Did the charcoal-based iron industry really drive the forest cover decline in the Northern Pyrenees?

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Abstract

Through a reconstruction of the chronology and intensity of charcoal-making activities, this paper re-opens the debate about the supposed impact of the charcoal iron industry on forest cover in the French Pyrenees. This reappraisal focuses on the former territory of the communities of Haut-Vicdessos valley. This more refined chronology, based on the analyses of historical documents (n=617) and charcoal kiln remains (n=42), has highlighted the non-linear industrial development. The emergence of water-powered bloomeries during the early 14th c. led to a brief expansion of the iron industry, but was followed by a slowdown in the 15th c. The combined effect of regulation and the outsourcing of a part of the charcoal supply on other territories, mitigated the impact of the iron industry on local forest, avoiding a forest crisis. The most significant industrial growth occurred from the mid-17th c. with development of the Catalan bloomery. Forests underwent major changes in structure and composition but cover was maintained to satisfy the local economy and people's needs. Charcoal production always occurred in well-stocked forests dominated by beech and fir. The increase of charcoal supply combined to the agro-pastoral growth led to the prohibition of charcoal-making in the mid-18th c. and to the exclusive recourse to an external fuel supply. Minimum forest cover was only reached in the mid-19th c. due to the demographic explosion resulting in the increase of daily needs and in the refocus on agro-pastoral economy. Conversely to the common premise, the iron charcoal industry in European mountains did not necessarily induce forest depletion but rather its maintenance through sustainable management and policies.

Key words: charcoal iron industry, fuel supply, historical archives, charcoal kiln analysis, forest cover decline, Northern Pyrenees

Introduction

Starting in the mid-17th c., at a time when Navy officials, elites, urban and rural communities feared the exhaustion of forests and their wood supply, the impact of pre-industrial activities and common uses on forest cover was debated all around Europe (Warde, 2006; 2015). At this time, the growing charcoal iron industry was accused of sharply reducing forest cover (Devèze, 1964). Historical studies mostly deemed charcoal-based iron smelting as the most important driver of deforestation, leading to the mid-19th c. minimum forest cover in Western Europe (Mather, 1992), in addition to agro-pastoral uses and clearing (Ashton, 1924; Sclafert, 1926; Chevalier, 1956, pp. 529–538; Houzard, 1983). Based on experimental fuel estimates, archaeologists have supported this assertion (Pleiner, 2000, pp. 126–129). However, some researchers have mitigated the impact of charcoal iron smelting considering forest management and social practices (Birrell, 1969; Hammersley, 1973; Lindsay, 1975; Belhoste, 1990; Voss, 1995).

Studies of metallurgy-related remains combining archaeology and charcoal analysis have renewed our knowledge and deepened our understanding of forest-industry interactions in pre-industrial times (Backer et al., 1992; Bielenin, 1992; 1992; Bonhôte, 1998; Davasse, 2000; Montanari et al., 2002; Gale, 2003). In the 2000s, charcoal kiln remains (hereafter platforms) became privileged tools for assessing how charcoal metallurgy modified forest ecosystems, thanks to the improvement of charcoal analysis and remote-sensing methods (Ludemann and Nelle, 2002; Paradis-Grenouillet et al., 2015; Hazell et al., 2017; Rassat et al., 2018; Gana and Malik, 2019; Deforce et al., 2020). Nevertheless, an improved characterisation of the impact of iron charcoal metallurgy on woodlands also requires an accurate assessment of the running time and productivity of ironworks, as well as an understanding of how users ensured their fuel supply and its sustainability (Woronoff, 1990; Baraldi, 1993; Horikoshi, 2008; Arribet-Deroin, 2013; 2018; Oury, 2020).

From the 1990s, the French Pyrenees is a pioneering multidisciplinary laboratory for the study of human-environment interactions, bringing together historians, geographers, archaeologists and palaeoecologists. Previous researches provided the first syntheses correlating the history of the charcoal iron industry to the evolution of woodland cover in the late Holocene in several Pyrenean valleys (Métailié and Jalut, 1991; Galop and Jalut, 1994; Bonhôte, 1998; Davasse, 2000; Bonhôte et al., 2002). The Haut-Vicdessos valley has received particular attention because of its long-lasting iron industry associated with the Sem mines (Verna, 2001; Cantelaube, 2005). Variations in the intensity of this activity through time, however, remained largely unknown (Py-Saragaglia et al., 2019). Despite the scarcity of written and archaeological data, the common working hypothesis was the continuity, or even the increase, of iron production between Gallo-Roman times and the 14th c. AD (Dubois, 2000). Moreover, historical research has focused on the development of iron metallurgy made possible by the technical innovation of the water-powered direct bloomery, called *moulines*, at the turn of the 14th c. (Verna, 2001), while archaeological surveys carried out in some parts of the valley demonstrated that platforms became significantly abundant only from the 16th c. onwards (Bonhôte et al., 2000; Davasse, 2000; Dubois and Métailié, 2001). The strong fluctuations in the iron economy during the early modern era (Woronoff, 1984; Bonhôte, 1998; Davasse, 2006) suggested a highly variable pressure on local forest resources.

At variance with the common assumption that it induced forest depletion due to intense harvesting (Galop and Jalut, 1994; Verna, 2001; Bonhôte et al., 2002; Galop et al., 2013), Davasse (2000) suggested that charcoal iron metallurgy was based on specific woodland management practices. Little is known, however, about the evolution of former silvicultural practices and how they drove forest ecosystem change. Moreover, silvopastoralism, wood-based crafts and domestic uses were likely considered in forest management strategies (Davasse, 2000). Consequently, a revision of the iron industry-induced forest depletion assumption is crucial to improved understanding of how this activity actually interacted with the formation of the mid-19th c. open dominated landscapes.

This paper proposes to reconsider the history of the iron-charcoal industry fuel supply and its impact on forest cover in the Haut-Vicdessos. The global and integrated study is based on (i) a review and original analysis of historical archives, (ii) previous historical ecology studies conducted in the Soulcem and Artigue valleys, and (iii) original data from archaeological and charcoal analysis produced in the Suc-et-Sentenac valley (hereafter Suc). On the basis of this data, we address the following research questions: (i) what were the variations of the iron industry over time? (ii) To what extent did the fuel demand involve specific forest management strategies? (iii) To what extent did fuel consumption drive environmental changes leading to a reduction in forest cover?

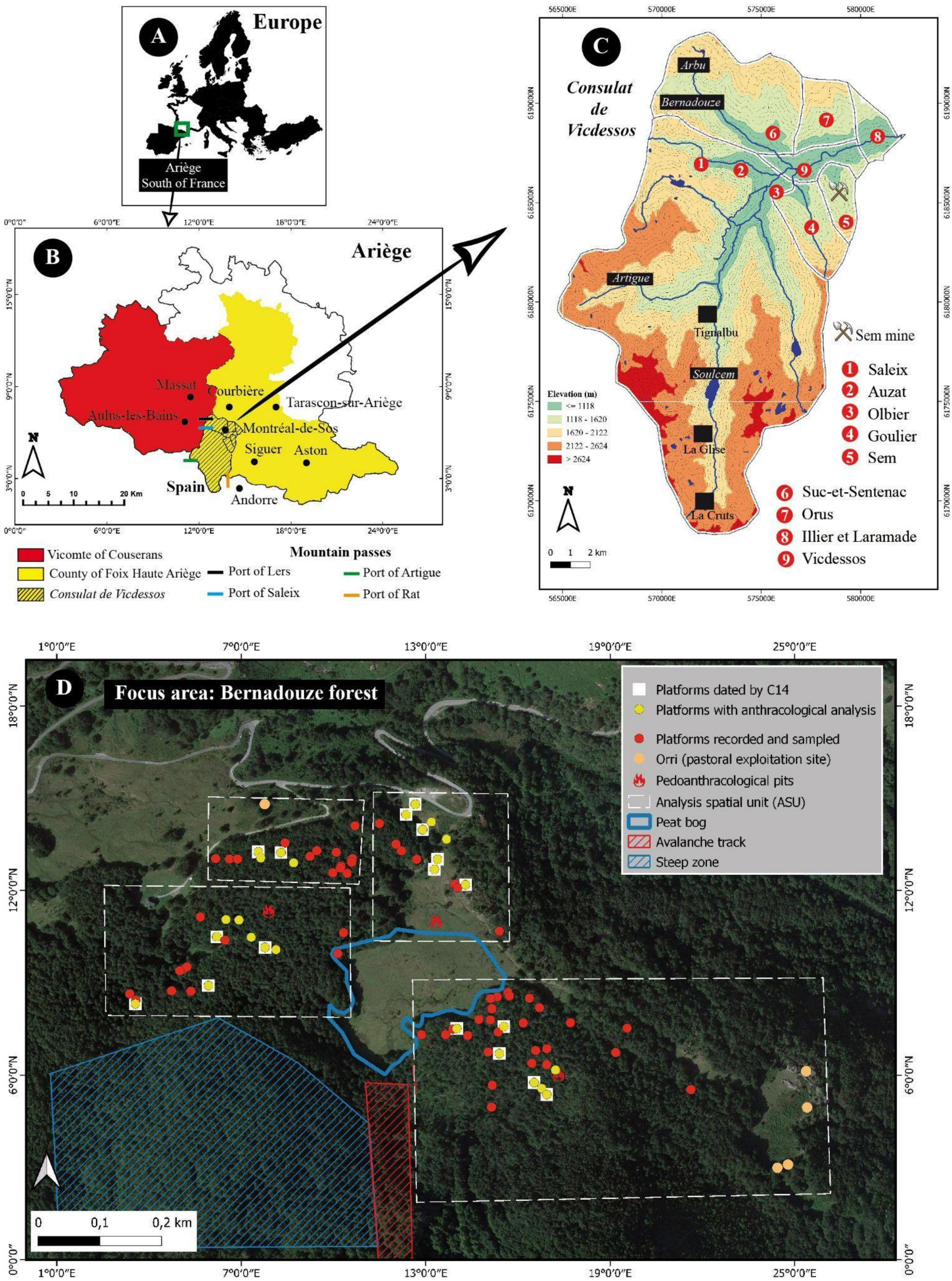

Fig.1: (A) European and national location; (B) *consulat de Vicdessos* location in Ariège administrative district; (C) Mapping of the *consulat de Vicdessos* and locations of study areas (Bernadouze forest -focus area-, Arbu, Artigue, Soulcem -Tignalbu, La Glise, La Cruts-), (D) Focus area with (i) platforms recorded and sampled (red

points), (ii) platforms dated by C14 (white squares), (iii) 28 platforms with charcoal analysis (yellow points), (iv) sampling points for pedoanthracological analysis (small fires) published in Saulnier et al. (2020), (v) pastoral sites (orange points). The focus area is divided into four Analysis Spatial Units (ASU) surrounded by white dotted lines.

1. Material and methods

1.1. Study area

The study area is a north-south oriented valley (a. 23,000 ha) located in the central French Pyrenees (Ariège) and connected with Spain and Andorra by several mountain passes that facilitated trade (Fig. 1 A, 1B). The Haut-Vicdessos was part of the early medieval Sabarthès which was progressively incorporated to the County of Foix between the 10th-12th c. (Pailhès, 2006; Guillot, 2009). Starting in the late 13th c., the local communities were grouped into the *consulat de Vicdessos*, an administrative district covering the Haut-Vicdessos valley (Fig. 1C). The ownership of ore, forest and water resources belonged to the earl of Foix before passing to the French crown in 1607. In 1786, the former *consulat de Vicdessos* and the neighboring *consulat de Siguer* merged into the *canton de Vicdessos*.

Since 2010, this area has comprised the Human-Environment Observatory of Haut-Vicdessos devoted to the interdisciplinary study of mountain mountain socio-ecosystems. The Bernadouze forest in Suc, which is an Instrumented Site in Global Ecology, provides a focus area where several in-depth studies have already been implemented (Py-Saragaglia et al., 2019; Saulnier et al., 2020; Fouédjeu et al., 2021b; 2021a). Current vegetation around Bernadouze peat bog is almost exclusively composed of beech (*Fagus sylvatica* L.). Beech woods exist in three different forms: (i) high forest (between 130 and 160 years old) resulting from the conversion of former coppices with scattered young silver fir trees (*Abies alba* Mill.), (ii) on the edge of the bog, tall-grown coppices browsed in the past by livestock and (iii) in some places, tall-grown coppices of old trees resulting from historical silvicultural treatments. This forest composition and structure is representative of former mountain charcoal manufacturing forests in the Ariège Pyrenees (Davasse, 2000).

1.2. Historical approach

We performed a review of previous historical studies focusing on (i) iron metallurgy from medieval to contemporary times (Rouzaud, 1908; Cantelaube, 1992; 2005; 2009; Verna, 1994; 1996; 2001; 2003; Verna and Cantelaube, 2000; Cabau de Fauroune, 2021), (ii) Pyrenean economy and society (Barbe, 1900; Dufau de

Maluquer, 1910; Dengerma, 1934; Chevalier, 1956; Pailhès, 1992; 2006; Ruffié, 1997; 2003; Poujade, 2008; Guillot, 2009), (iii) historical ecology of forest ecosystems (Taillefer, 1939; Bonhôte and Fruhauf, 1990; Bonhôte et al., 2000; Dubois and Métailié, 2001). This literature review was supplemented by an original analysis of unpublished medieval and post-medieval documents (Supplementary file 1).

The synthesis comprises a total of 617 documents unequally distributed: 4 for the 13th c., 18 for the 14th c., 2 for the 15th c., 81 for the 16th c., 331 for the 17th c. and 181 for the 18th c.. Medieval and early modern written records are poorly preserved. Besides a few original Latin diplomas, a large part of the medieval documentation is composed of modern copies and/or French translations and brief summaries of the vanished acts. The 16th c. presents a few more documents thanks to several notarial deeds (purchases, debts, exploitation contracts, etc.) and the accounting registers of the County of Foix (from 1580s). These two types of sources constitute most of the 17th c. material, in addition to the 1669 Forest Reformation archives. Data remains very qualitative until the second part of the 17th c. For the 18th c., we focused our original study on Vicdessos Council deliberations. We only used published data regarding the 19th c.

1.3. Archaeological investigations

While we only used published data concerning mining and iron ore smelting-related archaeological sites (Bonhôte and Cantelaube, 1986; Dubois and Métailié, 2001; Disser and Dubois, 2017; 2018; 2019; Dubois and Disser, 2020); we performed an original systematic archaeological survey on 46-ha, i.e. in the Bernadouze peat bog buffer zone (Fouédjeu et al., 2021b) according to the methodology described in Py-Saragaglia et al. (2017, 2018) (Fig. 1D). Platforms were sampled using a soil auger, preferably on the central part, with stepwise sampling at every 20 cm of depth until the continuous mineral layer is reached. The focus area was divided into four “Analysis Spatial Units” (ASU) (Fig. 1D) according to their exposure and topography. In each ASU, we randomly selected 4 to 9 platforms (n=28), i.e. about 35% of the total number of inventoried platforms, for charcoal analysis.

- ASU 1 includes tall-growing coppices, high forest and open grazing area, and is located on a gentle, north facing slope. We selected platforms 1, 4, 6, 7, 8, 9, 10 and 62.
- ASU 2 is located on the northwest part of the peat bog, within the high beech forest. The selected platforms (27, 34, 35 and 36) are located on a ridge line of a small relief overhanging the ASU.
- ASU 3 is located south of the peat bog, on a gentle north-facing slope within the high beech forest, overhung by a cliff and a very steep slope. We selected the platforms 11, 14, 17, 18, 19, 63, 64 and 65.

- ASU 4 corresponds to a relatively steep slope, facing northeast, in the western part of the focus area's watershed. We selected platforms 29, 31, 44, 47, 48, 49, 73, 74 and 79 located under the high beech forest.

These original data have been completed by a synthesis of previous studies performed in Arbu (Py-Saragaglia et al., 2019) and in the Artigue and Soulcem valleys (Davasse, 2000, pp. 155–157).

1.4. Laboratory analyses

In the focus area, charcoal taxonomic determination was carried out using a reflected light microscope (Leica DM4) with magnifications of 100 - 1000 according to the three anatomical planes of wood (transverse, tangential and radial), xylological atlases (Schweingruber, 1990; Vernet et al., 2001) and the reference collection of the GEODE laboratory. Charcoals were identified at the level species, genus, family or sub-family. Moreover, we performed a multiproxy approach on charcoal, integrating the study of hyphae infestation of cells and radial cracks, allowing to assess the state of wood before carbonization and finally, wood diameter reconstruction, allowing to characterize the size of the wood used by the charcoal burners (Fouédjeu et al., 2021b). When charcoal has retained bark cells, we reconstruct the logging season based on the state of progress of the last ring's formation. Concerning Artigue and Soulcem, we used charcoal data published in Métailié and Jalut (1991) and Davasse (2000).

We randomly selected 17 platforms distributed in all ASUs and one sampling layer per platform, usually the deepest one, has been radiocarbon dated (Fig. 1D; Table 1). Due to the considerable depth of platform 17, we dated both the deepest and the uppermost layer. To avoid the "old tree effect" i.e. reducing the "inbuilt age" (Stouvenot et al., 2013), we selected young twigs with bark, and/or charcoal fragments with bark and/or, if such charcoal has not been preserved, bark fragments alone. Accelerator Mass Spectrometry (AMS) C14 dates were calibrated using OxCal (Reimer et al., 2013). To get a temporal overview of charcoal production activity at the *consulat de Vicdessos* level (Fig. 1C), we integrated former radiocarbon dates from Arbu (Py-Saragaglia et al., 2019), Artigue and Soulcem (Métailié and Jalut, 1991; Davasse, 2000).

We performed statistical analyses using R software 3.5.1 (R Core Team, 2018) with "stats" and "graphics" packages. A hierarchical ascendant classification gathered the platform layers into clusters, based on the tree-species platforms composition similarity. We used the Ward's minimum variance criterion (ward.D2) to implement the hierarchical ascendant classification, in order to minimize the total within-cluster variance or, to be more precise, to minimize increase in the sum-of-squares (of errors) (Ward, 1963).

2. Results

2.1. Variation of iron industry intensity according to historical data

The first textual evidence of mining and iron ore smelting in this area only dates back to 1294[1], but the charter recorded earlier activity that is impossible to date accurately. The first decades of the 14th c. are marked by the birth and development of water-powered direct iron metallurgy, supported by the Earl of Foix[2]. However, the first mention in the *consulat de Vicdessos* dates from 1390 with two running bloomeries reported and another already inactive[3] (Figs. 3, 5, 7). C. Verna assumed that these *moulines* were created before the second half of the 14th c., and were preceded by unpowered bloomeries. Underground mining works were clearly established at Sem, as they required exploitation regulation in 1414. The 15th c. saw a decrease in the number of water-powered bloomeries, from two to one, caused by an economic crisis in the local iron trade and political instability[4] (Figs. 3, 7).

Our original study invalidates the former assumption of a considerable growth in the iron industry during the 16th c., based on (i) the economic recovery of the first half of 16th c., (ii) the French Wars of Religion-related iron demand boost, and iii) the emergence of the more productive "Genoa style" direct watered-bloomery. From the mid-15th to early 16th. c., the iron industry did not recover[5] (Fig. 3). A small revival occurred in the 1530s with one new bloomery[6] (Fig. 4). The same two *moulines* were still running in 1553[7] and 1560-61[8] (Figs. 3,4,7). During the second half of the century, while six new *moulines* were recorded in enfeoffment acts[9], some of them were likely never built[10] or were only built later[11]. Other bloomeries were short lived, and sometimes rebuilt later[12] (Figs. 3-6). The success of these entrepreneurial initiatives faced repeated plague epidemics and insecurity. War did stimulate iron demand, but it restricted industrial development at the same time. Due to the return to relative security, the bloomeries number provisionally rose to three for the 1582-1595 period[13], before decreasing to two in 1596[14] (Fig. 3,4,5, 7). Abandoned projects or the short life of some upper-valley bloomeries might also have

[1] Supplementary file 1, doc n°3.
[2] Supplementary file 1, doc. n°8.
[3] Supplementary file 1, doc n°21.
[4] Supplementary file 1, doc n°23
[5] Supplementary file 1, docs n°24-25.
[6] Supplementary file 1, docs n°38-39; 43-44; 48.
[7] Supplementary file 1, doc n°53.
[8] Supplementary file 1, doc n°56.
[9] Supplementary file 1, docs n°57-62; 67-69; 71-73.
[10] Supplementary file 1, docs n°63-66; 71-72; 70; 74-78.
[11] Supplementary file 1, docs n° 57-60; 63-66; 68; 70; 74-78.
[12] Supplementary file 1, docs n°63-70; 73; 74-78; 80; 82; 85; 91; 94; 96; 99; 102.
[13] Supplementary file 1, docs n°77-78; 79; 82; 85; 91-94.
[14] Supplementary file 1, doc n°96.

resulted from harsh natural conditions, i.e. torrential flows, accessibility issues, significant snow cover and avalanche risk[15].

A boom did occur briefly in the early 17th c., evidenced by the rebuilding of several former bloomeries and by new construction in the bottom valley, close to trade routes (Fig. 2-7). Between 1601 and 1642[16], their numbers fluctuated but finished at the same level. Between 1630 and the 1650s, two new bloomeries were built in Vicdessos[17] and Suc[18] (Figs. 4, 5). Our results also mitigate the spread of the Genoa style bloomery because only Guilhe was successful in a long-term perspective (Fig. 5).

The mid-17th c. correspond to the birth and generalization of the Catalan direct water-powered bloomery. Between the 1640s and 1660s, the number of bloomeries increased from four to six and stabilized over the second part of the century[19](Fig. 5; 7). An unlocated tilt hammer was also reported in 1669[20].

The numerous economic and health crises did not significantly impact local iron industry, where five out of six bloomeries were still running in 1720[21] (Figs. 3-5, 7). While Ournac was no longer mentioned in 1720, the Forge-Neuve bloomery was created in c. 1722[22] (Fig. 3). In the 1750s, the functioning of some bloomeries was disrupted by ore supply problems[23] or floods[24], but all of them were still running in 1772[25]. Cabre did close, however, in 1775. In addition, two tilt hammers were illegally built[26].

The first half of the 19th c. saw the rebuilding of Cabre in 1817-20 (Fig. 5) and the creation of two new bloomeries at Laramade in 1836-1837 and 1847. At the same time, Laprade closed (1846) (Fig. 3). The 1860-70s. saw the end of the iron industry, with the progressive closure of all the bloomeries of the area (Figs. 3,4).

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[15] Supplementary file 1, doc n°122.
[16] Supplementary file 1, docs n°103-109; 111-112; 116-129; 134-138; 140-144; 149-150.
[17] Supplementary file 1, doc n°150.
[18] Supplementary file 1, doc n°133.
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[20] Supplementary file 1, doc n°249.
[21] Supplementary file 1, doc n°451.
[22] Supplementary file 1, docs n°461; 465.
[23] Supplementary file 1, doc n°530.
[24] Supplementary file 1, doc n°525.
[25] Supplementary file 1, doc n°577.
[26] Supplementary file 1, docs n°539; 566.

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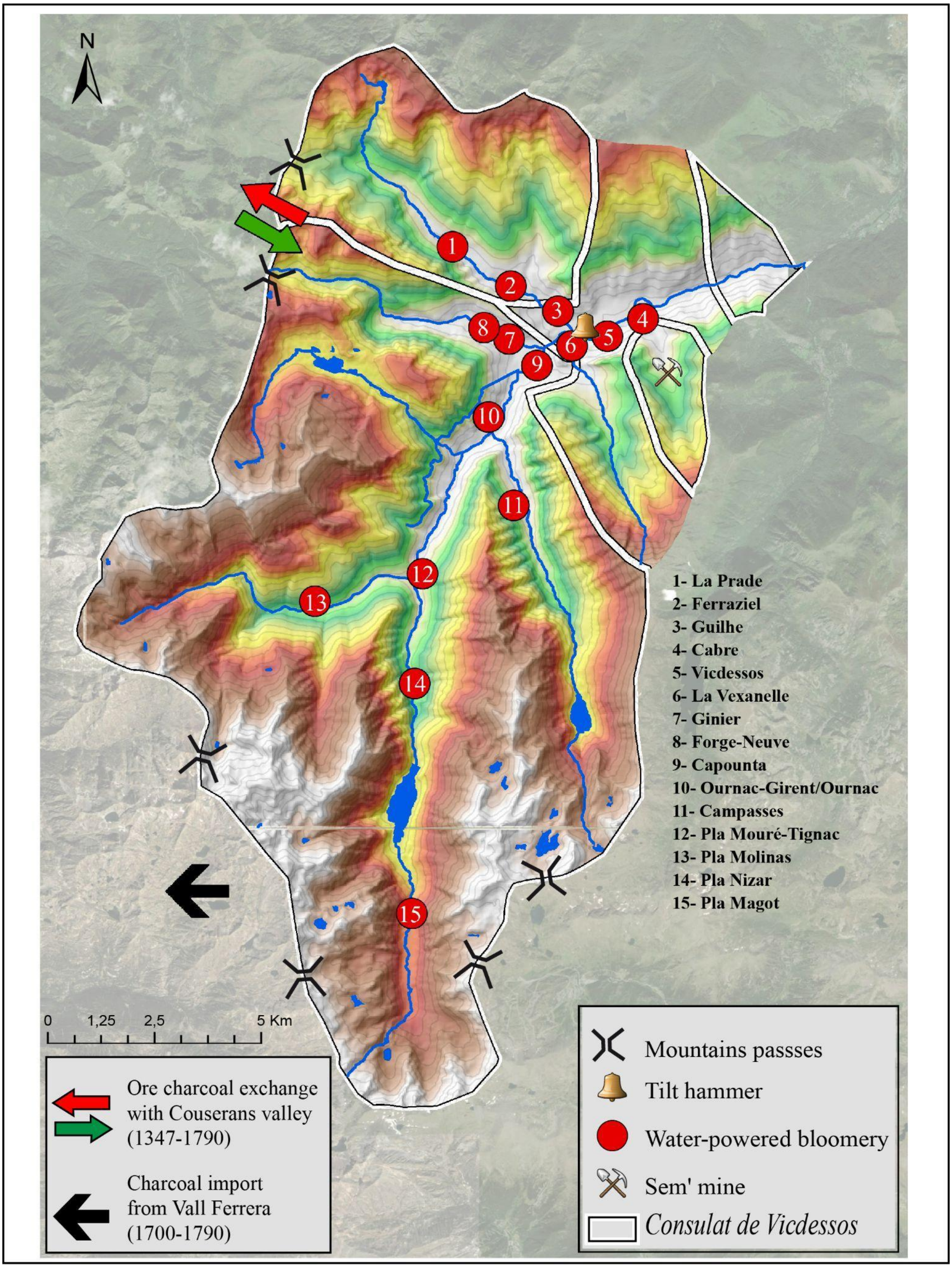


213 Fig. 2: General location of the water-powered bloomery in the *consulat de Vicdessos*.

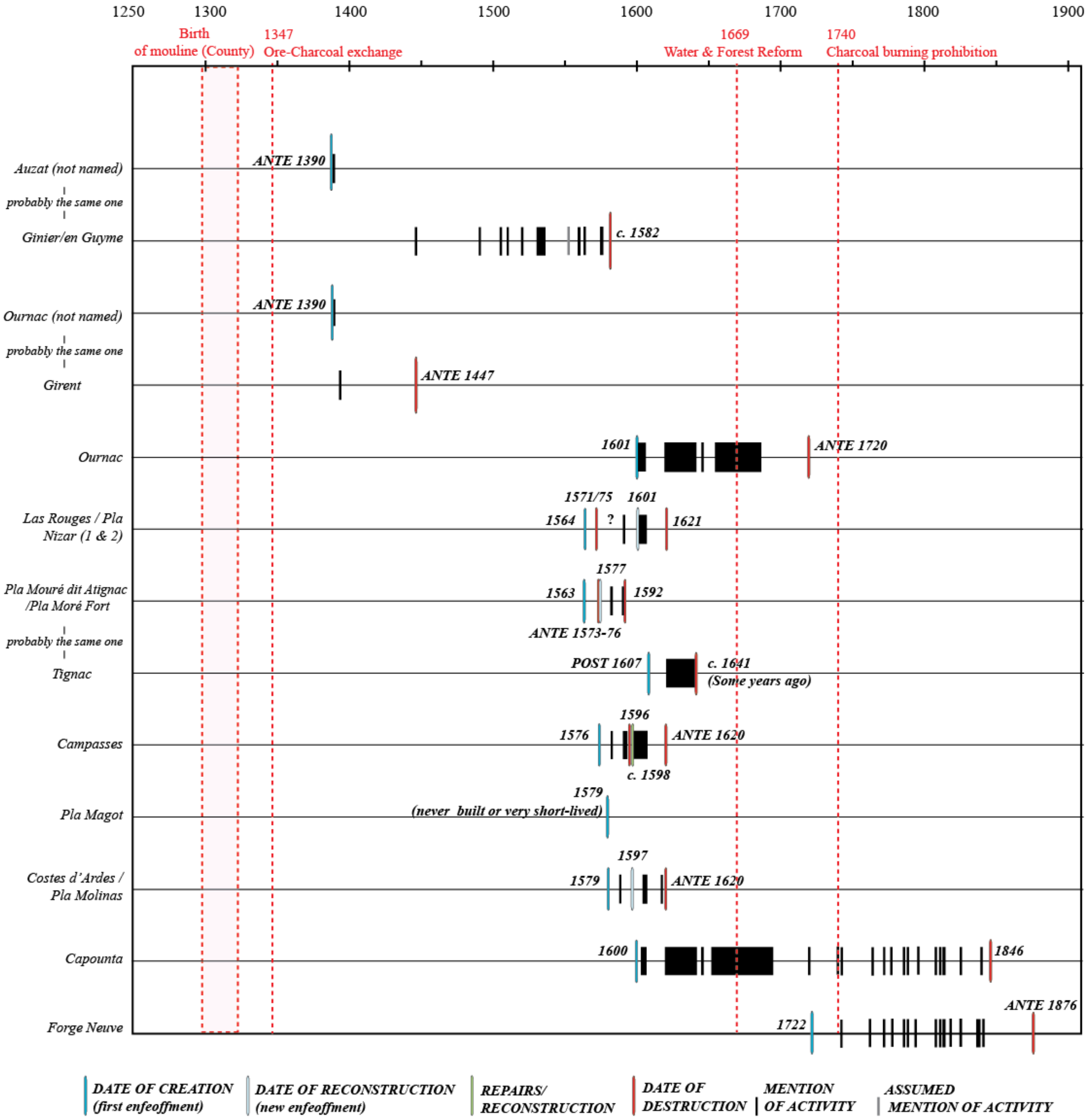


Fig. 3: Restitution of bloomery activity in Auzat territory.

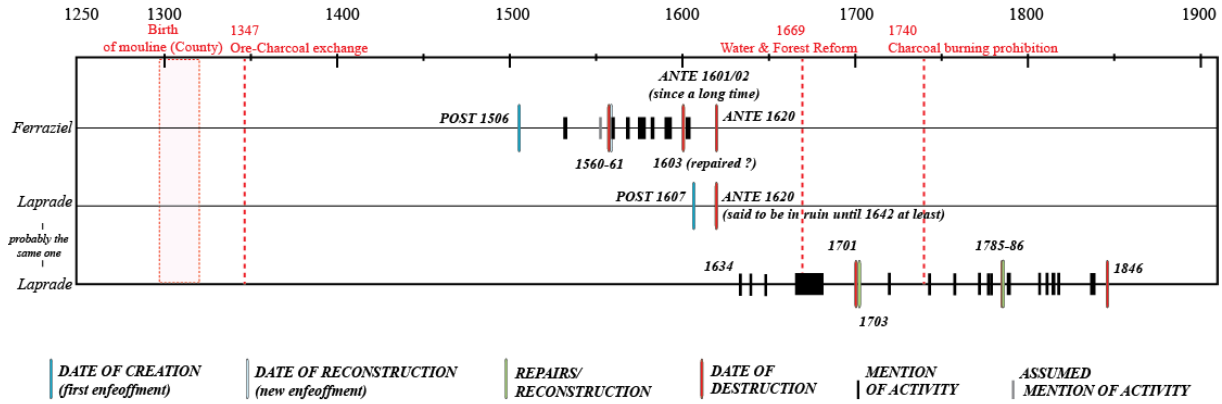


Fig. 4 : Restitution of bloomery activity in Suc territory.

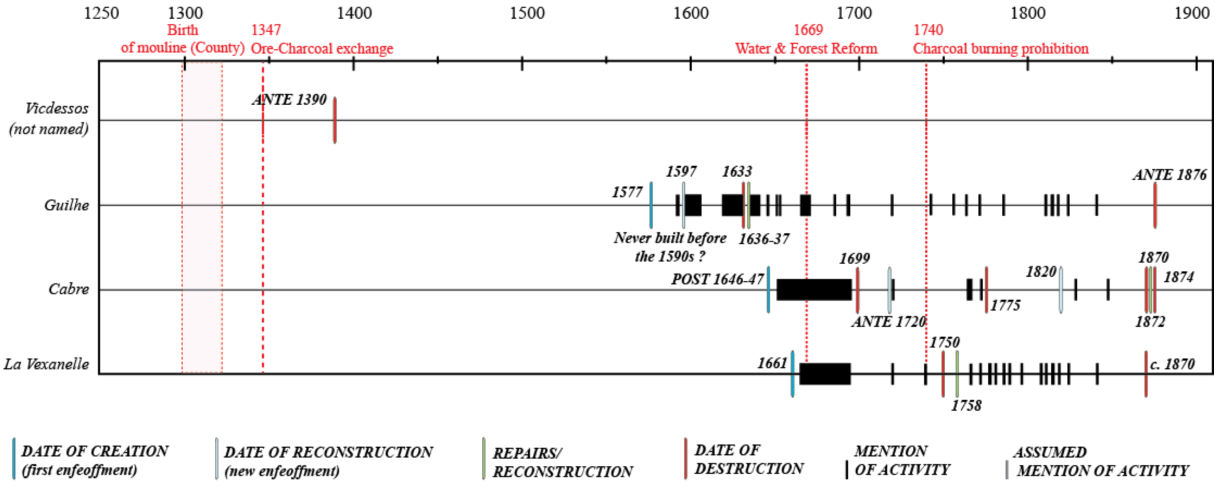


Fig. 5 : Restitution of bloomery activity in Vicdessos territory.

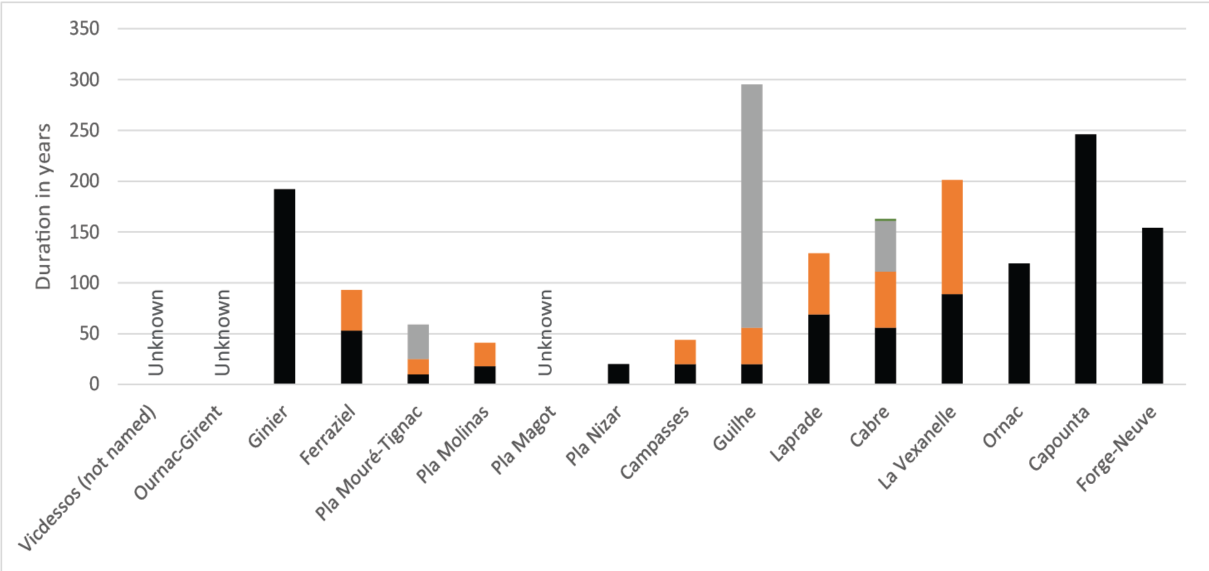


Fig. 6 : Evaluation of the maximum running duration for each bloomery (colors correspond to successive phases of activity).

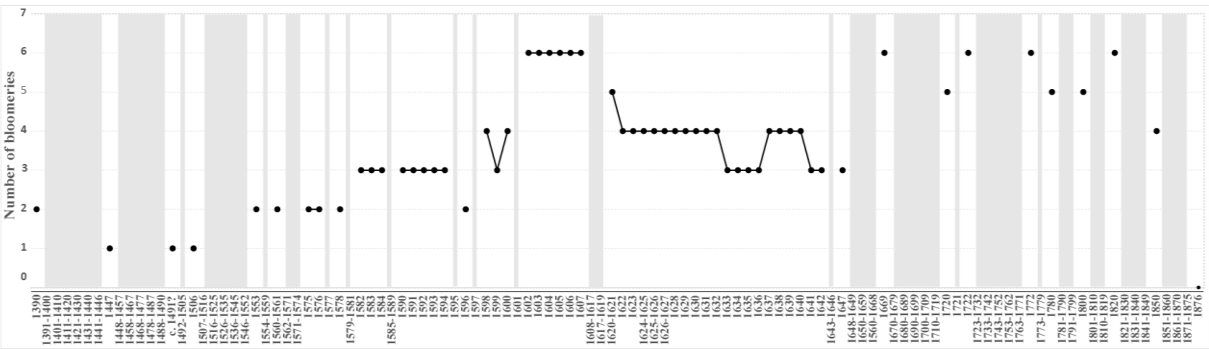


Fig. 7 : Number of bloomeries over time in the *consulat de Vicdessos* according to written records (Only the years for which we have an overview of the total number of bloomeries are represented; contracted undocumented periods in grey).

2.2. Archaeological evidences

For now, in lack of archaeological excavations and radiocarbon dating, archaeology provides little information about ancient and medieval bloomeries in the former *consulat de Vicdessos*. While a couple of ironworks were radiocarbon dated to the 3rd-5th c. AD in the neighboring valleys of Siguer and Courbière, no evidence was found in the *consulat de Vicdessos*. Despite some textual evidence, for now, no medieval bloomeries remains have been recognized. Based on the scarcity of iron artifacts from the *castrum* site of Montréal-de-Sos, archeologists speculated on the existence of small-scale open-cast mining works between the late 12th c. and the late 13th c. But this hypothesis must be supported by iron isotope analyses to confirm their local provenance and manufacture. Thus, it is impossible to conclude that medieval iron making activity was continuous and intensive (Figs. 3,4,5). For the early modern era, only the Las Moulinas bloomery have been partially investigated but not radiocarbon dated. For late modern and contemporary times, all the bloomeries documented by archives were recognized. Recent surveys detected several undated ironwork evidence.

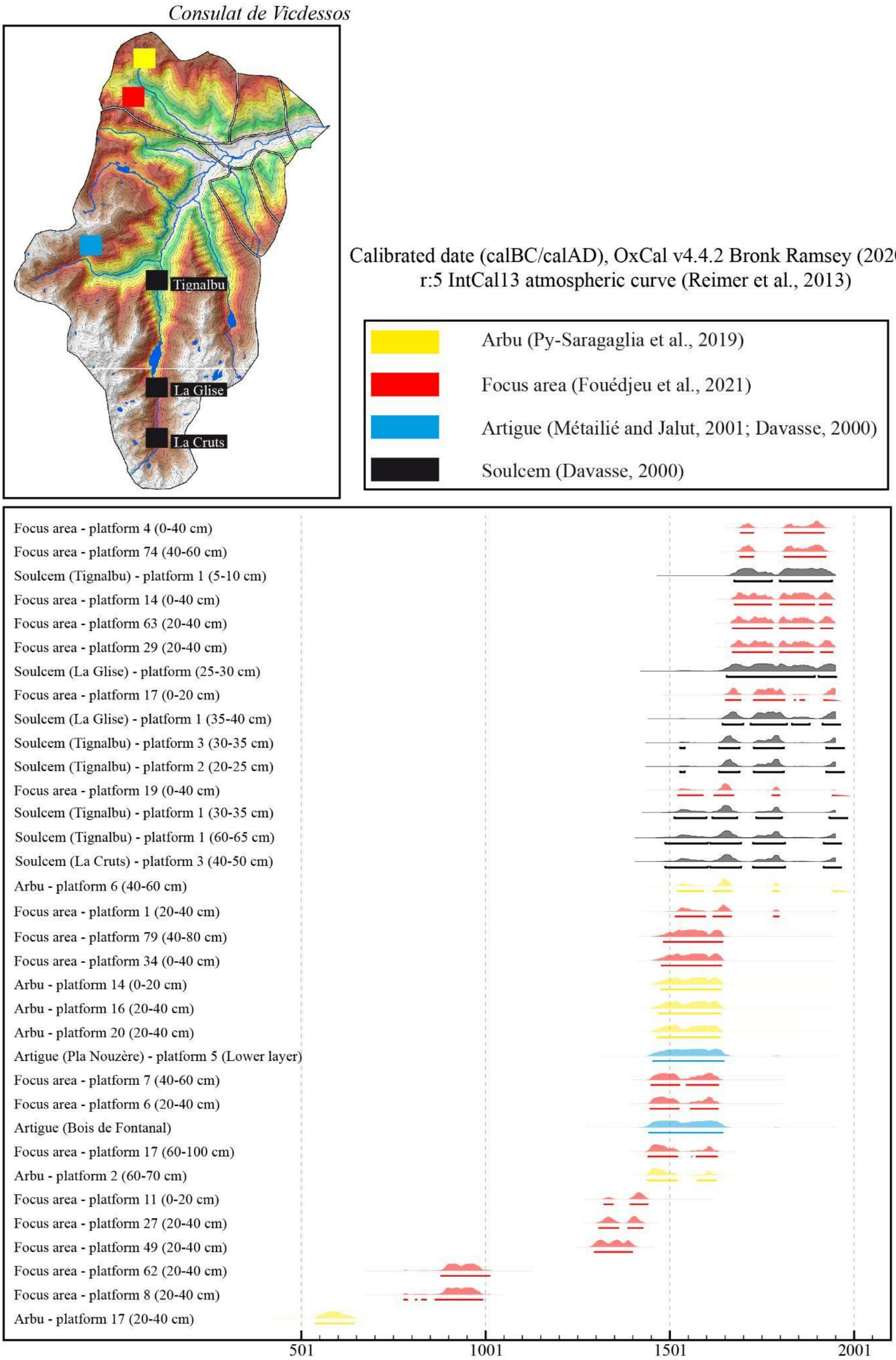
Concerning charcoal production, we detected a total of 80 platforms in the focus area. Platforms were distributed along slopes with 31% located on the steep slope (50 to 90%), 35% on medium-grade incline slopes (20 to 50%) and 33% on low to moderate slopes (low grade, up to 20%). Platforms recorded on steep slopes show visible signs of construction: excavation, overdeepening directly into the slope to prepare the location of the platform where charcoal kilns were settled. Smaller platforms with a moon shape are mainly found on steep slopes, while larger platforms (round shape) are located on gentle slopes. Almost all platforms are located within the current forest, except a dozen located in the current open grazing area (n° 1, 2, 3, 4, 6, 7, 8, 9, 10 et 62) (Fig. 1D). The past centuries had little effect on the conservation of platforms located in forest, unlike the platforms in open areas, which show weaker conservation, probably due to heavy human use and grazing by livestock. Almost all platforms show a homogeneous and regular black layer, more or less rich in charcoal, which usually extends to a depth of 40 to 60 cm, sometimes to 80 cm (platforms 19, 74 and 79). Platform 17, which is the only one reaching 120 cm depth, is characterized by three charcoal deposits separated by two fine mineral layers suggesting three use phases. Platforms with 120 cm depth remain exceptional, because the thickness of the black layer usually ranges from 5 and 30 cm on most of the platforms observed on different European sites. It could be a pit platform, the existence of which has sometimes been mentioned by historical sources in the French Pyrenees (Gourbit valley, Pays de Sault) and Catalan Pyrenees.

At the *consulat de Vicdessos* level, radiocarbon data from platforms cover a period ranging from the 6th c. to the 20th c. AD (with 95.4% of probability) (Table 1, Fig. 8). In the focus area, they bring 11 centuries of charcoal production to light, beginning in the 9th c. AD. For platform 17, the deepest layer corresponds to the mid-15th-mid-17th c. period, and the uppermost layer, to the mid-17th to the 19th c., confirming its use at different periods.

Study area	Plat-form	Depth (cm)	Age 14C BP	N° Lab	Tree-species	Cal BC-AD (95.4%)	Most probable dates (% probability)	Historical periods	Source
Focus area	4	0-40	65 ± 30	Poz-73024	Beech	1691-1921	1811-1921 (71.6%)	19th-20th c.	(Fouédjeu et al., 2021b)
Focus area	74	40-60	80 ± 30	Lyon-14958 (SacA-53114)	Beech	1690-1926	1810-1926 (70.6%)	19th-20th c.	(Fouédjeu et al., 2021b)
Soulcem (Tignalbu)	1	5-10	100 ± 50	Gif 8734	n/a	1676-1941	1799-1941 (61.4%)	19th-20th c.	(Davasse, 2000)
Focus area	17	0-20	185 ± 30	Lyon-14951 (SacA-53107)	Beech + bark	1650-present day	1726-1814 (52.5%)	Mid 17th-19th c.	(Fouédjeu et al., 2021b)
Soulcem (Tignalbu)	1	60-65	190 ± 40	Gif 8736	n/a	1644-present day	1720-1819 (47.9%)	Mid 17th-19th c.	(Davasse, 2000)
Focus area	14	0-40	130 ± 30	Lyon-14950 (SacA-53106)	Beech + bark	1675-1942	1675-1894 (80.5%)	Mid 17th-19th c.	(Fouédjeu et al., 2021b)
Focus area	29	20-40	140 ± 30	Lyon-14953 (SacA-53109)	Beech + bark	1669-1945	1669-1891 (80%)	Mid 17th-19th c.	(Fouédjeu et al., 2021b)
Focus area	63	20-40	140 ± 30	Lyon-14957 (SacA-53113)	Beech	1669-1945	1669-1891 (80%)	Mid 17th-19th c.	(Fouédjeu et al., 2021b)
Soulcem (La Glise)	5	25-30	160 ± 60	Gif 8733	n/a	1655-present day	1655-1894 (78.3%)	Mid 17th-19th c.	(Davasse, 2000)
Soulcem (Tignalbu)	2	20-25	220 ± 35	Gif 8738	n/a	1529-present day	1635-1810 (79.5%)	Mid 17th-19th c.	(Davasse, 2000)
Soulcem (Tignalbu)	3	35-40	220 ± 35	Gif 8737	n/a	1529-present day	1635-1810 (79.5%)	Mid 17th-19th c.	(Davasse, 2000)
Focus area	19	0-40	255 ± 30	Poz-73023	Beech + bark	1521-present day	1620-1675 (55%)	Mid 17th-19th c.	(Fouédjeu et al., 2021b)
Soulcem (Tignalbu)	1	30-35	250 ± 40	Gif 8735	n/a	1513-present day	1616-1684 (41.6%)	Mid 17th-19th c.	(Davasse, 2000)
Soulcem (La Glise)	1	30-35	240 ± 50	Gif 8530	n/a	1489-present day	1610-1813 (63.4%)	Mid 17th-19th c.	(Davasse, 2000)
Soulcem (Pla de la Crouts)	3	45-50	240 ± 50	Gif 8739	n/a	1489-present day	1610-1813 (63.4%)	Mid 17th-19th c.	(Davasse, 2000)
Arbu	6	40-60	260 ± 30	Poz-104699	n/a	1520 - present day	1520-1670 (53.1%)	Mid 15th-mid 17th c	(Py-Saragaglia et al., 2019)
Focus area	1	20-40	270 ± 30	Poz-73022	Beech + bark	1514-1799	1514-1669 (89.2%)	Mid 15th-mid 17th c	(Fouédjeu et al., 2021b)
Focus area	79	40-80	320 ± 30	Beta-480930	Beech + bark	1482-1646	1482-1646 (95.4%)	Mid 15th-mid 17th c	(Fouédjeu et al., 2021b)
Focus area	34	0-40	330 ± 30	Lyon-14954 (SacA-53110)	Beech	1477-1643	1477-1643 (95.4%)	Mid 15th-mid 17th c	(Fouédjeu et al., 2021b)
Arbu	14	0-20	335 ± 30	poz-104579	Beech	1475-1641	1475-1641 (95.4%)	Mid 15th-mid 17th c	Py-Saragaglia et al. (2019)
Arbu	16	20-40	340 ± 30	Poz-104580	Beech + pine + bark	1470-1640	1470-1640 (95.4%)	Mid 15th-mid 17th c	Py-Saragaglia et al. (2019)
Arbu	20	20-40	345 ± 30	Poz-104700	Fir + fir/juniper	1465-1638	1465-1638 (95.4%)	Mid 15th-mid 17th c	Py-Saragaglia et al. (2019)
Artigue (Pla Nouzère)	5	Lower layer	330 ± 50	Gif 8109	n/a	1454-1649	1454-1649 (95.4%)	Mid 15th-mid 17th c	(Métailié and Jalut, 1991)
Focus area	7	40-60	365 ± 30	Lyon-14949 (SacA-53105)	Beech	1449-1634	1449-1634 (95.4%)	Mid 15th-mid 17th c	(Fouédjeu et al., 2021b)
Focus area	6	20-40	375 ± 30	Poz-77095	Bark	1446 - 1633	1446 - 1527 (58.3%)	Mid 15th-mid 17th c	(Fouédjeu et al., 2021b)
Artigue (Bois de Fontanal)	n/a	n/a	360 ± 60	Gif 9433	n/a	1442-1646	1442-1646 (95.4%)	Mid 15th-mid 17th c	(Davasse, 2000)

Focus area	17	60-100	390 ± 30	Lyon-14952 (SacA-53108)	Bark	1441-1631	1441-1524 (69.3%)	Mid 15th-mid 17th c	(Fouédjeu et al., 2021b)
Arbu	2	60-70	396 ± 30	Poz-104658	Beech + bark	1438-1628	1438-1523 (73.7%)	Mid 15th-mid 17th c	(Py-Saragaglia et al., 2019)
Focus area	11	0-20	525 ± 30	Poz-73025	Fir + beech + bark	1321 - 1442	1392-1442 (80.5%)	End 13th c.- early 15 th c.	(Fouédjeu et al., 2021b)
Focus area	27	20-40	560 ± 30	Poz-97774	Bark	1307 - 1429	1307 - 1429 (95.4%)	End 13th c.- early 15 th c.	(Fouédjeu et al., 2021b)
Focus area	49	20-40	615 ± 30	Lyon-14955 (SacA-53111)	Beech	1295-1401	1295-1401 (95.4%)	End 13th c.- early 15 th c.	(Fouédjeu et al., 2021b)
Focus area	62	20-40	1110 ± 30	Lyon-14956 (SacA-53112)	Fir + fir/juniper	878-1014	878-1014 (95.4%)	Early Middle Ages	(Fouédjeu et al., 2021b)
Focus area	8	20-40	1120 ± 30	Poz- 109062	n/a	778 - 995	863-995 (91.8%)	Early Middle Ages	(Fouédjeu et al., 2021b)
Arbu	17	20-40	1480 ± 30	Poz-104621	Beech	538-646	538-646 (95.4%)	Early Middle Ages	(Py-Saragaglia et al., 2019)

Table 1 Combine Accelerator Mass Spectrometry (AMS) dates of the focus area, Soulcem, Arbu and Artigue



Consulat de Vicdessos
Tignalbu
La Glise
La Cruts
Calibrated date (calBC/calAD), OxCal v4.4.2 Bronk Ramsey (2020); r:5 IntCal13 atmospheric curve (Reimer et al., 2013)
Arbu (Py-Saragaglia et al., 2019)
Focus area (Fouédjeu et al., 2021)
Artigue (Métailié and Jalut, 2001; Davasse, 2000)
Soulcem (Davasse, 2000)
Focus area - platform 4 (0-40 cm)
Focus area - platform 74 (40-60 cm)
Soulcem (Tignalbu) - platform 1 (5-10 cm)
Focus area - platform 14 (0-40 cm)
Focus area - platform 63 (20-40 cm)
Focus area - platform 29 (20-40 cm)
Soulcem (La Glise) - platform (25-30 cm)
Focus area - platform 17 (0-20 cm)
Soulcem (La Glise) - platform 1 (35-40 cm)
Soulcem (Tignalbu) - platform 3 (30-35 cm)
Soulcem (Tignalbu) - platform 2 (20-25 cm)
Focus area - platform 19 (0-40 cm)
Soulcem (Tignalbu) - platform 1 (30-35 cm)
Soulcem (Tignalbu) - platform 1 (60-65 cm)
Soulcem (La Cruts) - platform 3 (40-50 cm)
Arbu - platform 6 (40-60 cm)
Focus area - platform 1 (20-40 cm)
Focus area - platform 79 (40-80 cm)
Focus area - platform 34 (0-40 cm)
Arbu - platform 14 (0-20 cm)
Arbu - platform 16 (20-40 cm)
Arbu - platform 20 (20-40 cm)
Artigue (Pla Nouzère) - platform 5 (Lower layer)
Focus area - platform 7 (40-60 cm)
Focus area - platform 6 (20-40 cm)
Artigue (Bois de Fontanal)
Focus area - platform 17 (60-100 cm)
Arbu - platform 2 (60-70 cm)
Focus area - platform 11 (0-20 cm)
Focus area - platform 27 (20-40 cm)
Focus area - platform 49 (20-40 cm)
Focus area - platform 62 (20-40 cm)
Focus area - platform 8 (20-40 cm)
Arbu - platform 17 (20-40 cm)
501
1001
1501
2001

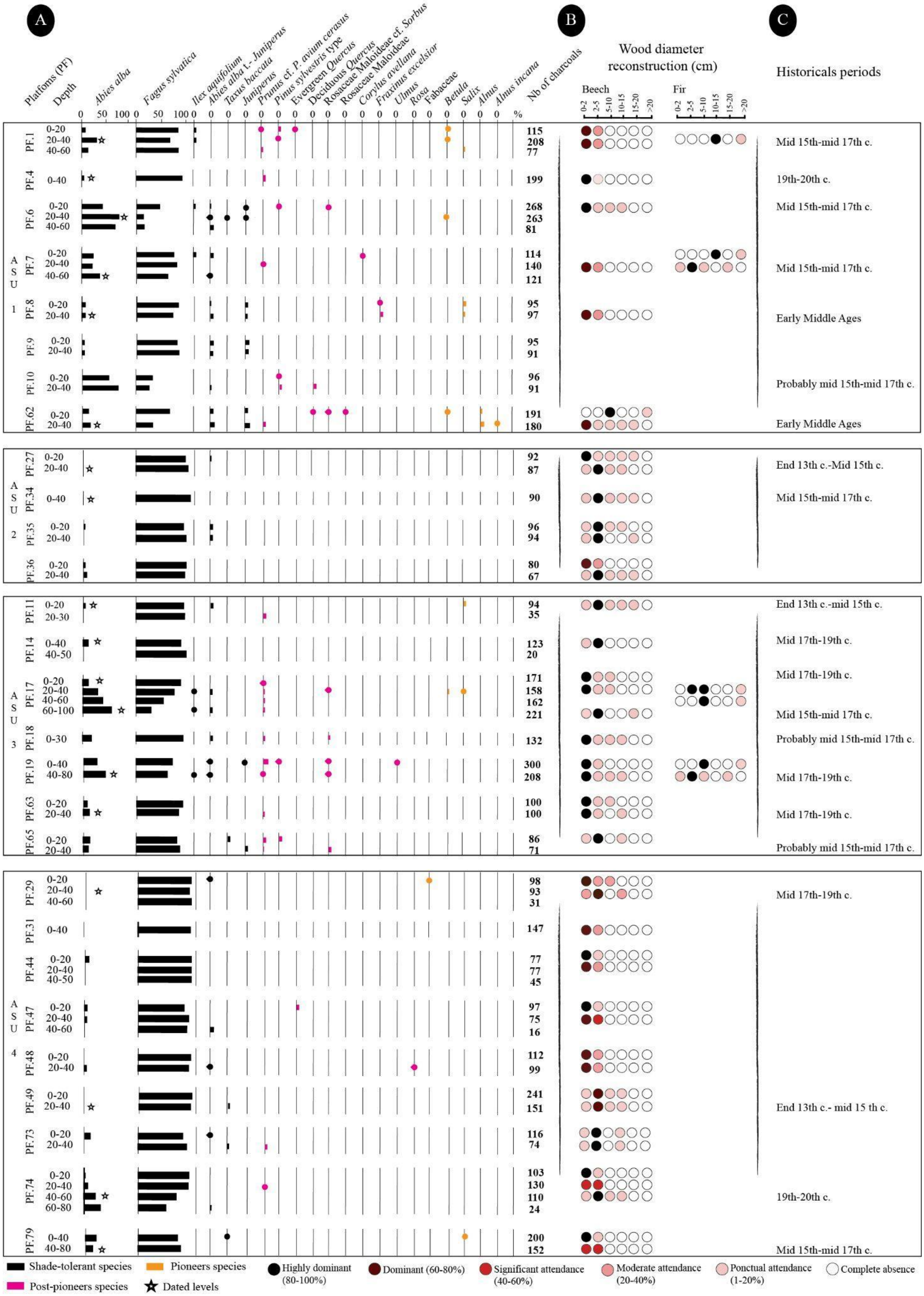
Fig. 8: Radiocarbon dates of platforms showing 15 centuries of charcoal manufacturing

2.3. Results of charcoal analysis for the focus area

Among the 7990 charcoal samples analyzed, we identified 21 taxa classified into three main categories (Fig. 9A): (i) shade-tolerant tree taxa so-called "dryads" including silver fir, beech, holly (*Ilex aquifolium* L.), common yew (*Taxus baccata* L.), fir/juniper (*Abies alba*/*Juniperus*); (ii) pioneer taxa, i.e. legume family (Fabaceae), birch (*Betula*), willow (*Salix*), grey alder (*Alnus incana* L.), alder (*Alnus*), juniper (*Juniperus*) and (iii) post-pioneer taxa including wild cherry (*Prunus*), scots/mountain pine (*Pinus*), evergreen and deciduous oak (*Quercus*), apple sub-family (Rosaceae, Maloideae), mountain ash (Rosaceae, Maloideae cf. *Sorbus*), hazel (*Corylus*), ash (*Fraxinus*), rose (*Rosa*), elm (*Ulmus*), wild cherry (*Prunus*). The corpus of charcoal is largely dominated by beech (81.2%), followed by silver fir (15.4%). The 19 other taxa had mean relative frequencies below 2% and were not identified in all platforms (Supplementary file 2).

The anthracological spectra of platforms in the ASU 2 are characterized by very low taxonomic diversity (n=3) and a large predominance of beech. Nine taxa were recorded in platforms located in ASU 4. Beech is always predominant, but platforms 73 and 74 recorded high proportions of silver fir. The platform spectra in the ASUs 1 and 3 show the greatest taxonomic diversity (n=18 and 12). They are characterized by significant frequencies of silver fir, even though beech is predominant overall (Fig. 9A).

Hierarchical clustering analysis grouped platforms into three main clusters according to their taxonomic composition and the relative frequencies of the taxa (Fig. 10). Cluster I included platforms (62 and 8) with the greatest taxonomic diversity (n=12), and the oldest dates, i.e. 9th-10th c. AD. C II included sampling layers dominated by beech and, in the deeper layers of the same platforms, rich in fir. Those platforms were dated for three different periods: end 13th- mid 15th c., mid 17th c.-19th c. and 19th-20th c. The oldest are composed of sampling layers in platforms 11, 27 and 49. The most recent are composed of most of the layers of platforms 4, 14, 17 (except 20-40, 40-60 and 60-100 cm), 29, 63 and 74 (except 60-80 cm). Cluster III included platforms whose layers were dominated by fir. These platforms were dated between mid-15th to mid-17th c.



A
B
C
Platforms (PF)
Depth
Abies alba
Fagus sylvatica
Ilex aquifolium
Abies alba t.- Juniperus
Taxus baccata
Juniperus
Prunus cf. P. avium cerasus
Pinus sylvestris type
Evergreen Quercus
Deciduous Quercus
Rosaceae Maloideae cf. Sorbus
Rosaceae Maloideae
Corylus avellana
Fraxinus excelsior
Ulmus
Rosa
Fabaceae
Betula
Salix
Alnus
Alnus incana
Nb of charcoals
Wood diameter reconstruction (cm)
Beech
Fir
0-2
2-5
5-10
10-15
15-20
>20
Historicals periods
ASU 1
PF.1
PF.4
PF.6
PF.7
PF.8
PF.9
PF.10
PF.62
ASU 2
PF.27
PF.34
PF.35
PF.36
ASU 3
PF.11
PF.14
PF.17
PF.18
PF.19
PF.63
PF.65
ASU 4
PF.29
PF.31
PF.44
PF.47
PF.48
PF.49
PF.73
PF.74
PF.79
Mid 15th-mid 17th c.
19th-20th c.
Early Middle Ages
Probably mid 15th-mid 17th c.
End 13th c.-Mid 15th c.
End 13th c.-mid 15th c.
Mid 17th-19th c.
End 13th c.- mid 15 th c.
Shade-tolerant species
Pioneers species
Post-pioneers species
Dated levels
Highly dominant (80-100%)
Dominant (60-80%)
Significant attendance (40-60%)
Moderate attendance (20-40%)
Ponctual attendance (1-20%)
Complete absence

Fig. 9: (A) Anthracological diagram of the focus area showing the relative frequencies of taxa classified by reference spatial unit. Points represent taxa with relative frequencies of lower than 1%; (B) Results of wood diameter reconstruction carried on (Fouédjeu et al., 2021b); (C) Historicals periods

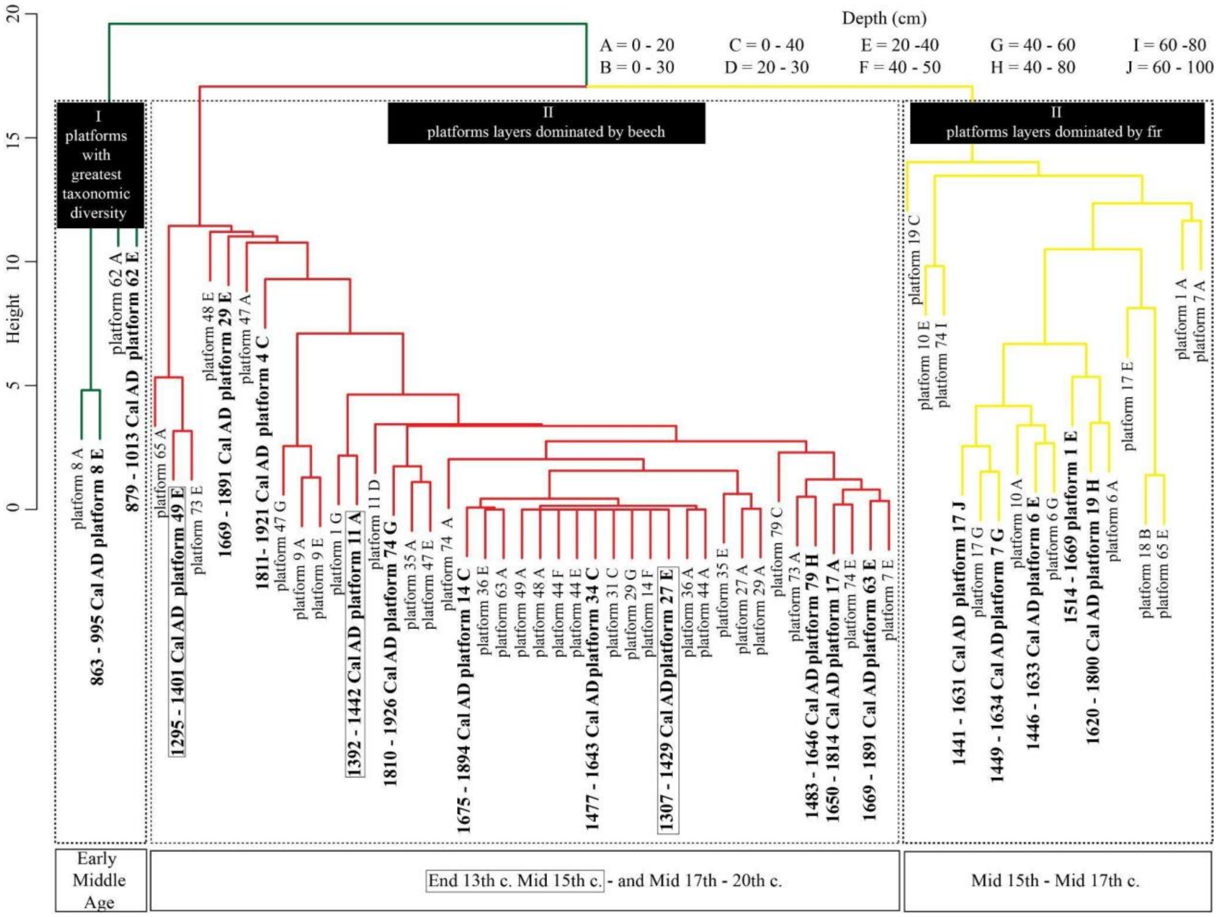


Fig.10: Hierarchical clustering conducted on the basis of the similar taxonomic composition of dated and undated platforms highlighting three groups (green, red, yellow).

3. Discussion

3.1. Fuel consumption for the iron industry and woodland management strategies over time

Presently, no data is available to assess and characterize late antique and early medieval unpowered direct furnaces charcoal consumption. Dubois' estimation (2000) is excessive as it was based on insufficient experiments and on unrecognized hypotheses: the continuity of production and silvicultural practices over long periods (Arribet-

Deroin, 2013). Consequently, we assume low intensity iron production supplied by the local charcoal industry, as in Vall Ferrera (Pèlachs et al., 2009).

The first evidence of forest management dates from a. 1272 when the inhabitants of the *consulat de Vicdessos* were recognized in their customary right to freely use common natural resources[27] (Verna, 2001, pp. 115–116, 167). Charcoal burning is attested as soon as 1281[28] and the right to make charcoal freely and without limitation is confirmed in 1294[29]. In 1301, the common rights of inhabitants were reconfirmed, but charcoal burning was forbidden[30], probably because the earl sought to control the rising charcoal trade. In this sense, the 1303 regulation[31] defined new rules for charcoal production, requiring producers to use dry and dead trees before using entirely green trees, but enforcement remains uncertain. In 1347-48, an iron-charcoal agreement was signed between the *consulat* and the Couserans viscount[32]. The former obtained the right to harvest timber and charcoal in the Couserans viscounty's forest. In exchange, the Viscount was allowed to supply his bloomeries at Ercé and Massat with the iron ore from Sem mines. However, the Viscount excluded small-sized oaks and firs from the agreement (Verna, 2001, pp. 96–98). The regulation of local production[33] and the outsourcing of charcoal supply was intended to ensure forest resource sustainability in a long-term industrial development perspective.

Medieval and modern charcoal consumption also remains largely unknown. Generally water-powered bloomeries allowed a higher iron production rate and involved higher charcoal consumption (Arribet-Deroin, 2018). However, without local information on the rhythm and duration of smelting operations, it is impossible to estimate the annual consumption of each bloomery.

In the context of industrial variability (Fig. 7), charcoal supply was both locally sourced and imported from Couserans[34], through the Port de Lers, probably in the framework of the iron-charcoal exchange, but their respective shares are unknown. Local charcoal was generally supplied by the rights granted in bloomeries enfeoffment[35] and secondarily by purchases and debt repayments[36]. This local production is confirmed by nine platforms in the focus area, four in Arbu and two in Artigue (Davasse, 2000, pp. 163–164) (Fig. 8, 10). The low

[27] Supplementary file 1, doc n°1.
[28] Supplementary file 1, doc n°2.
[29] Supplementary file 1, doc n°3.
[30] Supplementary file 1, doc n°5.
[31] Supplementary file 1, doc n°6.
[32] Supplementary file 1, doc. n°16; 17.
[33] Supplementary file 1, doc n°20.
[34] Supplementary file 1, doc n°41.
[35] Supplementary file 1, doc n°48; 57; 60.
[36] Supplementary file 1, docs n°36-37; 41; 130-133.

accuracy of radiocarbon probability ranges does not allow us to relate them to the individual bloomeries running phases.

While only the use of beech is mentioned in written records[37], charcoal analysis revealed a large variety of species. Las Moulinas bloomery (Artiès, late 16th-early 17th c.) was mainly fueled with beech, fir and birch (*Betula*) with numerous other broadleaved trees and conifers (Métailié and Jalut, 1991; Dubois, 1995; Davasse, 2000, pp. 163–164). In Artigue, fir was almost exclusively charred. Indeed, while fir was expected to be used primarily as a building material[38] (Barbe, 1900; Ruffié, 1997), it was also significantly identified among charcoal. Wood diameters of fir charcoal raise issues about the charring of logging slash (Fouédjeu et al., 2021b). The contemporaneous intensification of anthropogenic canopy removal (Saulnier et al., 2020) suggests the harvesting of a large number of fir standards. The combination of charcoal and timber productions is also suggested by the ownership of sawmill by ironmasters and the spatial proximity of both activities[39].

During the 17th c. industrial intensification (Fig. 7), forest administration reports emphasized the role of charcoal imports from Couserans[40] (Davasse, 2000, p. 135; Cantelaube, 2005, pp. 224–228; Poublanc, 2019, p. 54). Although charcoal delivered at the Port de Lers were partly produced in Massat, Ustou[41] and in the Earl of Rabat's forests[42], the sourcing of imported charcoal is often unknown[43]. However, charcoal was also locally manufactured as stated by historical[44] and archaeological evidence (Fig. 8). Forest court condemned bloomery owners for "abusive use" but maintained their rights[45]. While beech was considered to produce better charcoal than fir[46], charcoal analysis still evidences a combined use of conifers (pine, fir, juniper) and broadleaved trees (hazel, birch, alder, etc.) (Davasse, 2000, pp. 175–180).

Improving technical processes led to a 30-50% reduction in charcoal consumption between 1667-1868 (Cantelaube, 2005, p. 245). The charcoal/iron ratio was around 6/1 or 4/1 according to François (1837, p. 588; 1843, p. 321). However, the annual consumption of each bloomery remains unknown for the reasons previously exposed (e.g. the Guilhe only ran 2-3 months per year[47]).

[37] Supplementary file 1, doc n°130.
[38] Supplementary file 1, doc n°39; 49.
[39] Supplementary file 1, doc n°29; 56-58; 67-71; 82.
[40] Supplementary file 1, doc n°231, fol. 418 (1667); 249, fol. 136 (1669).
[41] Supplementary file 1, doc n°170.
[42] Supplementary file 1, doc n°215.
[43] Supplementary file 1, doc n°165; 175; 230; 242; 254; 289.
[44] Supplementary file 1, doc n°36-37; 41; 48; 57; 60; 130-133; 149-176; 178-182; 187-195; 197-210; 212-230; 232-248; 254-274; 276-312; 315-351; 353-368; 371-378; 387-394; 396-403; 410-413; 415; 418-419; 423-425; 427.
[45] Supplementary file 1, doc n°251-253.
[46] Supplementary file 1, doc n°150; 152; 165; 167; 170; 176; 180; 187-188; 201; 207; n°249, fol. 140 ; 296-297; 302; 305; 308; 319-321; 367; 373-375.
[47] Supplementary file 1, doc n°249.

Despite strong control, illicit charcoal burning occasionally occurred in woodland reserves during the 18th c.[48]. In 1740, the fear of timber shortages led authorities to create new reserves to ensure timber supply for mining and construction, and to prohibit charcoal burning in the entire *consulat*[49]. This prohibition was globally respected[50] (Picot de Lapeyrouse, 1786, p. 64; Davasse, 2000, pp. 106–110), but was renewed after the French Revolution due to new offenses[51]. Charcoal making continued in private woodland away from commons (Davasse, 2000, p. 117). The 1740 prohibition led the *consulat* council to enforce the respect of the iron-charcoal exchange with Couserans[52]. Due to rising charcoal prices, the lords of Massat and Ercé tried to end it (Davasse, 2000, pp. 135–143; Cantelaube, 2005, pp. 224–233). In response, the *consulat* signed new exchange agreements with other Couserans lords[53], then with the Donnezan (1770)[54] and Vall Ferrera communities[55] (until the prohibition of charcoal exportation in 1773)[56]. The iron-charcoal exchange ultimately stopped in the 1780-1790s (Davasse, 2000, p. 137; Cantelaube, 2005, pp. 224–233). In the 1780s, about 1.706 t. of outsourced charcoal per day were consumed by the six bloomeries of the *consulat*[57] (François, 1837, p. 585; Cantelaube, 2005, pp. 206–209).

Iron production no longer drove mountain woodland exploitation. Several decrees leading to the 1810 law required those who wanted to create a bloomery to indicate the sourcing of charcoal supply to the Waters and Forests administration to demonstrate the absence of impact on local woodland. Most charcoal supplies came from external purchases or from the bloomery owner's private woodlands outside the *consulat* (Bonhôte, 1986; Davasse, 2000; Cantelaube, 2005, pp. 505–519).

Later, the development of an agro-pastoral-based economy led to a global wood shortage resulting in tensions between local communities and state forestry administration. The fuelwood and timber supply of each commune was restricted to its own territory and required legal authorization. It was problematic because the spatial distribution of fir high woodlands was unequal as it resulted from former common organization (Davasse, 2000, pp. 123–125). The 1827 Forest Code, again restraining common rights, and the Mountain Lands Restoration plantation of exotic conifers, initiated in the 1820s, caused an increasing conflictuality (e.g. War of the Demoiselles) (Chevalier, 1956, pp. 873–877; Baby, 1972; Whited, 2000).

[48] Supplementary file 1, doc n°446; 456; 460; 477-478; 497; 501-502.
[49] Supplementary file 1, doc n°506.
[50] Supplementary file 1, doc n°587; 592; ; 601-604; 609.
[51] Supplementary file 1, doc n°614-615; 617.
[52] Supplementary file 1, doc n°428; 430; 443-445; 447-448; 452-455; 457-459; 467-468; 479-486; 488-490; 496; 498; 503; 505; 508-511; 514; 516-521; 523-524; 516; 528-529; 531-536; 538; 547; 549-551; 553; 560; 567-573; 579-580; 587; 591-592; 594-601; 605.
[53] Supplementary file 1, doc n°455; 457; 480; 4826-485.
[54] Supplementary file 1, doc n°567-572.
[55] Supplementary file 1, doc n°539-542; 561.
[56] Supplementary file 1, doc n°575; 578; 583.
[57] Supplementary file 1, doc n° 598.

3.2. Long-term forest evolution driven by human practices

Previous studies have highlighted the early medieval altitudinal rising of agrarian lands and clearing of pine forest for pasture in subalpine areas (Galop, 2000; Galop et al., 2003; 2013; Rendu, 2003). Until now, there has been little evidence of local high-altitude pasture occupancy (Guillot, 2014). While agro-sylvo-pastoral activities were the main driver of woodland clearings, charcoal manufacturing was usually considered to have contributed to landscape opening (Galop, 1998; Galop et al., 2013).

In the focus area, soil charcoal analysis (Fig. 1D) highlighted the introduction of woodland grazing systems, inducing changes in forest species composition: decrease of fir and yew in favor of beech between the Gallo-Roman and the Carolingian periods (Saulnier et al., 2020). Charcoal analysis also suggested a preferential use of beech, probably related to a selective management strategy (Fig. 9A). Post-pioneer taxa confirms forest clearings suitable for grazing. These canopy openings imply the existence of open coppice-type sylvo-facies and/or the absence of large trees suggested by wood diameters (Fig. 9B) (Fouédjeu et al., 2021b). Beech, which is able to resprout from stumps, was promoted to improve fuel and fodder production (Petit and Watkins, 2004). These indications suggest a multi-use management of woodland where the impact of charcoal production was low.

In the early 14th c., the increased regulation of charcoal production has been interpreted as the result of a “first forest crisis” (Bonhôte et al., 2000; 2002; Davasse, 2006). Despite the incontestable extension of clearings (Galop et al., 2013), charcoal analysis has shown that woodland was managed and conserved in mountain and subalpine areas (Davasse, 2000; Py-Saragaglia et al., 2017). They were privileged places for domestic and industrial uses, causing episodic and local over-exploitation (Verna, 2001, p. 95) and motivating improved regulation and the creation of forest reserves (e.g. for mine timber[58]).

In the focus area, three platforms ran between 1295-1442 cal AD, but probably not simultaneously (Fig. 9A, Table 1). While charcoal from these platforms suggest that fuel wood was probably harvested in beech woodland, soil charcoal has revealed the existence of mixed fir-beech stands (Saulnier et al., 2020). Consequently, we assume that fir was excluded from charcoal supply and reserved for other purposes, involving a specific management system with beech treated as coppice and fir as standard (Fouédjeu et al., 2021b).

[58] Supplementary file 1, doc n°14.

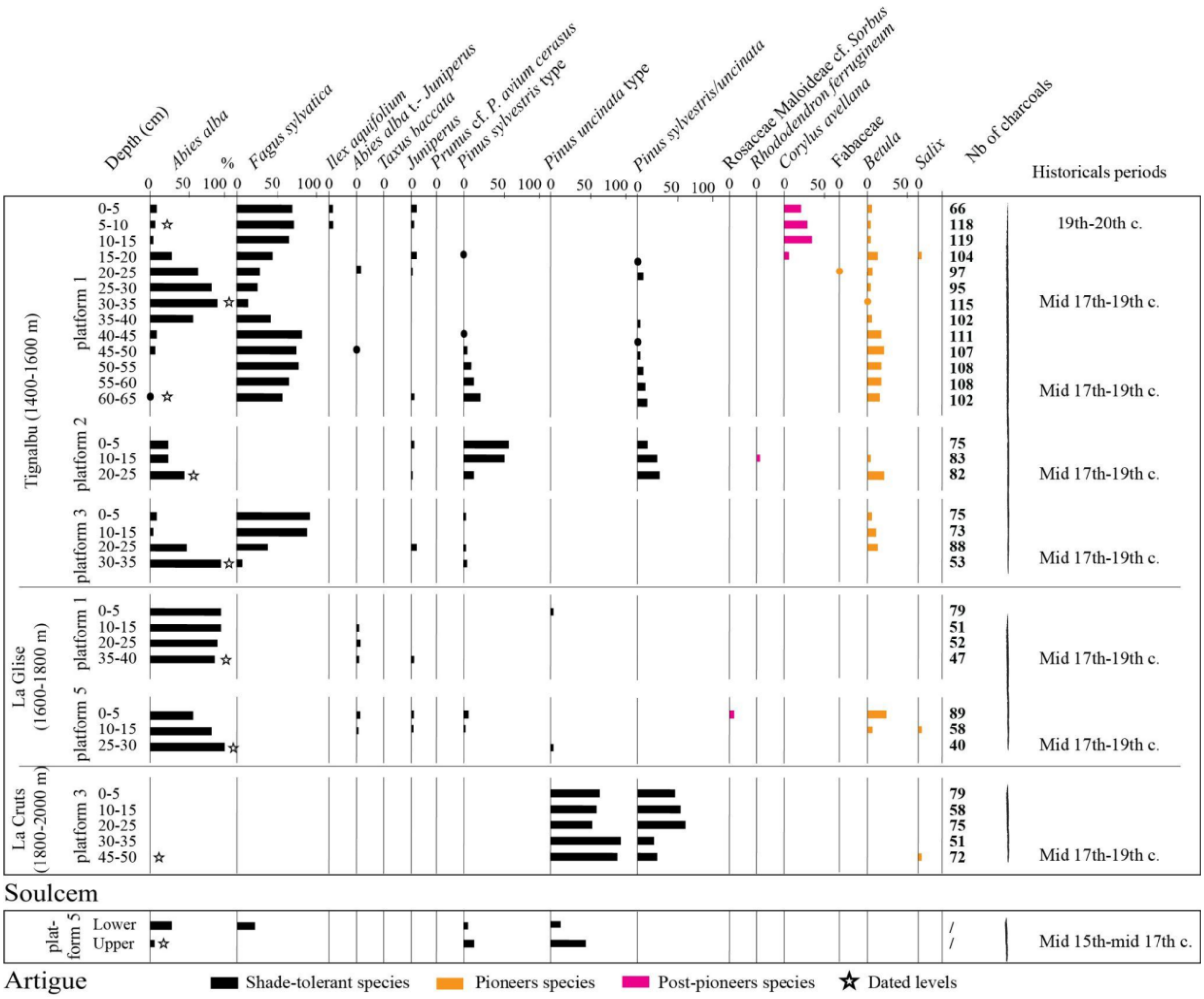


Fig. 11 Anthracological diagram of Artigue and Soulcem showing the relative frequencies of taxa. Points represent taxa with relative frequencies of lower than 1% (Davasse, 1989; 2000).

Two field surveys performed in the Auzat valley (1563-64) reported the existence of an old-growth forest composed of a significant proportion of senescent trees[59]. Charcoal burning was presented as the only way to enhance these woodlands that could not be exploited for timbering due to poor accessibility. Although this account may overstate bloomeries installation, it suggests that large forest areas still covered these valleys.

Six platforms from the focus area and six others located in Arbu (4) and Artigue (2) ran between the mid-15th c. to mid-17th c.(Figs. 8, 9A, Table 1) (Davasse, 2000, pp. 163–164). Charcoal analysis reflects the use of more diversified species (beech and fir, with weak proportion of other species) (Fig. 9A). It still suggests that a mixed fir-beech woodland was maintained, with wide structural diversity, as observed at Artiès (Fig. 11) (Dubois, 1995).

[59] Supplementary file 1, doc n°64-65; 67.

A shift in charcoal burning practices would have occurred following an increase in the use of fir and a decrease in wood caliber (Fouédjeu et al., 2021b; Fig. 9B), probably between the 16th c., when Ferraziel bloomery was built, and the early 17th c., when the iron industry was booming. In Artigue, the almost exclusive use of fir assumes a high fir-dominated forest (Métailié and Jalut, 1991; Davasse, 2000, pp. 163–164).

In 1669, forest Reformation reports described “degraded” woodland, insufficiently stocked to ensure industrial demand[60]. This perception was probably inherited from fears of lacking high forests suitable for timber (Poublanc, 2019; 2020). Far from the high forest ideal, beech coppice-dominated woodlands were composed of 60% beech, 34% mixed beech-fir stands and 6% fir (Davasse, 2000, pp. 90–97; 237–238; Poublanc, 2019, pp. 55–56). The stands where dominated most were located in the valleys downstream and in the upper part of slopes, and were mainly composed of 25-50 to 100 year-old trees. Information about 18th c. woodland composition and structure is scarce and dispersed (Davasse, 2000, pp. 111–113). Beech was omnipresent, sometimes associated with hazel and oak. The harvesting of beech seeds for replanting is also attested[61]. Fir was still present in several valleys, where it was mixed with oak.

In the focus area and Soulcem (Figs. 9A, 11), some platforms could date to after the 1740 prohibition. Charcoal analysis showed the preferred use of beech with the occasional admixture of fir. In addition to poor fir regeneration induced by canopy removal leading to scattered trees, the beech coppice-dominated system did not favor large high forest trees. Canopy removal was most likely unfavorable to both young fir and beech, which are shade species in the juvenile stage (Unrau et al., 2018). In the absence of an upper-story, people solved this problem using a coppice selection system (Salvador, 1930; Nicolescu et al., 2018). Conversely, the predominant use of fir with beech, pine and a greater diversity of broadleaved trees at Soulcem reveals the persistence of a fir-beech forest with clearings (Davasse, 2000).

The 1807 forest inventory depicted woodland as still covering large but fragmented areas, shaped by the extension of mid-altitude agro-pastoral settlements (Davasse, 2000, pp. 242–244). Woodland was mainly composed of young beech coppice (10-20 year-old), sometimes mixed with fir hardwood species. However, adult beech woodlands (100-200 year-old) were maintained in some areas. Fir-dominated forest, with 80 to 100 year-old high trees, still existed in five districts, but some of them were “badly managed” or “exhausted”(e.g. at Sem). The upper part of the Suc forest was composed of a beech-fir forest and the lower part by degraded beech coppice.

[60] Supplementary file 1, doc n°249, fol. 136 (1669); 231, fol. 418 (1667).
[61] Supplementary file 1, doc n°576.

Forest cover dropped sharply between 1807 and 1860, reaching its historical minimum (Davasse, 2000, pp. 124; 130–132), which coincides with the population and agro-pastoral economy maximum (Dengerma, 1934; Davasse, 2006; Gibert et al., 2012). In Suc, the beech-fir forest was almost entirely converted into a beech coppice in 1860, with isolated firs (Davasse, 2000, pp. 124–130). Charcoal analysis confirms the near disappearance of fir around the 19th-20th c. in the focus area (Fig. 9A). In the same way, in Soulcem, results suggest the harvesting of relict fir trees (Fig. 11). In 1892, the focus area was managed in a coppice selection system, with 20-50 year-old beech trees, and was then gradually converted into high forest (Fouédjeu et al., 2021a).

Conclusion

The results presented allow us to answer the research questions posed. First, our reappraisal of the iron industry chronology highlighted significant fluctuations over time. As such, and contrary to widespread ideas, continuity of iron production from late Antiquity to the central medieval period cannot be demonstrated as of yet. Moreover, the emergence and spread of the water-powered bloomery in the 14th c. did not result in the stabilization or significant growth of local iron smelting. Late medieval industrial development was short-lived and had already slowed in the mid-15th c. Despite the entrepreneurial boom initiated in the mid-16th c. in the upper valleys, the real catalyst for the iron industry came only in the early 17th c. in the lower valleys. In the mid-17th c., the Catalan technology gave new impetus to charcoal iron smelting, which reached its greatest intensity. The industrial fabric then remained more or less the same until the charcoal iron industry ended in the late 19th c.

Second, local management policies tried to ensure the sustainability of charcoal supply, and consequently, of forest resources, to support industrial development efforts through woodland use restrictions and the outsourcing of a part of charcoal supply. Although some authors have noted a first forest crisis as soon as the 14th c., caused by increased charcoal consumption by water-powered bloomeries, in-depth analysis of platforms shows industrial pressure on mountain forest resources remained relatively weak. Likewise, instead of the residual "shreds" previously proposed for the 16th c., charcoal making still occurred in a well-stocked mountain woodland that was conservatively managed. But the conversion of certain forest areas into beech-dominated coppice led to changes both in forest structure and biodiversity features, with the declining regeneration of fir and the increase of light-demanding species.

Third, significant forest cover decline began most likely during the 17th c. and accelerated in the 18th c., after charcoal manufacturing prohibition, mostly because of increased domestic, pastoral and agricultural needs, due to the 18th c. demographic explosion. Consequently, our results do not support the historical decline of the Pyrenean mountain forest cover induced by the growth of the iron charcoal industry. The intensification of agro-pastoralism was apparently the real cause of the mid-19th c. minimum forest cover, but deeper investigation of intensive livestock breeding and extensive mountain agriculture is required.

To conclude, this integrated study rejects the common premise that the charcoal-based iron industry in European mountains necessarily led to forest depletion. Conversely, it supports the hypothesis of the sustainable management of woodland (practices and policies), allowing the perpetuation of fuel resources and the support of industrial growth. Such interdisciplinary research should be applied in other places in order to unveil interactions between forest and pre-industrial societies.

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