



# Anthracological analyses of charcoal production sites at a high spatial resolution: the role of topography in the historical distribution of tree taxa in the northern Vosges mountains, France

David Gocel-Chalté<sup>1</sup> · François Guerold<sup>1</sup> · Hannes Knapp<sup>2</sup> · Vincent Robin<sup>1</sup>

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## Abstract

The rising demand for charcoal from industrialization during the eighteenth century led to the establishment of a large number of charcoal production sites (CPSs) within the woodland ecosystems of Europe. The CPSs still present today can be investigated to assess the past woodland composition in terms of taxa present and timber size, at a high spatial resolution. The present study was done in the northern Vosges region in France, an area of low mountains covered by woods with some important past industrial sites in several of its valleys. We aimed to investigate the possible role of topographical variables such as altitude and aspect in the distribution of CPSs and in the past distribution of tree taxa. Charcoal production sites were found, identified and sampled in four valley catchment areas, and a numerical model of elevation was used to compute the topography of the landscape. A total of 233 sites were recorded and anthracological (charcoal) samples from 121 of these were analysed. The radiocarbon dates of 20 CPSs range between the late 17th and the early twentieth century AD, which corresponds to the peak of industrial activity in this region. The spatial distribution of CPSs appears to increase in density close to streams, and 14 tree taxa were identified in the charcoal records, with *Fagus* and *Quercus* being dominant by far. Our results revealed the strong influence of the direction in which the slope faced on the taxon composition of the anthracological spectra. These results suggest that the local woodland stands which were used to supply the charcoal kilns depended on the local environmental conditions. Furthermore, the composition of the woodland has changed significantly over time, with more *Pinus sylvestris* at present.

**Keywords** Charcoal production · Anthracology · Woodland history · Topography

## Introduction

Wood charcoal has long been a key fuel resource for human activities, and its production became of paramount importance during the European industrial revolution, which began in the eighteenth century (Hammersley 1973; Guo

et al. 2015). Charcoal was made by the incomplete combustion of wood in charcoal production sites (CPSs) which were located in wooded areas (Duhamel du Monceau 1761; Kluiving and Guttman-Bond 2012). Today, the remains of CPSs are commonly found throughout Europe, under various terms such as platforms or charcoal hearths; Ludemann 2010 Knapp et al. 2013, 2015; Fruchart 2014; Schmidt et al. 2016; Carrari et al. 2017; Dupin et al. 2017). In order to assess the history of industrial development (Py-Saragaglia et al. 2017), as well as the ecological consequences upon woodland composition from past timber extraction (Ludemann et al. 2004; Ludemann 2010, 2011; Robin et al. 2015), numerous research works have investigated the spatial distribution (Ludemann et al. 2004; Schmidt et al. 2016; Raab et al. 2019), anthracological (charcoal) assemblages (Nelle 2003; Dupin et al. 2017), chronologies of production (Pèlachs et al. 2009; Knapp et al. 2015), and methods of charcoal burning at the CPSs. Among various significant

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✉ David Gocel-Chalté  
david.gocel-chalte@univ-lorraine.fr

<sup>1</sup> Laboratoire Interdisciplinaire des Environnements Continentaux (LIEC), UMR 7360 CNRS, Université de Lorraine, 15 Avenue du Charmois, Vandoeuvre-Les-Nancy 54500, France

<sup>2</sup> LabEx DRIIHM, OHM Pays de Bitche LIEC, Université de Lorraine, Campus Bridoux, 8 Rue du Général Delestraint, Metz 57070, France

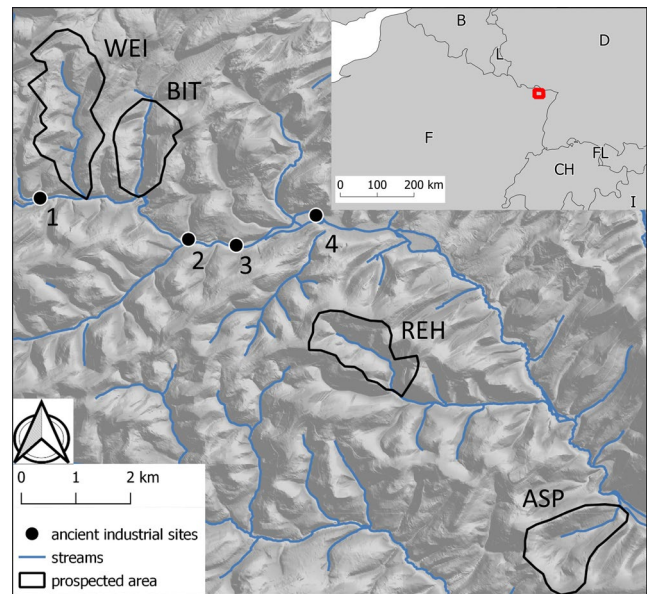
insights, these investigations have shown that CPSs represent valuable records of past taxon composition and tree dimensions at a local woodland stand scale (Deforce et al. 2013; Schmidt et al. 2016), even if human selection of the resources may have biased the representativity of the data (Chabal 2008; Théry-Parisot et al. 2010). Thus, the study of CPSs provides relevant information about the human impact on woodland composition (Ludemann 2010; Deforce et al. 2013; Carrari et al. 2016) and thus on environmental processes linked to changes in land use and land cover over time, such as soil erosion and nutrient availability (Dotterweich 2008, 2013; Compton and Boone 2010; Larsen et al. 2016; Suliman et al. 2016). These various studies also highlighted the great differences in spatial distributions and densities of the CPSs in various parts of Europe. This indicates the variation in the amount of production, which is itself related to the time period when this took place, and the variability in the use of resources and/or local conditions. It may therefore be crucial to take into consideration local scale topographical factors that could have helped or hindered charcoal making (Fruchart 2014) and which could have affected the distribution of tree taxa (Ludemann et al. 2017). This key issue remains poorly documented, despite the many research studies done about CPSs (Ludemann 2002, 2011; Ludemann et al. 2004).

In the present study, we discuss an analysis of charcoal making history carried out at a high spatial resolution in four catchment areas located in northeastern France to identify: (1) the type of wood resources that were used locally; (2) the period of charcoal making; (3) the environmental variables that significantly influenced charcoal production, and (4) how such environmental variables may explain the variability seen in the archaeological charcoal records. Lastly, a comparison between charcoal records and current woodlands was done in order to reveal possible changes that have occurred since the beginning of the charcoal making period.

## Data and methods

### Study area

The study took place in the northern Vosges which is an area of hills in a sandstone region between the Lorraine plateau to the west and the Rhine valley to the east, which consists of hills between 250 and 580 m a.s.l. (Fig. 1; Gall 1971; Mosser et al. 1972; Richter et al. 1996). The local climate is oceanic with continental influence and has distinct seasons. The mean annual temperature is 10.3 °C. The mean annual precipitation is 944.6 mm (data: Météo-France, Mouterhouse forecast station, 2009 to 2019). Nowadays, the local woodlands are dominated by *Fagus sylvatica* (beech), *Quercus sp.* (oak), and by conifers such as *Pinus sylvestris*



**Fig. 1** Location of the four studied catchment areas. Background: shaded relief map based on the RGE ALTI57 5 M digital terrain model. The studied areas are shown by black lines around them (data from PNRVN); WEI, Weissbachthal; BIT, Bitscherthal; REH, Rehbachthal; ASP, Aspenthal. Black dots represent the position of eighteenth century industrial sites according to the 1755 Cassini map (Vallauri et al. 2012). 1, smelter; 2, smithy; 3, hammer; 4, furnace

(Scots pine) and *Picea abies* (spruce) (Muller 2005), which cover 30% of the total wooded area. These are associated with vegetation communities of acidic soils (Bohn and Golub 2006; Geldreich 2008; Des et al. 2015) and in low-lying places, damp soils lead to the development of *Alnus glutinosa* (alder), peatbogs and grassland ecosystems maintained by human influence, with few agricultural activities except making hay (Muller 1986).

### Historical context

The presence of human populations in the region since the Palaeolithic period is indicated by the existence of several Neanderthal occupation sites (Schmit 2005, 2006; Touzé et al. 2016). However, the density of settlement remained low and fluctuating throughout history considering the rare archaeological evidence found in this area (Schmit et al. 2008; Schmit 2013; Touzé et al. 2016; Schnitzler et al. 2017). This may be related to the local topography and poor sandy soils that probably limited the development of agriculture throughout time. Nevertheless, during the European industrial revolution between the 17th and 19th century, various industries were established there, especially in metal such as forges and timber, such as saw mills (Jéhin 2004). Consequently, these activities directed the use and management of European woodland ecosystems during this period (Hammersley 1973; Kluiving and Guttman-Bond 2012). In

the northern Vosges mountains, charcoal making became a dominant activity in the woods to supply industries such as glassworks, and copper and iron smelting furnaces (Veronnais 1992).

### Sampling strategy

The four studied catchment areas are located in the upper Zinsel du Nord river valley (ZDN), and along its main tributaries. These are the valleys which form the catchments of the Weissbachthal (284 ha), Bitscherthal (209 ha), Aspenthal (186 ha) and Rehbachthal (181 ha) (Fig. 1). These wooded areas were selected because of their location near to ancient metal industrial sites that remained active until the beginning of the twentieth century (Fig. 1; Dupré 2005). The charcoal production sites are flat and oval platforms which were built by the charcoal burners (Ludemann and Nelle 2002). They are mostly visible as specific features of the landscape such as a flatter area within a slope (Ludemann 2012). Thus, in the four studied catchment valleys, CPSs were found and recorded by field surveys and their positions georeferenced at the centre of each platform using a Garmin GPSMAP 64 outdoor GPS device.

About half of the identified platforms were sampled and measured, and selections made so that for each study area, 30 CPSs would be sampled that were widely distributed in the catchment areas and represented as much as possible various topographical situations. At each sampled CPS, the following parameters were measured and recorded: the length and breadth of the platform, which were used to estimate the surface based on the ellipsoid area calculation formula, and the depth of the charcoal layer, which was a mixture of charcoal remains, ash, and in situ soil, and was measured with a soil auger in the centre of the platform.

Pieces of charcoal were sampled manually at five subsample locations within each CPS, by digging holes of about 20 × 20 cm<sup>2</sup> and approximately 20 cm deep, depending on the thickness of the charcoal layer. Two subsamples were taken in the middle of the CPS and three in the peripheral zone, down the slope. This zone was considered to be a charcoal accumulation area of the CPS, where charcoal was removed by the charcoal burners, mainly down the slope in steep places, thus creating a deeper charcoal layer than in the rest of the CPS (Ludemann 2010). From each hole, 30 charcoal pieces were sampled, giving a total of 150 charcoal pieces per CPS.

### Anthracological analyses

For each of the sampled sites, 100 charcoal pieces were randomly selected for anthracological analysis. Each piece was identified by observing the wood structure under a stereo microscope with magnifications 10× to 50× and/or

a microscope with reflected illumination at 100× to 500×, using the charcoal reference collection of the LIEC University of Lorraine (Metz, France) and a wood anatomy atlas (Schweingruber 1990). Identification was possible at least to genus level except for charcoal pieces that appeared to be pieces of pith or bark (Robin et al. 2015). In such cases, the charcoal piece was not counted and another one was analysed. Furthermore, when the fragment was too small, it was sometime not possible to distinguish taxa with similar anatomies, for example between *Salix* and *Populus*, or *Picea* and *Larix*. In those cases, the charcoal was considered as *Salix/Populus* or *Picea/Larix*-type.

Finally, a Principal Component Analysis (PCA) of the CPS charcoal composition was done for the seven most frequently represented taxa, to study the correlations between the various taxa and also to discriminate the four studied areas; Weissbachthal (WEI), Bitscherthal (BIT), Rehbachthal (REH) and Aspenthal (ASP) according to their taxon composition. In addition, the importance of each taxon in the discrimination of catchment composition was measured by partial least squares (PLS) discriminant analysis that gives the variable importance in projection (VIP value). Taxa with a VIP score close to or greater than one can be considered important in the PLS model whereas those with a VIP score significantly less than one can be excluded from the model.

### Dating strategy

The ages of the charcoal pieces were estimated by accelerator mass spectrometry (AMS) radiocarbon dating at the Poznań radiocarbon laboratory in Poland, and calibrated with Oxcal v 4.3 (Bronk Ramsey 2013), using the IntCal13 atmospheric curve (Reimer et al. 2013). A single charcoal piece was dated for each CPS by selecting a sample from a fast-growing taxon or from outer wood, to avoid bias due to the age of the inner wood of large timbers at the carbonisation event (Gavin 2001; Gavin et al. 2003). Dating was carried out for 20 different CPSs of various sizes, topological situations and taxon compositions. At least four CPSs were dated from each catchment area, four each from Weissbachthal and Rehbachthal, and six each from Bitscherthal and Aspenthal.

### Dendro-anthracological analysis

For each of the 100 taxonomically identified charcoal pieces, the original wood diameter was also estimated by measurement of the curvature of the visible growth rings (Nelle 2003; Dufraisse and Garcia 2011; Ludemann 2011). The charcoal pieces were then classified into five diameter categories: ≤ 2 cm; 2–3 cm; 3–5 cm; 5–10 cm; > 10 cm, using a binocular microscope with a calibration eyepiece. In some instances when the sampled pieces were small and

rays or growth rings were not visible, the fragment was counted in the identification, but the diameter class was considered as unmeasurable (NA). From diameter estimates of the individual charcoal pieces, an estimation of the mean diameter (mD) of the wood pieces burned in the sampled CPS was calculated with the following formula (Ludemann 1996; Ludemann and Nelle 2002; Knapp et al. 2015):  $mD [cm] = [n(0-2 \text{ cm}) \times 1 + n(2-3 \text{ cm}) \times 2.5 + n(3-5 \text{ cm}) \times 4 + n(5-10 \text{ cm}) \times 7.5 + n(> 10 \text{ cm}) \times 15] / n \text{ total}$ .

This method for dendro-anthracological analysis was preferred to the use of microscopic imaging software (Dufraisse and Garcia 2011; Théry-Parisot et al. 2011), due to its faster data gathering and processing, as speed of analysis is a critical element for the measurement of the significant number of samples needed for a high spatial resolution dataset. Furthermore, this technique is adapted to the measurement of diameters smaller than 20 cm (Ludemann and Nelle 2002), which was mostly the case for charcoal pieces from coppiced woodlands with small sized trees producing underwood.

### GIS database gathering

Altitude (AL), distance from the closest stream (SD; stream distance), slope inclination (SI), slope exposure (SE) and topographical wetness index (TWI) at the middle of each platform were acquired using QGIS v.2.18.20 with SAGA algorithm extension. Calculation of altitude, slope inclination, slope exposure and topographical wetness index was based on the IGN RGE ALTI 5 M elevation raster map. TWI is a dimensionless variable, commonly used to quantify the effects of topography on hydrological processes from the local slope inclination and the upslope contributing area (Tarboton 1997; Guo et al. 2017). The influence of topographical factors on the distribution of sites was observed by measuring the density of CPSs (n/ha) in classes of value for AL (altitude), SD (closest stream), SI (slope inclination) and SE (slope exposure). AL was divided into 11 classes at intervals of 20 m; SD consists of 16 classes at intervals of 50 m; SI was divided into eight classes of 4°, and SE was separated into eight classes (N, NE, E, SE, S, SW, W, NW) according to the direction of slope, from 0° to 360°. A redundancy analysis (RDA) was done to evaluate the effect of altitude, slope inclination, slope exposure and topographical wetness index on the logarithmic number of the seven most represented taxa using the Vegan package and R software (Oksanen et al. 2018). An analysis of variance was done with ANOVA to estimate the significance of the linear correlations (p-value) between these ecological variables and

each of the taxa, and the taxon composition in the eight exposure classes was studied with a histogram.

## Results

### Chronology of charcoal burning

A total of 20 single charcoal pieces were selected to assess the <sup>14</sup>C dates of the CPSs from the four catchments. No significant chronological separation was found in the dating ranges of 19 of the charcoal pieces, and only one extended period of charcoal production, spanning from the middle of the eighteenth century to the beginning of the twentieth century, was identified for the four studied catchments and for the seven taxa (Table 1). Only CHASP6 dated back to before the seventeenth century, with a dating range clearly distinct those of the other CPSs.

### Spatial distribution of 233 CPSs

During the field work, a non-exhaustive total of 233 CPSs (including the 121 that were sampled) was spatially recorded in the four catchments, with 47 in Weissbachthal, 85 in Bitscherthal, 45 in Rehbachthal and 56 in Aspenthal (Fig. 2, Table 2). These data revealed an average spatial density of 0.35 CPS per ha for the entire area studied. The highest density was recorded in the Bitscherthal catchment with 0.67 CPS per ha and the lowest in the Weissbachthal catchment with 0.17 CPS per ha. CPSs were found at distances from 4 to 718 m from a stream, but 52.7% of the total CPSs were located between 0 and 200 m from a stream, whereas only seven CPSs were found further than 500 m from one (Fig. 3A). This shows a decreasing frequency of sites as the distance from the stream increases.

The altitude in the study area ranges from 200 m at ASP to 415 m at REH, however, all CPSs were between 201 and 395 m, and in all intermediate 20 m classes. Therefore, no altitude was preferentially selected (Fig. 3B). The slope inclinations (steepness) ranged from 0 to 32° in the study area, and all sites had inclinations ranging between 0.2 and 28°, with the density of sites decreasing beyond 20°, and no sites being found in the 28–32°-class (Fig. 3C). For the direction in which the slope faces, the density of CPS varies from 15° (SW) to 50° (W), but does not show any particular pattern. No trend in the direction of slope of a particular site is evident either, even if an important gap is seen between the W and the SW classes, the latter having a CPS density twice as great (Fig. 3D).

**Table 1** Radiocarbon dates of charcoal samples from 20 analyzed CPSs from the four studied catchment areas

Catchment	Lab.code	Taxa	CPS	Age conv. BP	Age cal BP	Age cal BCE/CE
Aspenthal	Poz-108122	<i>Alnus</i>	CHASP4	50 ± 30	269–17	1682–1934
	Poz-101552	<i>Fagus</i>	CHASP18	140 ± 30	281–6	1669–1945
	Poz-108191	<i>Populus</i>	CHASP2	175 ± 30	302–0	1649–1950
	Poz-108124	<i>Alnus</i>	CHASP12	220 ± 30	428–0	1522–1950
	Poz-108123	<i>Quercus</i>	CHASP8	255 ± 30	462–0	1489–1950
	Poz-108192	<i>Fagus</i>	CHASP6	370 ± 30	508–310	1443–1641
Bitscherthal	Poz-99392	<i>Betula</i>	CHAM12	65 ± 30	270–12	1680–1939
	Poz-99393	<i>Pinus</i>	CHAM22	105 ± 30	281–7	1670–1944
	Poz-92262	<i>Salix</i>	CHAM1	125 ± 30	273–10	1677–1940
	Poz-92263	<i>Betula</i>	CHAM6	160 ± 30	286–0	1664–1950
	Poz-92265	<i>Betula</i>	CHAM4	185 ± 30	300–0	1650–1950
	Poz-99395	<i>Fagus</i>	CHAM32	205 ± 30	316–123	1635–1837
Weissbachthal	Poz-99397	<i>Fagus</i>	CHWEI4	90 ± 30	274–9	1676–1941
	Poz-108005	<i>Fagus</i>	CHWEI11	115 ± 30	282–5	1668–1945
	Poz-99396	<i>Pinus</i>	CHWEI2	120 ± 30	283–4	1668–1946
	Poz-108004	<i>Betula</i>	CHWEI10	145 ± 30	287–0	1664–1950
Rehbachthal	Poz-101537	<i>Fagus</i>	CHREH5	70 ± 30	260–26	1691–1924
	Poz-108006	<i>Pinus</i>	CHREH1	75 ± 30	271–11	1679–1940
	Poz-108007	<i>Quercus</i>	CHREH11	170 ± 30	299–0	1651–1950
	Poz-101551	<i>Quercus</i>	CHRE14	175 ± 30	294–0	1656–1950

Ages, calibrated with Oxcal v. 4.3 (Bronk Ramsey 2013) on the IntCal13 atmospheric curve, are given in conventional radiocarbon age before present (conventional BP), calibrated age before present (cal BP) and calibrated year of the current era (cal BCE/CE)

### Size parameters, anthracological and dendro-anthracological analysis of the 121 sampled charcoal production sites

The analysis of the soil layers of the measured CPSs revealed a single charcoal layer at each one, with a thickness ranging from 7 to 60 cm, mean  $28 \pm 13$  cm. Only one site showed two charcoal layers separated by sand and these were anthracologically analysed separately. The possible correlations between CPS area, charcoal layer thickness and topographical variables were assessed by using the Pearson correlation (Table 3). The charcoal layer thickness was significantly and positively correlated with the area of the site and with its distance from a stream, but with a low correlation value in both cases (Table 3).

A total of 12,324 charcoal identifications for the four studied areas have been made. Fourteen different taxa were identified in the charcoal assemblages with a mean of 3.8 taxa per CPS (min 1, max 7). *Fagus* and *Quercus* were the dominant taxa by far, representing 86.6% of the total analysed charcoal pieces and found in 97.5% and 90% of the 121 CPSs, respectively. For six CPSs, *Fagus* was the only identified taxon. Other taxa such as *Betula*, *Carpinus*, *Pinus* (identified as *P. sylvestris*-type), *Populus* and *Alnus* were also identified and accounted for 13% of the total analysed charcoal pieces. *Betula*, however, was observed in 93 CPSs

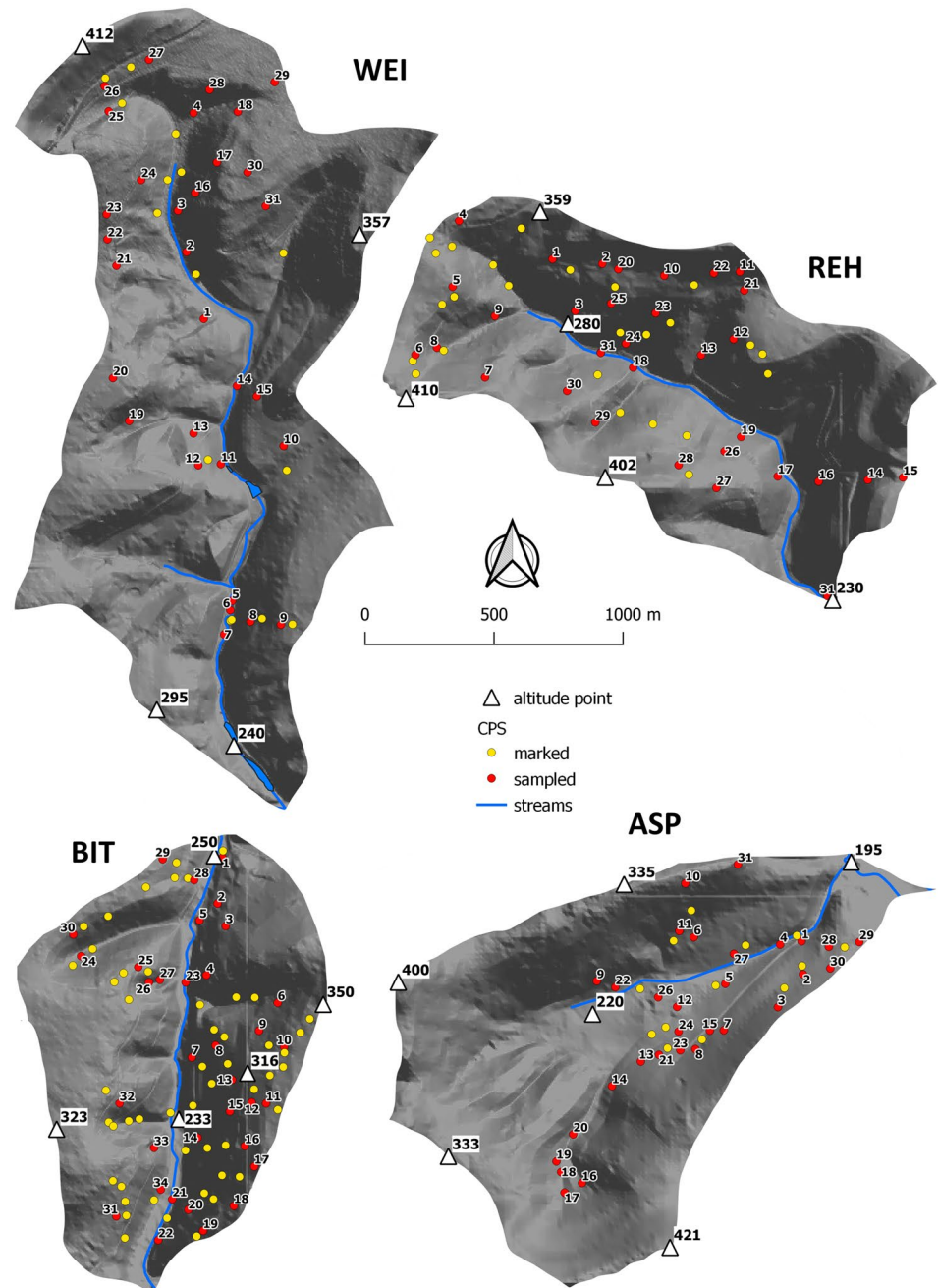
(77%) whereas other taxa were found in less than 40% of the 121 CPSs. *Salix*, *Castanea*, *Tilia*, *Picea*, *Aesculus* and *Euonymus* were rare taxa that were only found in 0.1% or fewer of the assemblages (Tables 2, 4). *Picea* was first identified as *Picea/Larix*-type and then interpreted as *Picea* because spruce is widespread in this area nowadays, while *Larix* has been introduced but is rare.

The estimated mean diameter of the charcoal pieces was 8.07 cm, and the number of pieces increased from the smallest diameter class (n 1,063) to the largest (n 3,756). Among the seven most represented taxa, *Quercus* showed the largest mean diameter (10 cm), followed by *Populus* (9 cm), *Fagus* and *Alnus* (8 cm), *Betula* (7 cm) and *Carpinus* and *Pinus* (6 cm). All the rare taxa had a mean diameter smaller than 6 cm (Table 4), and the diameter was impossible to measure in 793 samples (6.4%).

### Analysis of taxon distribution

A principle components analysis (PCA) was done on the taxon composition. The first factorial plan of the PCA accounts for 50% of the data variability, with the horizontal axis (Dim 1) and the vertical axis (Dim 2) explaining 31.4% and 18.6% of the data variability, respectively (Fig. 4). CPSs are discriminated along the first axis based on the dominance of *Fagus* (right) and *Quercus* (left), whereas the occurrence

**Fig. 2** Detailed maps of the four studied catchment areas with the positions of the 121 sampled charcoal production sites (CPSs) (red), and the 112 identified CPSs (yellow). The blue lines represent streams and triangles are altitude points. Mapping with RGE ALTI57 5 M digital terrain model



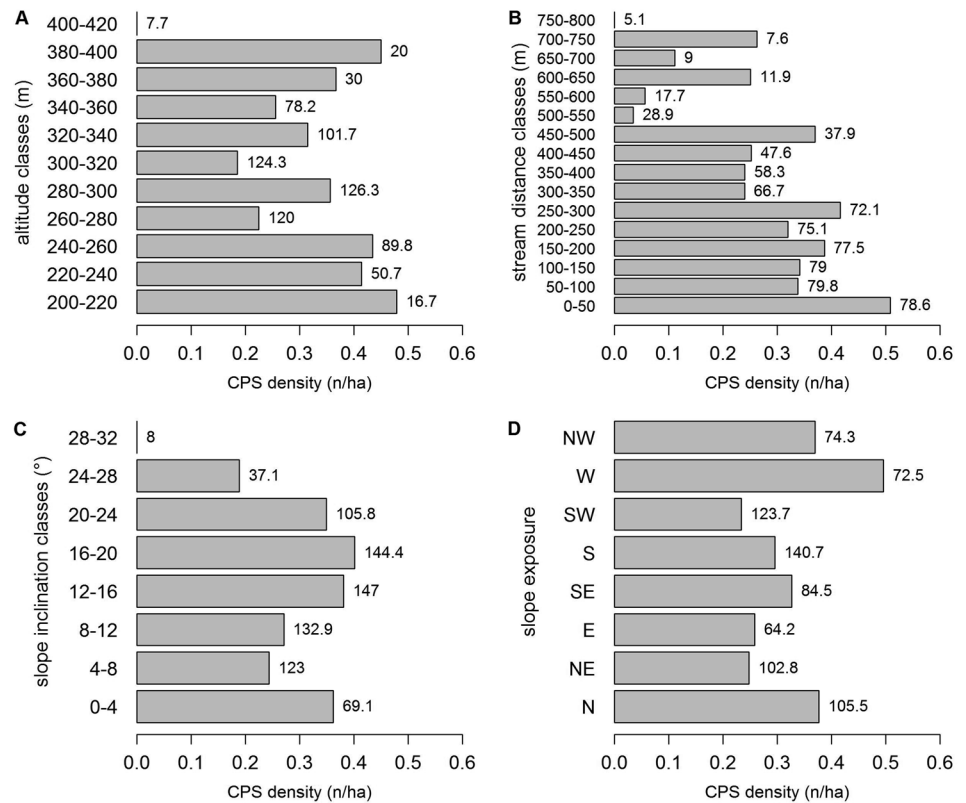
of *Carpinus*, *Populus* and *Alnus* distinguishes CPSs along axis 2. The taxon composition of the two neighbouring catchments of Weissbachthal and Bitscherthal appears to be largely similar, with equivalent proportions of *Fagus* and *Quercus*, and to a lesser extent of *Betula*, while Rehbachthal had a large number of CPSs which were dominated by *Quercus* (VIP taxon importance = 1.4 and 1.21) and a higher proportion of *Pinus*. Aspenthal was characterized by the presence of significant proportions of *Populus* (VIP = 1.44 and 1.41), *Carpinus* and *Alnus*, whereas these three taxa were rare or absent in the other catchments.

In the redundancy analysis of the total variability for the seven most represented taxa, the altitude, slope direction and topographical wetness index showed significant relationships with the proportions of taxa (Fig. 5). Altitude (AL) has the greater effect and is correlated with *Quercus* ( $p = 3 \times 10^{-3}$ ), *Carpinus* ( $p = 2.7 \times 10^{-4}$ ), *Populus* ( $p = 3.8 \times 10^{-2}$ ) and *Alnus* ( $p = 2 \times 10^{-2}$ ). Wetness (TWI) is only significant for *Carpinus* ( $p = 2.5 \times 10^{-3}$ ) with a positive correlation. *Fagus* was not correlated with any variable but shows a negative correlation with *Quercus* (Fig. 4). Other taxon vectors were not well represented and therefore cannot be correlated with these

**Table 2** Number of charcoal pieces of each taxon identified in the sampled charcoal production sites sorted by code number, from Aspenthal (ASP), Bitscherthal (BIT), Rehbachthal (REH) and Weissbachthal (WEI)

Catchment	No.	Fagus	Quercus	Carpinus	Salix	Alnus	Betula	Pinus	Picea	Castanea	Populus	Platanus	Tilia	Aesculus	Evonymus	Catchment	No.	Fagus	Quercus	Carpinus	Salix	Alnus	Betula	Pinus	Picea	Castanea	Populus	Platanus	Tilia	Aesculus	Evonymus			
																																No.	Fagus	Quercus
ASP	1	74	6				16	1			3					REH	1		47				3	50										
	2	53	1				34				12						2	3	93				2	2										
	3	97	1									2					3	14	65					15	6									
	4	74	1	14			4	5				2			1		4	86	11															
	5	78	14	3								5					5	75	16					9										
	6	75	22	3													6	77	15	1				7										
	7	98						2									7	10																
	8	36	64														8	88	3	3				4						2				
	9	94	6														9	49	50					1										
	10	10															10	25	72					1	2									
	11	84	16														11	4	94					1	1									
	12	62	4	16			10	8									12	31	42					14	13									
	13	92	2	2				2				2					13	37	4					3	56									
	14	57	32	1				2				7					14	16	62					22										
	15	93	1	3				3									15	74	26															
	16	83	5	4					3	1		3					16	20	63					10	7									
	18	99										1					18	93	3	2				2										
	19	95	4	1													19	10																
	20	62	20	11								7					20	90	9					1										
	21	38	21	23				13				5					21	18	64					6	12									
	22	10															22	34	58	2				2	4									
	23	10															23	3	94					3										
	24	80	15	3			1					1					24	12	54					20	14									
	25	71		13				1				15					25	39	52					6	3									
	26	72	6	19			1	2									26	87						13										
	28	88	2	4				1				5					28	63	37															
	29	89						11									29	76	20					4										
	30	62						18				20					30	89	3					6							2			
	31	89	8					1				2					31	69	23	3				4							1			
	BIT	1	36	22	32	1	1	8										30	83	8				5										
		2	33	50	10	1		6										31	86	14														
3		38	54				8									31	5	95																
4		2	81				17	6								WEI	1	71	5	6			18	1										
5		49	34	5		1	10	1								2	30	29			3	22	16											
6		84	11				1	3				1				3	77	15				5	3											
7		58	27	1			11	3								4	61	25			3	4	6	1										
8		47	46				7									5	29	37	6			3	8	18	2									
9		74	21				5									7	40	51	5				4											
10		69	9				21				1					8	4	64					32											
12			80				20									9	72	21					1	6										
13		41	56				3									10	1	98					1											
14		72	20				4	4								11	43	1	36				20											
15		24	55	1	1		5	14								12	65	1	28				4						2					
16		14	69				16	1								13	41	56					3											
17		33	59				4	4			16					14	38	31	18				6	6				1						
20		54	27				15	4								15	43	48	3				2	4										
21		72	11	6			3	8								16	68	20		1			11											
22		39	34	4			11	12								17	92	2					1	5										
24		67	2	31												18	91	6					3											
25		83	2	6			8						1			19	37	25	30				8											
26		76	12	10			1							1		20	59	34					7											
27		71	7	18	2		2									21	59	39					2											
28		45	11	40			2	2								22	71	24					5											
29		81	6	7	1		4	2								23	74	22	1				3											
30		80	5	4	1		7	4								24	85	14																
31		81	17	2												25	79	12	4				1				4					1		
32		87	8	3				2								26	95	5																
33		83	14	3												27	100																	
34		76	19	2			2	1								28	25	70					5											
																29	16	77					5	1					1					
		</																																

**Fig. 3** Spatial density of charcoal production sites at each class of altitude (A), distance from the stream (B), slope inclination (C) and slope exposure (D), for the four studied catchment areas. Altitude is divided into classes of 20 m, distance from a stream is divided into classes of 50 m, slope inclination is divided into classes of 4°, and exposure is classified according to the eight directional exposure classes. The area in ha of each class is indicated at the right of each bar



**Table 3** Pearson correlation coefficient ( $r$ ) of area and deposit thickness of charcoal production sites, compared with each other and with geographical factors of altitude, stream distance and slope inclination

	Area	Altitude	Stream distance	Slope inclination
Area	1	0.09	0.08	-0.03
Thickness	0.20*	0.06	0.20*	-0.08

Significant correlations estimated by analysis of variance ( $p < 0.05$ ) are marked with a star

variables. The slope inclination was not well represented in this factorial plan, which means that it does not affect the taxon composition. Other correlation analyses did not reveal any relationship between the size of the platforms, in surface area or charcoal layer thickness, and the taxon composition.

When considering the contribution of the seven main taxa, a clear gradient was observed from the NE to the SE facing slopes (Fig. 6). *Fagus*, *Quercus* and *Betula* were present in all, with a change of dominance occurring from NE to SW. *Fagus* is clearly the dominant taxon in the NE (81%), NW (65%), N (71%), E (74%) and SE (71%). It progressively decreases when the exposure changes to the SW. An opposite pattern was observed for *Quercus*, which is dominant in the SW (60%) and S (52%) facing slopes, and co-dominant with *Fagus* (42%) on W slopes. To a lesser extent, *Pinus* follows the same pattern as *Quercus*, reaching 14% on SW slopes.

## Discussion

### Chronology of charcoal production

A peak of charcoal making in Europe resulting from the high demand for fuel supplies during the industrial revolution and before the transition to the massive use of fossil fuels such as coal has been described in past publications (Kluiving and Guttman-Bond 2012; Madureira 2012; Ludemann et al. 2017). In our study, the estimated ages of the dated charcoal kilns appear to range from the middle of the seventeenth century to the middle of the twentieth century, but we cannot identify distinct shorter periods of charcoal production within these three centuries (Table 1). This is consistent with the identified period of local charcoal consumption. Indeed, in the northern Vosges, iron smelting was active from the 17th to the beginning of the twentieth century (Verronnais 1992; Jéhin 2004), and this is assumed to have caused an increase in the burning of charcoal in the local woods (Rochel 2004; Dupré 2005). Furthermore, the CPSs in the bordering regions of the high Vosges Mountains, upper Rhine region and Schwarzwald were mostly dated to later than the seventeenth century in previous studies (Nölken 2005; Ludemann 2010). In these works, a number of CPSs were also dated between the 10th and the fifteenth century, but they were fewer. The uncertainty range of radiocarbon dating does not allow the detection of short



periods of charcoal making typically related to management of coppiced woodland (Hosier 2003; Borchard et al. 2017; Girardclos et al. 2018). Nevertheless, a continuous or at least regular use of woodland was revealed by observing the soil layers at the sites. These show a single homogenous charcoal layer with no evidence of any soil layers that could have been formed only by a long break in the use of the site (Davasse 1992, 2000; Knapp et al. 2013). Therefore, the local CPSs seem to result from a single, but extended, charcoal production period between the late middle Ages (Deforce et al. 2013) and the twentieth century.

### Spatial distribution of charcoal production sites

The estimated, non-exhaustive, mean spatial density of CPSs in the four catchments is close to 0.35 per ha, which is consistent with that found in Hesse, Germany, where the density is less than 0.3 CPSs per ha (Schmidt et al. 2016). However, this is lower than in the Forêt de Chailluz, southern France, which has an estimated CPS density between 0.4 and 1.5 per ha (Ludemann 2012; Fruchart 2014; Dupin et al. 2017). In these studies, the CPSs were detected by light detection and ranging (LiDAR, airborne laser scanning) and the estimate of their spatial density can therefore be considered as complete. This was not the case in our study however, and the densities provided here are undoubtedly underestimated due to the uncertainty of detection during the field survey. In addition, the sampling effort was stopped when a total of 30 CPSs had been sampled per surveyed area. However, our density estimates for each of the four catchment areas can

be compared with each other, as the sampling method for them was similar. Thus, we found that the total CPS density was higher in the Bitscherthal catchment (0.67 per ha) than in the others (WEI, 0.17; REH, 0.38; ASP, 0.24 per ha). This may be explained by the closeness of this catchment to the old ironworks at Mouterhouse, to which 5,000 ha of northern Vosges woods were allocated for charcoal supplies (Verronnais 1992).

### Size and taxonomic composition of charcoal record

The 8.7 cm mean diameter (mD) of the total charcoal records might be related to the smallest wood diameters conventionally associated with underwood from coppiced woodlands, young trees or big branches (Table 4; Dufraisse and Garcia 2011; Ludemann 2011; Knapp et al. 2013). However, larger mean diameters were observed for *Quercus* (10 cm) and *Populus* (9 cm), and these may correspond to medium size wood (Table 4). *Fagus*, *Betula*, *Alnus* and *Castanea* had diameters of 6 to 8 cm, corresponding to smaller coppiced underwood, young trees and big branches. Less frequent taxa such as *Pinus* (6 cm), *Carpinus* (6 cm) and the remaining rare taxa *Tilia*, *Picea*, *Aesculus* and *Euonymus* which were smaller than 6 cm are more likely to have come from smaller branches (Ludemann and Nelle 2002). Pieces with mDs larger than 10 cm were not found in these charcoal records. This may indicate that any larger trees that may have been present were not felled by the charcoal burners, or that the typical coppiced woods allocated to charcoal production had all

**Table 4** Number of charcoal samples per diameter class (including unmeasurable; NA) for the 14 identified taxa

	Size class						N total	%	N CPS	mD (cm)
	≤2 cm	2–3 cm	3–5 cm	5–10 cm	> 10 cm	NA				
<i>Fagus</i>	660 (9%)	971 (13%)	1,489 (21%)	1,763 (25%)	2,021 (28%)	302 (4%)	7,206	58.7	118	8
<i>Quercus</i>	178 (5%)	243 (8%)	435 (13%)	785 (24%)	1,331 (40%)	332 (10%)	3,304	26.9	109	10
<i>Betula</i>	60 (9%)	73 (11%)	122 (18%)	180 (27%)	146 (22%)	90 (13%)	671	5.5	93	7
<i>Carpinus</i>	76 (17%)	77 (17%)	122 (27%)	83 (18%)	68 (15%)	30 (6%)	456	3.7	47	6
<i>Pinus</i>	73 (23%)	52 (17%)	56 (18%)	56 (18%)	57(18%)	18 (6%)	312	2.5	41	6
<i>Populus</i>	9 (8%)	12 (11%)	16 (14%)	20 (18%)	41 (36%)	15 (13%)	113	0.9	27	9
<i>Alnus</i>		5 (21%)	5 (21%)	7 (29%)	7 (29%)		24	0.2	8	8
<i>Salix</i>	4 (30%)	2 (15%)	5 (39%)	1 (8%)	0	1 (8%)	13	0.1	9	3
<i>Castanea</i>		2 (12%)	6 (36%)	2 (12%)	4 (24%)	3 (16%)	17	0.1	2	7
<i>Tilia</i>		1 (50%)				1 (50%)	2	<0.1	2	2
<i>Picea</i>	2 (50%)	1 (25%)	1 (25%)				4	<0.1	3	2
<i>Aesculus</i>			1(50%)			1 (50%)	2	<0.1	1	4
<i>Tilia/Prunus</i>	1 (100%)						1	<0.1	1	1
<i>Euonymus</i>		1 (100%)					1	<0.1	1	2
Sum	1,063	1,440	2,258	2,897	3,675	793	12,126	1	121	8

The headings indicate; *N total* total number of charcoal pieces, with percentages; *N CPS* number of CPSs where the taxon was identified; *mD* mean diameter (cm) of charcoal pieces of the identified taxa in the 121 sampled CPSs

been fully used in this area (Duhamel du Monceau 1761; Girardclos et al. 2018).

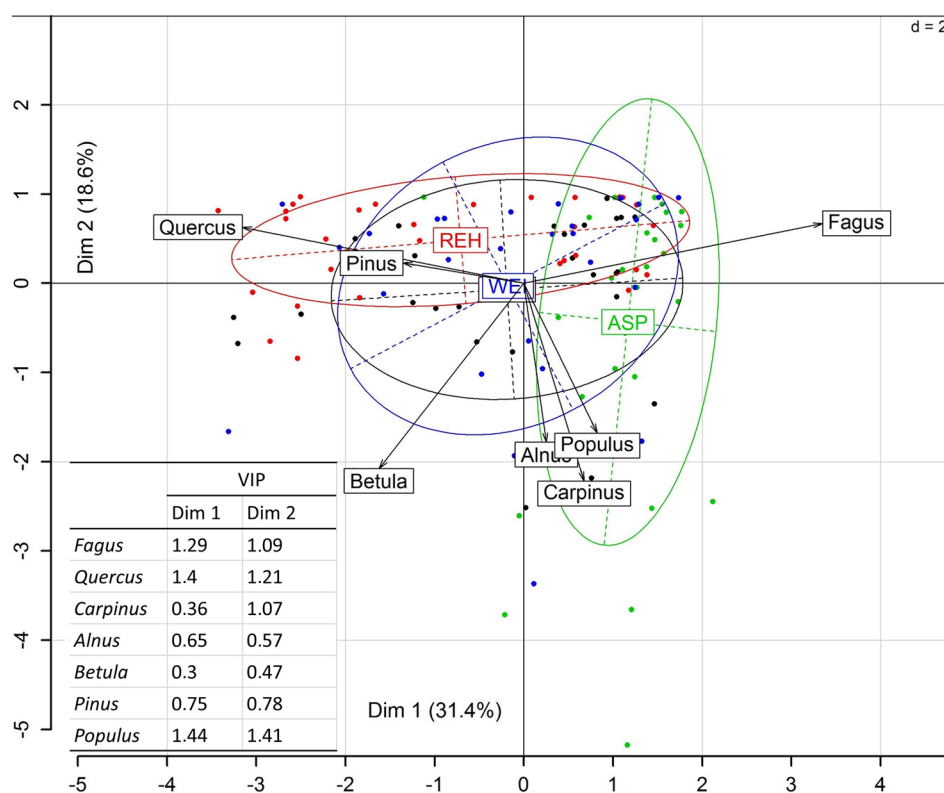
Among the 14 taxa identified in the charcoal records, *Fagus* is largely dominant, followed by *Quercus* and to a lesser extent by *Betula* (Tables 2, 4). These results are similar to the forestry records from the Moselle administrative region which indicate that the three most used trees during the nineteenth century were oak, beech and birch, with a higher amount of oak in the eastern part of Moselle, and a higher amount of beech in the western part (Rochel 2015). Beech is a late successional tree and oak an intermediate one in this region of France (Muller 1986; Richter et al. 1996; Geldreich 2008; Des et al. 2015), as well as in other European countries (Richards 2006; Bonanomi et al. 2018). The proportion of these two taxa is negatively correlated in charcoal assemblages, thus revealing the related presence of both *Fagus* and *Quercus* at the local scale or infra-catchment area (Fig. 4). Birch was also often identified in our charcoal assemblages, being present at 93 sites and representing 5.6% of the total charcoal samples. This is consistent with the regional tree felling records which list birch in moderate amounts (<10%). Unlike *Fagus* and *Quercus*, *Betula* is considered more as a pioneer colonizing tree which needs plenty of light (Mansion and Rameau 1989; Schnitzler and Closset 2003). Its presence could reveal the relatively open and managed nature of the woods during the past period of charcoal making. In

the charcoal assemblages, *Carpinus* (hornbeam), *Pinus* (pine) and *Populus* (poplar) are found in small amounts (<3%) and other taxa are even fewer (<1%). Nevertheless, while 118 CPSs showed a high proportion of beech, our high resolution approach reveals a differentiation between catchments according to the proportions of these latter taxa (Fig. 4). For instance, *Populus* was only found in the Aspenthal catchment, and the name of this valley may have originated from the presence of *Populus tremula*, which is named “espe” in German, “asp” in Swedish and “aspen” in English. The differentiation between this catchment and Rehbachthal may be related to the large amount of *Quercus* in Rehbachthal, which is rare in Aspenthal (Fig. 4). In the two catchments of Bitscherthal and Weissbachthal, the charcoal assemblages are very similar. The results of this approach at a high resolution scale confirm that the charcoal spectra of CPSs record specific patterns of local woodland composition (Ludemann 2010).

### From past vegetation to actual woodland composition

The taxon spectra of the charcoal records show large differences with the composition of the current vegetation. For example, based on data from the Institut National de l'Information Géographique et Forestière (IGN), conifers (*Pinus sylvestris*, *Picea abies*, *Abies alba*, *Larix decidua*)

**Fig. 4** Principal Component Analysis (PCA) of the proportion of the seven most represented taxa in the charcoal production site (CPS) assemblages. Each point corresponds to a single CPS. Clusters represent the four catchments where CPSs were found. Each point and cluster colour is related to a single catchment as follows, black, Bitscherthal (BIT); blue, Weissbachthal (WEI); red, Rehbachthal (REH); green, Aspenthal (ASP). The lengths of the vector lines corresponding to the taxon proportions are multiplied by four in order to be more visible on the diagram. The importance of variables in the projection (VIP) of each taxon for the two dimensions are given in the associated table on the lower left corner of the figure



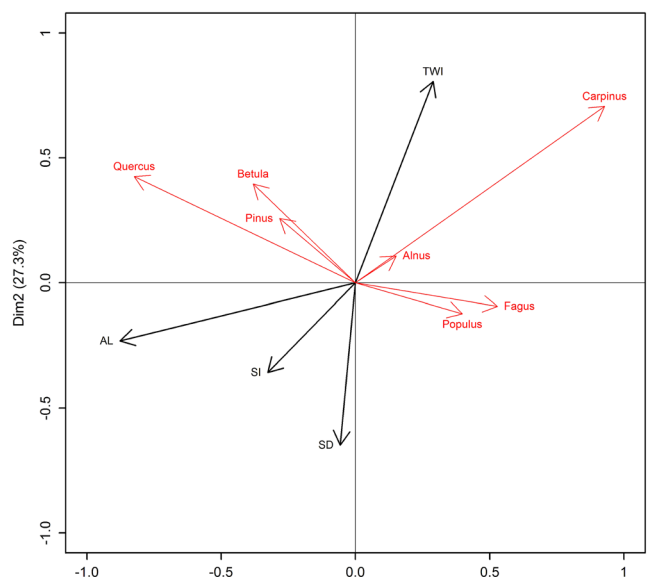
currently cover at least 26% of the studied area, yet only 2.5% of charcoal pieces were coniferous types (*Pinus*, *Picea*). On the other hand, deciduous taxa, which represented more than 97.5% of the charcoal pieces, currently cover only about 55% of the area. There are two possible explanations for the scarcity of conifers in the past compared to the present time. First, these trees may have been more widely present but were not selectively felled to make charcoal. This hypothesis is unlikely to be valid since other studies conducted in the high Vosges mountains in France and in Belgium and Germany have demonstrated that conifers are found in large proportions in local charcoal assemblages (Nölken 2005; Ludemann 2010; Deforce et al. 2013), showing that they were used for charcoal burning. The alternative hypothesis is that these conifers were scarce at the time of the charcoal burning, which is corroborated by Rochel (2004, 2015), who showed that they were not found in the local administrative records. Therefore, the conifers can be considered to have been rarer in past woodland ecosystems than nowadays. Comparing our results with other natural records such as from pollen could give us complementary information about the absolute tree composition (Robin et al. 2013). Nevertheless, considering that charcoal records are representative of historical tree communities, we can propose that this woodland resembled a late succession stage of natural woodland two centuries ago, characterized by a higher dominance of *Fagus* than now. The composition of present day woodlands may have been influenced by past management with forestry practices which influenced natural re-establishment of trees, thus favouring conifers.

**Fig. 5** Redundancy Analysis (RDA) of the correlation between the proportion of the seven most represented taxa (red vectors) in the CPS and four explanatory variables, altitude (AL); distance from closest stream (SD); slope inclination (SI) and topographical wetness index (TWI) at the CPS position (black vectors)

## Effect of environmental variables on CPS density and distribution of taxa

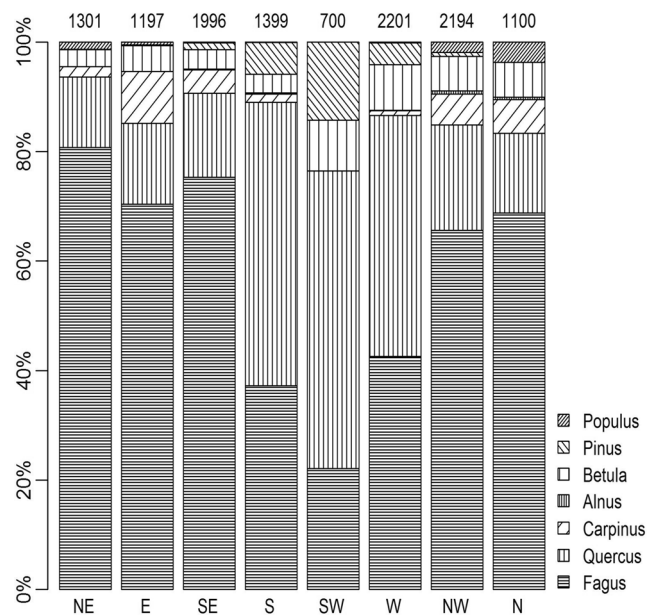
The charcoal production sites appear not to be randomly distributed. Comparing the CPS distribution of the four catchments, the higher density of sites in the Bitscherthal catchment seems to indicate that they were preferentially situated nearby (< 5 km in this case) the places where the charcoal was used, such as iron works (Fig. 1). At the catchment scale, CPSs are preferentially situated close to the valley bottoms. Sites have indeed been found in all the classes of distance from the stream up to 750 m away, with only the Aspenthal catchment having one beyond this distance (Fig. 3). The highest density of CPSs (0.58 n/ha) was observed in areas within 50 m of a stream and it decreased with increasing distance from the watercourse, with only eight sites further than 500 m away. The area of the catchment located in the furthest distance classes (> 650 m) is very small (less than 10 ha), compared to the area closer to a stream (between 70 and 80 ha are within 300 m of one). This suggests a preferential siting of CPSs near streams. Furthermore, nine sites (3.7% of the total number) have been found less than 10 m from a watercourse, with sometimes direct erosion of the platform by the stream. The need for water to manage the charcoal burning process and for supplying the charcoal makers can explain this preferential placing of sites near streams (Duhamel du Monceau 1761; Davasse 2000; Paradis-Grenouillet 2012).

Areas with a high slope inclination (28° to 30°) were avoided because platform building and charcoal delivery would be too hard on such steep slopes (Duhamel du Monceau 1761; von Berg 1860; Schmidt et al. 2016). This non-random pattern of CPS distribution has also been found in northwestern Europe, for instance in Belgium and Germany



(Deforce et al. 2013; Schmidt et al. 2016). In contrast, the distribution of CPSs in the Mediterranean region has been found to be more homogeneous (Allée et al. 2010; Carrari et al. 2017). Such trends and interpretations should be confirmed by more exhaustive surveys of sites using LIDAR data (Ludemann 2012; Schmidt et al. 2016; Dupin et al. 2017).

At the tree stand scale, and due to the characteristics of the natural ecological niches of the various tree species, the composition of the woodland is affected by temperature, exposure to the sun, water availability, soil pH and nutrient availability (Barbour et al. 1980; Mansion and Rameau 1989; Richter et al. 1996). Altitude, which in this study is correlated with distance from a stream (Table 3), is negatively correlated with the topographical wetness index (TWI) (Fig. 5). Altitude can be considered as a moisture gradient of the ground rather than a temperature gradient because of the low elevation ranges of the studied areas. *Carpinus*, and to a lesser extent *Alnus*, showed a high correlation with TWI and therefore these were present on low-lying land. This result is consistent with the ecological needs of hornbeam for deep alluvial soil layers with moderate acidity (Mansion and Rameau 1989; Thomas et al. 2002). Conversely, *Quercus* is more present at higher altitudes. *Quercus petraea* is known to be tolerant to dryness while *Q. robur* needs more moisture (Barbour et al. 1980; Muller 1986; Mansion and Rameau 1989). A co-dominance of oak and beech was indicated by the principle components analysis (PCA) (Fig. 4) and the redundancy analysis (RDA) of taxonomic diversity (Fig. 5), and sun exposure seems to have been a critical factor which determines the tree community by favouring oak dominance in areas exposed to the sun (Fig. 6). Indeed, *Fagus* is widespread and dominant in the total CPS spectra, but is replaced by *Quercus* and *Pinus* on the sun-exposed slopes which face south. *Quercus robur* and *Q. petraea* are less tolerant of being shaded than *Fagus sylvatica*, and according to Muller (1986), the Luzulo-Fagetum community of beech woodland has a preferential distribution on north-facing slopes where it becomes naturally dominant. Our charcoal records confirm this (Figs. 2, 6). Furthermore, according to Muller (1992), the Luzulo-Quercetum oak woodland and Leucobryo-Pinetum pine woodland communities are typically present in areas with unsuitable conditions for *Fagus* to grow, with a dominance of *Quercus* in sunny areas and of *Pinus* on peaty soil. This may explain the occurrence of *Pinus* or *Quercus* in our charcoal records according to the direction faced by the hill slope (Fig. 6). As earlier studies have discussed results at a local, rather than a regional scale, the importance of considering CPS analysis at a high spatial resolution is highlighted here.



**Fig. 6** Proportion of the seven most represented taxa in the CPSs, according to directional exposure classes. The total number of charcoal pieces per class is indicated on the top of each class bar

## Conclusions

The anthracological analysis of charcoal producing sites is known to yield useful data about recent woodland history. However, the bias of human wood selection and the very local origin of burned wood must also be considered for the interpretation of anthracological data. Analysing a large number of CPSs in a restricted area can be a valuable way to avoid this bias and to produce robust data for this historical period. Such a high density of CPSs was found in the northern Vosges mountains, and is strongly related to local industrial activities there between the 17th and the twentieth century. The anthracological study of CPSs revealed that in the Zinsel du Nord valley, the woods were dominated on a landscape scale by *Fagus* and *Quercus*, and it is assumed that woodland management and forestry led to an increase of conifers to the present day. Furthermore, at a higher spatial resolution, taxonomic composition at a slope scale was found to be affected by the elevation and orientation of the slopes. This result is consistent with the assumption that charcoal records from producing sites show a high dependency on local wood resources, which are themselves dependent on the local topographical conditions. The fine analysis of CPS distribution also revealed a non-random distribution pattern of charcoal deposits, characterized by an increase in site density close to streams. These results allow us to confirm the paramount importance of analysing large numbers of widely distributed CPSs in the studied area.

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