at the upper part of the mountain vegetation storey and/or on waterlogged soil conditions as we can see currently.

The main features of the current Ariège Pyrenees mountain vegetation storey with northern slopes, covered by beech between 900 and 1600 m asl, were thus put in place between the Late Antiquity and Carolingian times. Between medieval period and the first half of the 17th c., soil charcoal analysis (Berna 1 and 2) shows that beech was still the main dominant species, with fir poorly represented. This result corresponds with historical data. Two reports illustrated by a map written by Louis de Froidour during the reformation of Water and Forest Office in 1669 for the Vicdessos area, showed that beech was dominant and present everywhere but exclusively in the form of coppices, mostly degraded (DAVASSE, 2000). Fir woodlands were located in “unattainable summits” of slopes where they were “sparse” or mixed with beech. They were specified in more detail by the surveyors, who however did not visit the upper part of the basin. The presence of juniper - a heliophilous species - in the upper layers of Berna 2 could indicate that these woodlands were opened and degraded and also close to the “kampfzone” (meaning the altitudinal belt of stunted and often prostrate trees, located between the upper limit of tall, erect trees growing in forest densities and the upper limit of tree growth).

Charcoal analysis of charcoal kiln sites reveals that beech was almost exclusively exploited for charcoal manufacturing in the late medieval period i. e. from the 14th c. to the first half of the 15th c. From the second half of the 15th c. to the first half of the 17th c., charcoal makers exploited both fir and beech. This result suggests that fir was still present in the Bernadouze forest cover and not confined to the upper margin of the mountain vegetation storey or in the subalpine area. Indeed it was present close to both peat bog and current pasture area, as reflected by anthracological composition of charcoal kilns 1 and 6 (Fig. 2).

In the vicinity of the peat bog, it is possible that there were low-lying site conditions and/or waterlogged soils which the fir tolerated better than beech. These anthracological data confirm that surveyors did not visit the upper basin of the Vicdessos valley and their report was very approximate. Currently, charcoal kiln 4 is the only dating between the end of the 17th c. to the contemporary era. However from historical archives, its charred remains were almost exclusively composed of beech. At the beginning of the 19th c. (1807), the minute of Dralet described beech coppices (10-20 years old) “in good condition” within the north-western part of the forest; “degraded” beech coppices in the south-eastern one, and fir stands mixed with beech towards the southern steep margins (DAVASSE, 2000).

Finally, this long-term study shows that the Bernadouze forest is very ancient. Its canopy has been opened mainly from the Late Bronze age but a woodland cover more or less dense and continuous has been maintained throughout the time. Fir, which is currently a quite rare species, formerly reigned with yew in this forest. It was replaced by a beech (-fir) forest from the Late Bronze Age up to the Late Antiquity and Carolingian periods and then by almost mono-specific beech woodlands from the second half of the 17th c. up to the first half of the 19th c. Fir has never completely disappeared from the discussed area; it has been maintained in refuge position in waterlogged site conditions and in the southern steep slopes nearby the kampfzone. We will now examine anthropogenic and/or natural forcings, which have driven these processes.

Climate Changes and Human Impacts on Forest Ecosystems Throughout the Time

Around the world, numerous palaeoenvironmental studies have shown that past or recent climate variations triggered vegetation changes. In the Pyrenees, Late-Glacial fire activity reconstruction based on macro-charcoal lacustrine records has shown that climate but also vegetation and land-use changes are the main drivers of fire regimes (RIUS ET AL., 2011; 2014). At the millennial scale, major cold periods are characterised by negligible or low fire activity. At the onset of the Holocene, the fire regime increase was most probably driven by both rise of summer drought and development of deciduous woodlands in lowlands. However the variations in fire frequency during the last 3000 years are probably human-driven (RIUS ET AL., 2009). Thus we can draw on these works to characterise the nature of fire events registered in the Bernadouze area by soil charcoal analysis.

Firstly, our results show an outbreak of fire events between 1300-895 cal BC (with 95.4% of probability). The major part of the chronological sequence covered by radiocarbon curves was overall cold and humid. However, the very beginning coincides with a short warm-dry phase (at ca. 1450-1250 cal. BC) and the end just predated a worsening climate (at ca. 800-750 cal. BC) with increase in precipitation and/or decrease in temperature (TINNER ET AL., 2003) (Fig. 3). Consequently it is difficult to connect these fires events with a climate warming. Thus, we assume that they have been more probably caused by human activity.

In Western European high mountain areas, the Bronze Age was a major period of increase of anthropogenic activities (GALOP ET AL., 2013; WALSH ET AL., 2014). In the Pyrenees, two distinct phases of mountain population growth have been detected by archaeological and palaeo-environmental records: firstly, the beginning of the Bronze Age at ca. 2000 BC and the secondly, at the end, at ca. 1000 BC (GALOP ET AL., 2007; CAROZZA, GALOP, 2008). The development of agro-sylvo-pastoral and agro-pastoral systems led to the transformation of mountain territories using fire (RIUS ET AL., 2009). In our study area, only the second phase is registered in soil archives, which suggests a late anthropisation process at the local scale (SAULNIER ET AL., submitted). Beech can take advantage of the opening of fir forests carried out as part of slash-and-burn agriculture and/or grazing areas (KELLER ET AL., 2002; WICK, MÖHL, 2006; KOZÁKOVÁ, 2011). Although we cannot totally exclude that the 800-750 BC climate shift played a part in beech expansion, we think that this is questionable at the local level (SAULNIER ET AL., submitted for publication).

Fir starts to leaf-out earlier and so is more sensitive to late frost in spring because it is not able to remake leaves unlike beech and it is mainly less resistant than beech to grazing pressure because it relies on advance regeneration under the shade of its competitors for up to 200 years. This increases its vulnerability to wild ungulates and cattle browsing and to fire. Beech can also be more competitive because it is capable of regrowing from stumps and is more browse resistant. Thus beech has been mainly favoured by anthropogenic activity, leading to a shift from a fir-dominated forest to a beech-dominated one.

The second fire event registered in Berna 1 occurred between the 2nd c. AD and the Late Antiquity (137-347 cal AD) during a climate phase probably cold and humid (TINNER ET AL., 2003). This fire coincides with an erosive event (layer 7) and an increase in angiosperm taxa (other than beech) that could support the hypothesis of large forest clearings in northern and north-western slopes. The yew, which is the more stress-tolerant woody species (at least shade- and xeric-tolerant), was able to maintain itself. At the French Pyrenees scale, after an abandonment phase of upland areas during the Iron Age, which is also likely to be reflected at the local scale, the Gallo-Roman period is characterised by local

deforestation. Further agro-pastoral reconquest with new forest-clearings using fire leading a decline of mountain forest occurred during the Late Antiquity and Early medieval period (GALOP ET AL., 2013; GALOP, 2016). Consequently, it is highly likely that this local-scale fire event has been human in origin. No local archaeological data is currently available to reinforce this hypothesis but this phase coincides with the development of mining and iron metallurgy in the neighbouring Lercoul forest.

Other fire events registered in Berna 3 dated from the 7th and the first half of the 8th c. AD correspond probably to a warm-dry period (at ca. 700 AD) (TINNER ET AL., 2003). The return of fir in Berna 1 (layer 6) and its significant representation in Berna 3 suggest a low human-induced pressure between the Late Antiquity and the 7th c. AD. Although the natural origin of these fires affecting apparently the three '*dryade*' species cannot be dismissed, the hypothesis of its human origin is again more likely. This cultural phase corresponds to a second major phase of anthropisation in the Pyrenean massif which is characterised by large forest-clearings between 700 and 1300 m asl and also increase of pastoralism evidences (GALOP ET AL., 2013; RENDU ET AL., 2013). At the local level, during this period yew disappeared. This species had survived for centuries resisting several climate phases (cold and dry/warm and dry) and frequent human pressure, so we conclude that it was intentionally eliminated during the early medieval period. Apart from its aril, all parts of the plant are highly toxic for human and cattle (GUIDO ET AL., 2013; UZQUIANO ET AL., 2015). Between 1991 and 2006, it was a primary cause of plant poisoning of cattle in France (ISLER ET AL., 2007). This could be the reason for its drastic reduction at least partly by fire as shown by the anthracological composition of Berna 3 (Fig. 2 and see SAULNIER ET AL., submitted).

A new fire event that occurred in 1150-1256 cal AD is registered in Berna 2 (layer 2). This phase corresponds to the intensification of the agro-sylvo-pastoral system, at the origin of modern Pyrenean landscapes. Soil charcoal evidence again suggests that forest-clearance operations to create pasture at the upper dense beech-dominated forest limit and/or to maintain silvicultural thinning through fire (the herbaceous plants being favoured) as the most likely cause (MÉTAILLIÉ, 1978; 2006). This period was just prior to the early charcoal kilns located at both north-western and south-eastern parts of the forest (Fig. 3). Charcoal manufacturing had been developing within the beech (-fir) forest of Bernadouze when the *mouline* became established on the waterways of the Vicdessos valley. Before that, this activity was mainly achieved in the vicinity of iron mines (as in the Lercoul forest). In Bernadouze, it intensified almost certainly between the 15th and the beginning of the 18th century. The on-going radiocarbon dating of ten other sites will clarify this aspect. The ultimate fire event recorded in Berna 1 (layer 4) occurred during this period (1470-1640 cal. AD). It is difficult to define precisely its origin. It is followed by a main erosive event (layer 3) leading to a strong increase in slope deposits and charcoal accumulation. This event could be related to the superimposition of wood collecting for charcoal production, which still involved beech but also now fir, to sylvo-pastoral practices (e.g. undergrowth cleaned-out by fire for grazing). This assumes that the virtual elimination of fir took place at this time. This last point raises the question how charcoal makers managed the forest to ensure charcoal production.

Woodland Management and Seasonal Practices for Charcoal Manufacturing from the 14th c. to the Contemporary Period

The first radiocarbon dating results (time ranges with 95% probability and peaks) (Fig. 3) show that charcoal manufacturing proceeded in the Bernadouze forest over more than four centuries: between the first half of the 14th and the beginning of the 18th c., and in the 19th-first half of the 20th c. This last

phase is confirmed in the local memory, the gap perhaps being the consequence of the prohibition enacted in 1740. The right to use wood for charcoal manufacturing and the practices of wood collecting were regulated in the Vicdessos valley from the turn of the 14th c. (VERNA, 1997, 2001, 2017). An act of the Count from 1303 prescribed that people from the community first had to use dead or dried-out trees for charcoal making and then they could cut green ones (i.e. living trees) designated by forest guards. A tree had to be entirely used - trunk and branches - before felling another one but the species mainly used were not specified (VERNA, 2001, 121). However, we don't know if this forest legislation, which has been strongly rejected by consuls of the Vicdessos community, was actually applied.

The forest policy of the Count was completed with an agreement concluded in 1348 between the Vicdessos and the neighbouring county of Couserans, that operated until the 18th c. It involved the exchange of iron from Vicdessos for wood and charcoal from Couserans in order to reduce the pressure on forests of the former and to develop the iron economy for the latter (VERNA, 2001, 125-127). The terms and conditions of this treaty throughout this time are not clear because the original text, which is almost illegible, has been falsified. Moreover, it is not possible to know when and how it was really applied. Archaeological investigations show that it didn't suppress charcoal manufacturing in the upper valleys of the Vicdessos. In fact our research reveals that it increased in the Bernadouze forest from this time. Moreover, researches carried out in the Couserans nearby the Port de Saleix - the main road taken for the exchange - have demonstrated that charcoal-manufacturing increased significantly locally from the 17th c. up to the 19th c. (PY-SARAGAGLIA ET AL., 2017). Thus it is possible that this part of the Couserans was turned to for supplying charcoal to Vicdessos from the first half of the 18th c. when charcoal-making had been prohibited there (Vicdessos). In the study area, the shutdown of charcoal production allowed the return of sylvo-pastoral practices.

The anthracological spectra of charcoal kilns dating from the late medieval period (Ck 27 and 11) show a very marginal use of fir, which occupied a restricted place in the forest cover. This species being the main one used for timber production in the 14th c. (VERNA, 1994; 2001) may have been excluded from wood collecting for charcoal making. For example texts show that its use was prohibited for this activity in the Northern Catalan Pyrenees (IZARD, 1994; 1999). In the Vicdessos, it is only from the mid-17th c. that we have formal textual proof of the existence of fir forest reserves restricted for lumber (documents of the Reformation of 1669). But these stands were located nearby places of consumption, in the downstream part of the basin (DAVASSE, 2000). In the upper section, as within the Bernadouze forest, the fir was used in the same way as beech for charcoal-manufacturing from the 15th until the 17th c. (Ck 79, 6, 19, 1). Its dominant use in some of them (CK 6) while it was less available than beech in the forest cover could indicate its deliberately elimination by charcoal makers and/or woodcutters. Furthermore, this could also suggest that it had been able to regenerate in certain areas during the previous phase when beech wood was entirely removed for charcoal production. Thus, it could be between the 15th and 16th c., that forest management practices changed in the Bernadouze forest.

The first results of dendroanthracological analyses confirm and clarify this process (Fig. 5). Firstly, the log size through different charcoal-making periods shows a significant decrease of beech wood diameters used over time (Fig. 5, A). The oldest charcoal kilns (CK 27, 11, 6 and 79) show a dominance of a wood-mix with "small" diameters (i.e. between 2 cm and 5 cm) and "larger" diameters (i. e. 10 cm to more than 18 cm). In contrast, the latest ones (CK 1, 19 and 4) show a significant decrease of "larger" diameters in favour of smaller ones. This suggests an evolution of silvicultural practices, first with logging of stands close to coppice-with-standards - giving a wide range of diameters - and then their gradual conversion into short rotation coppices. This management mode was indeed more productive and profitable to iron-masters but it ended by leading to stump exhaustion. Fir charcoals present a

different pattern (Fig. 5, B). The oldest charcoal kiln (CK 6) shows a dominance of wood with diameters ranging from 1 cm to 18 cm with a very marginal use of “very large” wood (i. e. more than 18 cm). The later charcoal kilns (CK 1 and 19) clearly show an increase in use of “very large” wood diameters. In the first case, charcoal could be being made from branches and crowns only, while the bole was used for lumber. After the Renaissance, the change in logging practices probably led to the use of the entire tree hence the increase of larger diameters. This conversion of the Bernadouze forest into an “industrial forest” probably contributed to the elimination of other practices such as forest grazing and lumber production between the 16th and the 17th c. Finally, from the end of the 19th c., the steel industry stopped, and the majority of beech coppices have been progressively converted into a quasi-even-aged beech high forest.

The quantitative results of the charcoal analysis also suggest a change in charcoal-making practices around the 16th c. (Fig. 5, C). The decrease of charcoal fragments with fungal hyphae and increase of those with radial cracks over time could be interpreted as a reduction of drying period of wood used for charcoal production. The low frequencies of charcoal with high occurrence of hyphae (12.7%) associated with cellular collapses (2.4%) could suggest a marginal use of deadwood or dried-out trees. For this reason, the 1303 text must be revisited because using deadwood for charcoal making has not been confirmed by our preliminary results. Moreover would this practice be reasonable? Deadwood is highly degraded and produces low quality charcoal regarded for a long-time as not suitable for metallurgy ([BIRINGUCCIO, 1572](#), chapter 10; [FAO, 1983](#)). Secondly the stock of dead standing wood and deadwood on the ground was probably very low in forests, because of rights for firewood given to the local community and the effects of regular fires.

The proportions of charcoal fragments with hyphae contamination coupled with the fact that 60% of charcoals with the bark preserved (n=453) have the growth stop area at the last ring located in the late wood, allow reconstruction of the annual calendar of historical charcoal making activity (Fig. 6). As in the Couserans ([PY-SARAGAGLIA ET AL., 2017](#)), woodcutting was mainly done during the autumn and the off-season perhaps during winter just before the return of growing season. The cut wood was stored in the forest at least 6 months to one year for its seasoning allowing the contamination by fungi during the warm season. It was probably carbonised at the beginning of the following autumn. This implies that charcoal manufacturing was mainly practiced during the quiet season of agropastoral activities and could be carried out by poorest farmers ([VERNA, 2017](#), 126). These hypotheses will require testing with experimental data, which will also examine the change of the wood drying period over time.

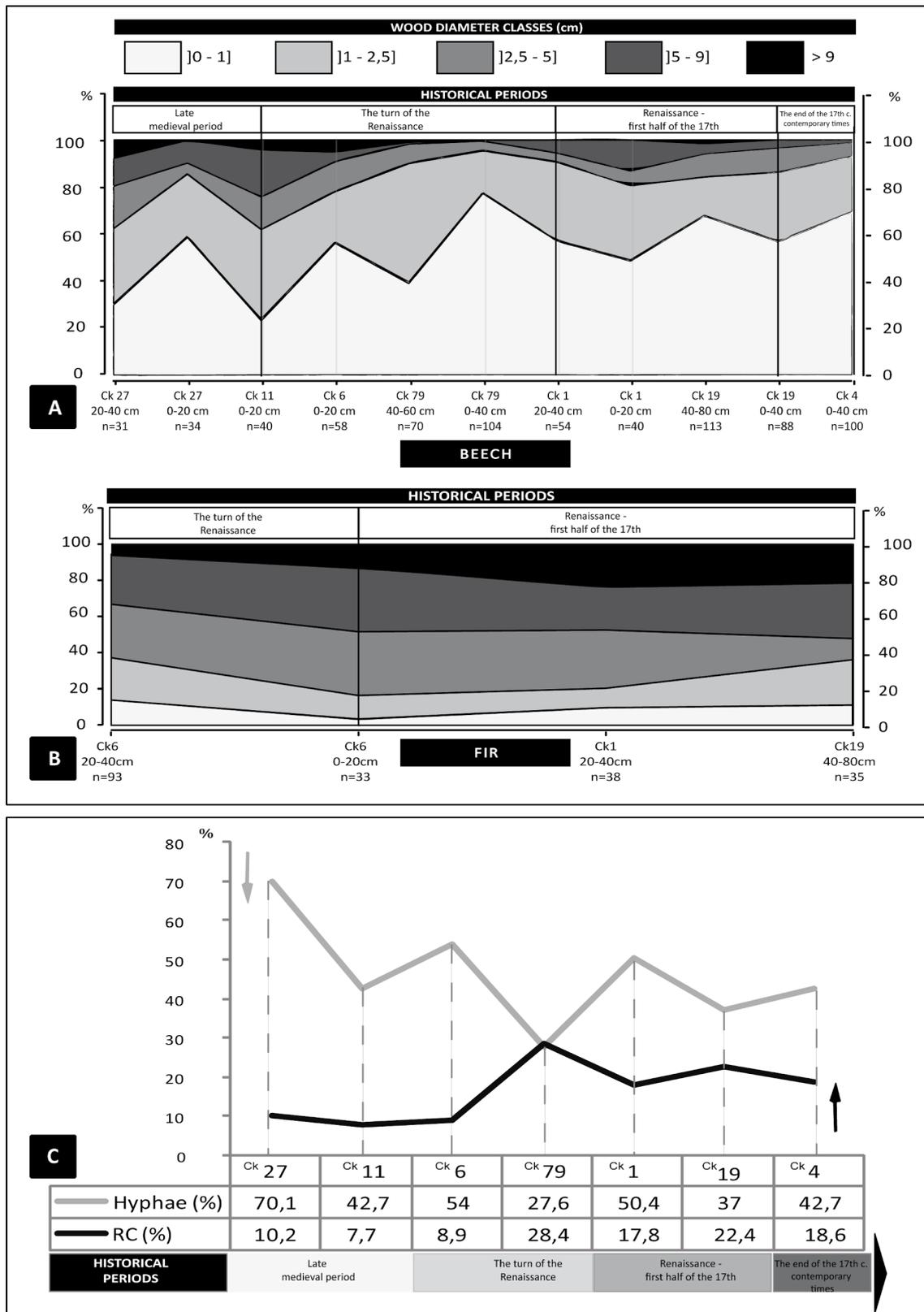


Figure 5. A. Evolution of beech wood diameters and B. fir wood diameters used in charcoal kilns over the time, and based on dendroanthracological analyses. C. Evolution of proportions (%) of charcoals with charred fungal hyphae and radial cracks over the time, © L. Fouédjeu Fomou, 2018.

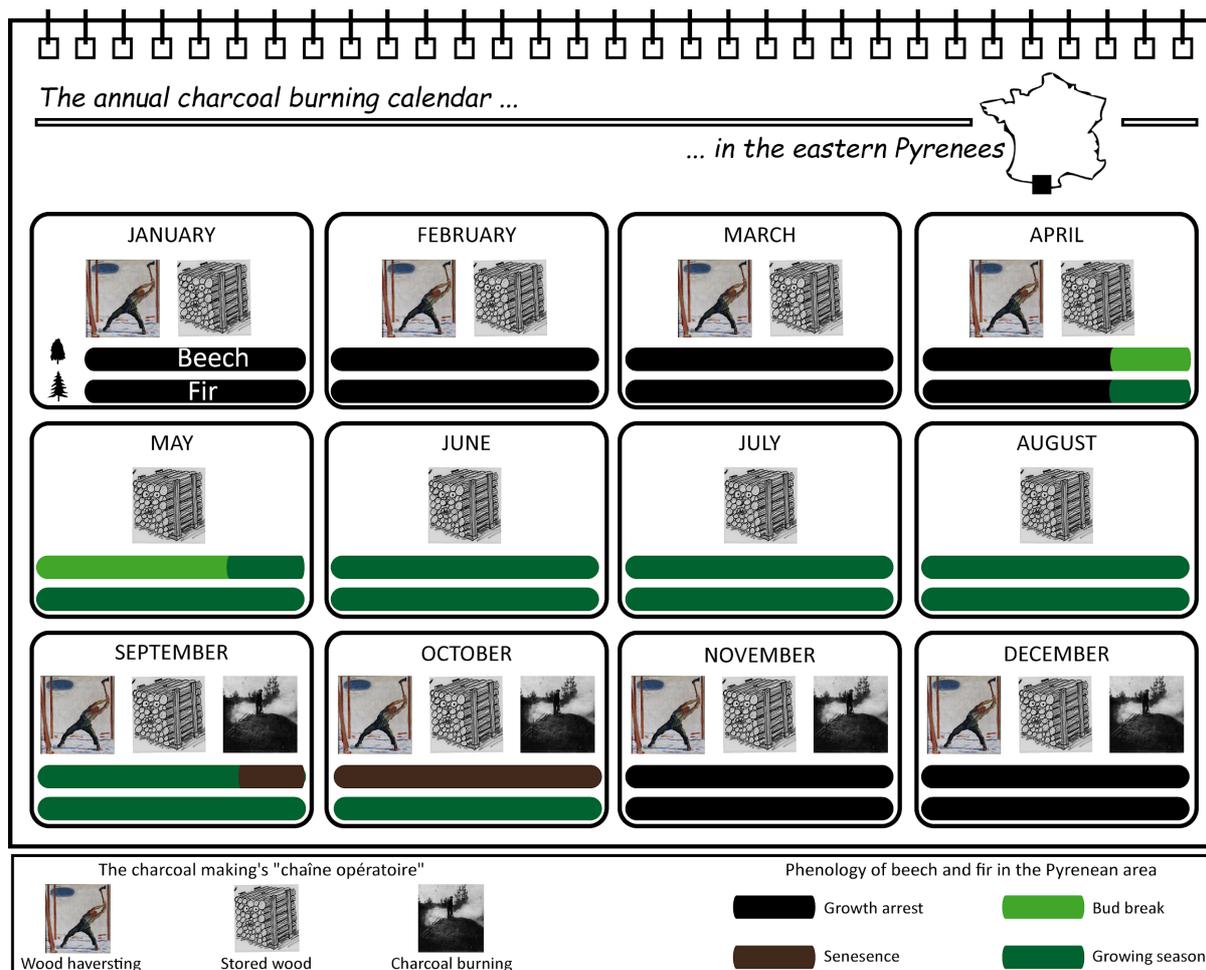


Figure 6. First reconstruction of the past annual charcoal burning calendar based on anthracological data and the phenology of beech and fir in the northern slope of the Pyrenees, © L. Fouédjeu Fomou, 2018.

Conclusion

The first results of this interdisciplinary study carried out at this micro-local level demonstrate its efficiency. Previous historical and palaeoecological documentation has allowed us to check the robustness of our methodology and validity of these results. We have been able to identify and clarify the long-term Bernadouze forest evolution from the Bronze Age to the contemporary era and to better characterise the state of the forest cover when charcoal manufacturing was introduced in the 14th c. AD. The ancientness of the Bernadouze forest has been clearly highlighted. The main opening of the canopy dominated by fir for development of grazing areas goes back to ca. 1300-900 BC. It allowed to the establishment of a beech-dominated forest where sylvo-pastoral practices (pastured woodlands) were being intensified between the Late Antiquity and the Carolingian era without eliminating the forest cover. There was eradication of yew, an extremely poisonous plant for livestock and yet appreciated for its wood mechanical properties. Its importance within past Northern Pyrenean mountain forest ecosystems was also highlighted and has resulted in a new research project on-going focusing on the Holocene history of this "relic" tree-species in the Pyrenean North slope.

This present study contributed to a synthesis in progress by Cunill et al., relating to the glorious past of fir in Pyrenean mountain forest ecosystems before the development of agro-sylvo-pastoral systems. Our results showed that it was the dominant tree-species before the first human incursions during mainly the Late Bronze Age. During historical periods, it was maintained within the Bernadouze forest cover in refuge position where site conditions were limiting for beech such as northern steep slopes beyond 1600 m asl and waterlogged soils. Logging in beechwood for charcoal burning in the 14th c. may have led to its return within smaller forest aisles. The virtual elimination of fir occurred during the 15th and 16th c. in order to put in place an “industrial forest” entirely devoted to supply iron metallurgy. The links between the forest transformation and the change in human activities has been identified thanks to the combination of dendro-anthracological and dendrochronological analyses. Thus, our preliminary results highlight the potential of our approach for estimating the degree of maturity of forests.

The scenarios proposed will be clarified in the future through the development of new experimental procedures looking at indicators of practices in charcoal cells (fungal hyphae, radial cracks, nitrification) and new reference chronologies for beech locally. The combination of all these data will surely open up a new light on eco-historical data that remain very fragile for the crucial phase of steel industry development in the Vicdessos during the Late medieval period. Finally, this study highlights that the Bernadouze forest, which is currently perceived as an exceptional natural place by walkers, has a very long and rich history closely related to evolution of human activities.

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