Charcoal analysis and dendrology: data from archaeological sites in north-western France

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Abstract

During the last 15 years, charcoal analysis of archaeological sites in north-western France has been carried out in conjunction with systematic and detailed dendrological examination. By considering these extrinsic criteria in association with the analytical results, palaeo-ethnographic and palaeo-environmental information can be obtained. The charcoals are classically identified under the microscope on the basis of their cellular structure. This examination is associated with an observation of the ligneous structure on transverse sections using a binocular lens. When charcoal fragments are large enough, the growth ring widths are measured. Tree ring curvature is also noted. Finally, alteration by fusion or radial cracks, the presence of fungal hyphae, and insect degradation are also recorded. Results are thus obtained on the nature of fuel used in domestic fireplaces and kilns. The selection of timbers and their catchment areas are also revealed. The average width of the growth rings in oak charcoal from domestic hearths coming from about forty sites in north-western France shows a significant increase from 6000 to 2000 BP. There is a similar increase in the number of heliophilic taxa used from the Neolithic to the Iron Age. This implies that the environment became more and more open because of use by society. The interpretation of the dendrology results applied to charcoal analyses is obtained through a convergence of criteria. Thus, charcoal analysis can provide more than just an identification of the species used, and can yield fundamental information on the interaction of society with the environment.

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1. Introduction

During prehistoric times, societies established an economy based on firewood. Therefore, charcoal analysis is an efficient approach for studying the relationship between people and the environment, reflecting the customs and techniques of management of ligneous vegetation. The collection of wood relates back to the knowledge of its physical properties or to an attitude motivated by traditions. However, the environmental conditions are decisive in controlling the availability and quality of any exploitable ligneous biomass. Charcoals are excellent indicators of exploited environments and the vegetation that developed within them.

1.1. Brief history of anthracology

The first identifications of charcoals were carried out using samples from archaeological sites in Switzerland, Germany and Hungary during the 19th century. In France, the forerunners of anthracology were Dangeard (1899) and Fiche (Breuil, 1903).

The application of episcopic microscopy to charcoal analysis led to the analysis of large quantities of charcoals (Dimbleby, 1967; Fietz, 1933; Stieber, 1957; Western, 1963). The first global studies on prehistoric charcoals of anthropic origin were carried out in the south of France, and later
in Spain by Vernet (1972) and his students. More recently, charcoal analysis has been used to study the relationship between humans and forests through the economy of fuel. Methods used for the study of firewood economy are in constant progress and many archaeological contexts are now studied. In this spirit, charcoal analysis of archaeological sites in north-western France has been systematically carried out for about 15 years using detailed dendrological examination (Marguerie, 1992). Marguerie and Hunot supplemented the taxonomic identification of charcoals by the study of rings as well as the origin and state of the wood before carbonization, thus providing palaeo-ecological and palaeo-ethnological information. This approach was referred to as a “dendrotypological” study by Billamboz (1987, 1992), who applied it to waterlogged woods of the lake-dwelling settlements of the Bodensee (Germany). He highlighted the first models of Neolithic forestry economy. This kind of approach was taken up again and developed in the Paris Basin (Bernard, 1998).

More recently, Bernard et al. (2006) worked on the effect of trimming and pruning on ligneous productivity by studying the radial growth of deciduous oaks.

After Lundström-Baudais, Dufraisse (2002) analysed the analysis of charcoals from the Mesolithic site on Teviec Island in Brittany (France) and, several years later, on the nearby Hoedic Island (Pé quart and Pé quart, 1954; Pé quart Island in Brittany (France) and, several years later, on the radial growth of deciduous oaks.upe et al., 1937). At these sites, Guinier recorded the presence of twigs, branches and trunks of oaks and Pomoideae. Furthermore, he noticed that several oak charcoals had marks of lopping. Salisbury and Jane (1940) studied a large number of charcoals from Neolithic and Iron Age layers from Maiden Castle in Dorset (U.K.). They measured nearly two thousand growth rings of oak and hazel charcoals and compared the results with the annual rings from recent specimens of the same species to obtain “evidence regarding the climatic conditions of the past by means of the width of the annual rings”. In the cave of Lascaux (Dordogne, France), Jacquirot (1960) systematically observed the aspect of rings of the charred wood. In this way, he obtained information about climate, density of forests and diameters of wood used.

In her analysis of charcoal from the Neolithic sites of Clairvaux-Les-Lacs (Jura, France), Lundström-Baudais (1986) developed a method to evaluate the maximum diameter of wood used based on the observation of tree ring curvature. After Lundström-Baudais, Dufraisse (2002) analysed the ring curvature of samples from the lake-dwelling sites of Chalain and Clairvaux to estimate the calibre of woods converted into charcoals. In Cabrières (Southern France), using construction wood (16th c.), observation and measurement of ring curvature were used to calculate the minimum diameters, with oak samples having the greater dimensions. By contrast, the samples with bark came from small twigs of coppice (Durand, 2002). In the study of the historic charcoal kiln sites in the Southern Black Forest and Bavarian Forest (Germany), Ludemann and Nelle (Ludemann and Nelle, 2002; Nelle, 2002) used a diameter stencil to estimate the original minimum diameter of the charcoal pieces.

Over a few years, dendrological analysis applied to carbonized wood became increasingly employed and concerned not only charcoals coming from archaeological sites but also those found in natural soils (Bégin and Marguerie, 2002).

The aim of this paper is to present methods used for dendrological studies of wood charcoal and give examples of palaeo-ecological and palaeo-ethnographical results obtained by dendro-anthracology in north-western France during the last 15 years.

2. Methods

There are numerous origins of charcoals from archaeological sites (Fig. 1):

- domestic fireplaces,
- craft combustion structures such as kilns,
- post-holes, pits or ditches,
- archaeological layers,
- burnt objects.

After sampling with the surrounding sediment, the charcoals are classically identified on the basis of their cellular structure under a reflected light microscope. To this determination, we add a systematic examination of the ligneous structure on transverse sections using a binocular lens (magnification 7 to 90×). This dendrological approach gives valuable data for aiding identification of the part of the woody plant the charcoals came from, recording the growth ring width, ascertaining the state of the wood before carbonization and about visible working marks where possible. A coding grid table is compiled for all transverse sections of charcoal samples of sufficient surface area having a readable record (Table 1) (Fig. 2).

2.1. Charcoal state

2.1.1. Presence of bark and pith

For fragments having both bark and pith, it is possible to measure a complete radius and estimate the calibre of the stem from which it came (Fig. 2A). Evidently, it is necessary to take into account the reduction of size caused by combustion (see Section 2.3.1).

2.1.2. Presence of reaction wood

Reaction wood can be observed in a branch or leaning trunk (Fig. 2B). To avoid drooping under their own weight, these stems develop eccentric growth (Wilson and White, 1986; Zobel and Van Buijtenen, 1989). In reaction wood, the walls of the tracheids are thick and show radial grooves on their inner surfaces. In longitudinal sections of the charcoal fragments, they appear as conspicuous parallel striations obliquely aligned to the cell axis, commonly at an angle of about 40–45°, thus forming helices around the cell. These features are clearly visible in the coniferous charcoals. The observation of reaction wood in charcoals indicates the origin of the fragments within the tree. Associated with strong ring curvature, this criterion demonstrates that the charcoal originates from a branch.
2.1.3. Presence of tyloses

In the transition zone between sapwood and heartwood, living cells of axial or ray parenchyma adjacent to vessels may grow out through the pits into the vessel cavity, forming tyloses (Fig. 2C). When this phenomenon becomes intense, the vessel cavity may become filled with a close-packed cellular structure, blocking it completely (Wilson and White, 1986). These extensions of the parenchyma cells, mutually compressed into irregular prismatic shapes, are very clearly visible under the light microscope. In charcoals, the tyloses are refractive. Such features can be readily observed in oak. This type of systematic observation indicates that the charcoals were derived from heartwood.

2.1.4. Presence of fungal hyphae

In longitudinal sections of vessels, white filaments can sometimes be observed (Fig. 2D). These correspond to fungal hyphae that penetrate into the dead or dying wood under aerobic conditions from fungus living on the surface. The fungal attack takes place over several hours or days in the parts of the wood not protected by bark. This process is all the more rapid when temperatures are high (in summer) and when wood humidity is about 70-90\% (Schweingruber, 1982). This observation gives information about the state of wood before carbonization. It is rare or impossible to find hyphae in the heartwood of oak and some other species with numerous tyloses.

Table 1
Example of coding grid for dendro-anthracological analysis

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Code</th>
<th>Species</th>
<th>No. of rings</th>
<th>Total width of rings (mm)</th>
<th>Rings bendinga</th>
<th>Carbonizationb</th>
<th>Hyphaec</th>
<th>Insect degradationc</th>
<th>Pithd</th>
<th>Barkd</th>
<th>Tylosesd</th>
<th>Reaction woodc</th>
<th>Working marksd</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Quercus sp.</td>
<td>5</td>
<td>4.74</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Quercus sp.</td>
<td>15</td>
<td>10.23</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>Juglans sp.</td>
<td>2</td>
<td>4.74</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
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</tr>
<tr>
<td>4</td>
<td>9</td>
<td>Fagus sylvatica</td>
<td>1</td>
<td>4.74</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>Corylus avellana</td>
<td>12</td>
<td>6.76</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>27</td>
<td>Ilex aquifolium</td>
<td>7</td>
<td>3.12</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a 1 = low curve rings; 2 = intermediate curve rings; 3 = strong curve rings.
b 1 = radial cracks; 2 = low brilliance; 3 = strong brilliance.
c 1 = "yes".
Fig. 2. Scanning electron micrographs showing systematically observed dendrological criteria. (A) Stem of archaeological charred oak (Quercus sp.) with bark and pith; (B) coniferous charcoal (Picea mariana) with reaction wood in tracheids; (C) tyloses in archaeological oak heartwood charcoal; (D) fungal hyphae in vessels of charred oak sapwood; (E) tunnels of wood-boring insects or woodworms in Scots pine (Pinus sylvestris); (F) radial cracks in a white spruce charcoal (Picea glauca); (G–I) different degrees of vitrification in archaeological charcoals; (J, K) different tree ring curves in archaeological charred oaks: (J) weakly curved rings, (K) moderately curved rings; (L) large rings and narrow rings in archaeological oak charcoal; (M) working mark on a charcoal from an incense-vase.
2.1.5. Presence of insect degradation

In some charcoals, tunnels are sometimes observed (Fig. 2E). Dimbleby (1967) mentioned that, in some Neolithic charcoals, irregular patterns of large holes could result from some wood-boring insect or woodworm degradation. Sometimes, it is possible to find beetles within these channels. Even when the animal is not preserved inside, the aspect of the channels can nevertheless indicate, not without some difficulty, the species of insect or worm that lived there (Serment and Pruvost, 1991). The presence of many such channels in charcoals is a good indicator of the combustion of drifted dead wood. In their study of charcoals from Maiden Castle (Dorset, U.K.), Salisbury and Jane (1940) mentioned that the wood employed was “dead wood rests” because the charcoals contained “bore-holes filled with carbonized frass”, the result of the activity of “beetle larvae of the type which attack dead and not living wood”.

2.1.6. Presence of radial cracks

Radial cracks are often common in charcoals (Fig. 2F). Their frequency depends on the anatomy of the wood (more frequent in the case of dense and large rays), the location in the wood (less frequent when close to the pith), the level of wood dampness (consequence of the discharge of “closed water”) and temperature (Théry-Parisot, 2001). According to Prior and Alvin (1986), the carbonization of waterlogged wood favours a substantial increase in the number of radial cracks.

2.1.7. Presence of vitrification features

The vitrification of charcoals corresponds to a variable fusion of anatomical constituents within the wood, leading to homogenisation of the structure that makes identification impossible when the process reaches its final stage. The vitrified charcoals become very dense and refractive with “sub-conchoidal” fractures. Many stages of alteration by fusion are known, ranging from a still-recognisable anatomical structure to a dense mass, completely molten and non-determinable (Fig. 2G–I):

- low brilliance-refractiveness (degree 1),
- strong brilliance (degree 2),
- total fusion—dense, non-recognisable mass (degree 3).

The fusion may be associated with radial cracks. Vitrification often affects small pieces of wood such as twigs. Rapid combustion at high temperatures frequently causes tissue deformation, fissures and fusion (Schweingruber, 1982). But, more generally, this alteration of the anatomical structure by fusion may result from specific conditions of combustion or taphonomy, and can reveal the state of the wood before combustion. There appear to be numerous types of conditions affecting fusion, and many anthracologists are currently attempting to understand this phenomenon in all its aspects.

2.2. Evaluation of growth-ring curvature

The evaluation of tree-ring curvature (and the angle of the rays) enables us to identify which part of the tree was used. For example, a weak or smooth curve corresponds to the tree trunk (Fig. 2J), while a strong or marked curve corresponds to the branches (Fig. 2K).

The ring curvature is estimated according to a standard classification: with a constant magnification and using a transparent test card placed on top of or under the fragment (Fig. 3). To apply this method, it would appear necessary to have a minimal tangential width of charcoal of around 3 to 4 mm to estimate the approximate parallelism of rays, or a radial length of 5 mm to estimate the curvature of the rings. These minimal conditions are not necessary when the fragments have both pith and bark and therefore correspond to a branch or twig.

Charcoals are divided into four groups, which exhibit:

- strongly curved rings,
- moderately curved rings,
- weakly curved rings (at this observation scale, the rings seem “straight” and the rays parallel),
- indeterminate curvature (on fragments without minimal conditions).

While such an approach reveals trends, it is not a measurement of the diameter of the wood, but merely a characterization. In one case, it was possible to measure the wood section (where pith and bark appear together in a charcoal; see Section 2.1.1). More generally, abundant charcoals with strongly curved rings in one sample indicate the use of small calibre wood or

![Fig. 3. Test card for evaluation of tree-ring curvature.](image-url)
branches. On the other hand, the predominance of charcoals with weakly curved rings suggests the use of large calibre wood such as trunks or large branches. Finally, by combining the criteria of ring-curvature and the presence of bark, pith or reaction wood, it is possible to demonstrate the use of branches.

2.3. Growth ring width

2.3.1. Measurement of growth ring width

When charcoal fragments were large enough, we systematically measured the growth ring widths (Fig. 2L). The average growth ring width can provide information on the growing conditions of the trees:

- narrow rings correspond to restrictive growing conditions,
- large rings indicate favourable growing conditions.

The average growth ring widths were only measured on charcoal samples with a weak curvature of rings (derived from trunks or large branches, far away from the pith), and with regular width rings. This measurement was indeed impossible on branches or small stems with eccentric growth because of the development of reaction wood. The ring widths are thus highly variable on two opposite rays. Furthermore, the rings near the pith are always thicker than the outer rings. In their response to Salisbury and Jane’s paper (1940), Godwin and Tansley (1941) put forward serious criticisms about the method of handling the tree-ring data obtained from specimens of young stems. They considered it was imprudent to ignore “the progressive diminution of tree-ring width with the age of the tree”. They suggested that comparison of ring widths is “valid only for the outer rings of large trees”.

2.3.2. Intra-site frequency distribution of the charcoal ring-widths

In one sample of charcoals, an average ring width was calculated for each charcoal sample of readable and measurable rings. Thus, we obtained as many average width values as measurable charcoals. This procedure minimizes the influence of extreme values and reveals trends in the growth of woods.

A bar chart is used to represent these measurements by classes of 0.25 mm or 0.5 mm for each taxon and for each sample of charcoal. Measurements were mainly performed on samples with substantial numbers of charcoals (>50 fragments with measurable rings). If not, there would be an excessive risk of taking exceptional rings into account.

It is interesting to characterize the distribution of these values for each taxon within a site and note their approximate dispersion using descriptive statistics. A unimodal distribution of these classes is interpreted as indicative of a homogeneous stand or a single tree (Fig. 10a). On the contrary, a multimodal distribution is interpreted as a heterogeneous community of trees or several populations (Fig. 10c).

Finally, it is possible to produce growth curves for large charcoals that contain dozens of rings. This method, for example, allows us to ensure that charcoals come from a single tree and assemble fragments with the same ring-width patterns coming from the same stand (Morgan, 2000).

2.3.3. Validity of the growth-ring width measurement modified by carbonization

Combustion processes have some effects on the morphology of the wood. While the size and shape of wood constituents can vary, the qualitative anatomical characteristics remain the same (Beall et al., 1974). The deformation of the charcoal microstructure varies with wood species. The loss of 70–80% of the substance of the wood causes a shrinkage of 7–13% longitudinally and 12–20% radially/tangentially. The cell wall is reduced to 1/5–1/4 of its original thickness (Schweingruber, 1982).

In 1940, Salisbury and Jane converted recent specimens of hazel stems into charcoal and measured the width of the annual rings both before and after carbonization using various techniques (slow and rapid combustion). These authors concluded that the widths were “not significantly different whatever method was employed to produce the charcoal” (Salisbury and Jane, 1940). Based on these data, it would appear possible to measure the radial growth that can be observed on transverse sections of a charcoal and compare these measurements from one charcoal to another. In any case, the present study does not aim to compare the absolute values measured on charcoals with data obtained from fresh or waterlogged wood.

In practice, we were able to measure the average ring-width with an electronic calliper or a dendrochronological digital positioning table (accuracy: 0.01 mm) by examining the ligneous structure of charcoals on transverse sections with a binocular lens. To compare these two methods of measuring the average ring width, we measured 161 fragments of oak charcoals (834 growth rings) from a Roman archaeological site (Allonnes, Sarthe). The extremely close similarity of results obtained shows that it is not possible to favour one of these measuring systems above the other (Table 2).

To improve our knowledge of the growth conditions, it is becoming increasingly necessary to measure systematically

| Table 2 | Comparison of two dendrological measuring systems for growth ring width |
|-----------------|---------------------|---------------------|--------|--------|--------------|
|               | Mean (mm) | Standard deviation | Min. (mm) | Max. (mm) | N charcoals | N rings |
| Electronic calliper | 1.64 | 1.14 | 0.2 | 6.53 | 161 | 834 |
| Dendrochronological table | 1.65 | 1.29 | 0.17 | 6.31 | 147 | 521 |
Fig. 4. Location map of the study sites.

Fig. 5. Percentage charcoal diagram for domestic fireplaces of north-western France. Upper diagram: Neolithic structures; lower diagram: Iron Age structures; black dots correspond to sparsely occurring taxa (≤1%).
within the growth ring of a charcoal (i.e. the width of early and late wood, vessel area, vessel density, frequency of rays, etc.). Such measurements should be automated as much as possible to facilitate the acquisition of results on many charcoals. From this perspective, and following an initial study by Vernet et al. (1983) on ring morphology in olive tree charcoals, Terral, 1999, 2002) used an eco-anatomical approach with morphometric analyses of wooden archaeological material to determine the origin of cultivation of olive trees and grapevines in the western Mediterranean region.

3. Results

Examples of dendrology applied to anthracology are taken from the studies of sites located in north-western France, most of these being located in Brittany. Around seventy archaeological sites have now been studied in this area (Fig. 4).

3.1. Palaeo-ethnographic information

3.1.1. Fuel

3.1.1.1. Fuel from domestic fireplaces. We considered the contents of charcoals from twenty domestic fireplaces situated at 12 archaeological sites in Brittany and Normandy (Fig. 4). They correspond to Neolithic burial sites or rural settlements of the Iron Age (Marguerie, 2003).

The studied fireplaces contain wood representing from one to nine taxa. Oak is found in 14 of the structures (Fig. 5). From 48% to 100% of oak charcoals in Neolithic fireplaces had weakly curved rings and originated from wood of large calibre. On the other hand, in the only example from the Iron Age where we could carry out this kind of examination, the oak charcoals have strongly curved rings in 89% of cases (Fig. 6A). Taking all the taxa together, the Neolithic structures...
contain wood of large or medium calibre. On the contrary, charcoals from the two Iron Age structures are of small cross-section (Fig. 6B). During the Iron Age, the use of stems with small cross-section was also the consequence of exploiting shrubs and small trees.

3.1.1.2. Fuel of kilns. The anthracological study of craft structures is based on material from 12 settlements (Fig. 4). The archaeological sites dated chronologically from the second Iron Age to the late Middle Ages. Twenty combustion structures were studied. They can be categorized into four groups of kilns: ceramic or tile, glass, metal and lime (Marguerie, 2002).

A taxonomic richness factor from one to seven is observed in the studied sites (Fig. 7). The tree ring curvature systematically observed indicates that the oak charcoals in craft structures originated from large-diameter timber (Fig. 8). In the case of the beech charcoals, fragments in the pottery kilns also came from tree trunks. Some oak and beech charcoals from the pottery kiln of La Haute-Chapelle display radial cracks (13.5%). On the contrary, such features are totally absent from the oak charcoals of the lime kilns of Jouars.

Shrubs or small trees such as hazel, Pomoideae, Prunus, birch, maple, broom and alder provide high flames over a short time when tied up into bundles. The “big fire” obtained in this way produces a high temperature. Gallo-Roman potters used some plant materials with fast combustion, such as straw, reed, heather, bark or pine cones, to obtain a high and very hot flame yielding a rapid rise in temperature. When added to the “small fire”, this additional plant-based fuel produced the “big fire” needed for the main firing process (Brongniart, 1977; Le Ny, 1988; Pillet, 1982).

The cellular tissue of some oak (15%) and beech (23%) charcoals found in the metal kilns of La Bazoge had been molten (vitrified). In the bell kiln of Ambon, more than 50% of oak charcoals were “vitrified”. The molten or vitrified features of some oak and beech charcoals suggest that some metal kilns could use burning charcoal and not exclusively wood. This hypothesis must be tested by identifying the origin of the process involved the vitrification of charcoals. The vitrification process is not yet well understood and its association with burning charcoal not clearly established. For the metalworking craft industry, the heat needed to be stable and intense.

In the “Ambroise Paré” site (Rennes), the excavation of a Roman kiln has yielded oak charcoals produced from large branches (Guitton et al., 2002). The majority of these have weakly curved rings and an average age of 15 years. They are assumed to be contemporaneous, representing the last phase of the kiln activity. For some of the charcoals, it was possible to measure the growth ring widths using a dendrochronological table (Lintab Rinntech). Matching the average dendrochronological curve for Ambroise Paré (M1: 36 years long), which groups together nine curves, was facilitated by the presence of one charcoal of the same length (AP13: 36 rings) and a fall in growth rate visible at the beginning of many sequences (Fig. 9). The ring-width patterns of these carbonized woods are so similar that they probably came from the same tree.

3.1.1.3. Fuel in incense-vases. Charcoals in incense-vases from Anjou were derived from oak branches. This was...
probably a result of the over-exploitation of forests around Angers over many centuries during Medieval times. The wood of oak represented from 90% to 100% of the remains contained in 70 vases dating from the Middle Ages to Modern times. The presence of bark and pith together, associated with a strong curvature of rings points to the use of small twigs (Hunot, 1992, 1996) (Fig. 10). Moreover, the working marks on several suggest the use of coppicing wood (Fig. 2M).

3.1.2. Timber: example of the Neolithic settlements of La Hersonnais

The site of La Hersonnais (Pléchatel, Ille-et-Vilaine) has provided a great number of charcoals coming from the timbers of different late Neolithic settlements (Tinevez, 2004). Each building is surrounded by an enclosure. They belong to the late Neolithic period, and it is possible to follow their architectural evolution from the 27th to the 26th century BC (Bernard and Thibaudeau, 2002) (Fig. 11).

The studied charcoals come from post-holes and ditches (Marguerie and Thibaudeau, 2004) (Fig. 12). The wooden super-structures were made from pieces taken from large branches or trunks of oak. The majority (74.4%) of oak charcoals from all the studied samples show a weak ring curvature. The charcoals of others species came from pieces with medium to small calibre. This is also the consequence of the morphology of the smaller trees or shrubs from which they came.

Very few charcoals of oaks (38/1959) from building A and enclosures B and C have insect tunnels. Combined with the frequent observation of tyloses in vessels, this result indicates the preferential use of heartwood for construction.

Oak has excellent mechanical properties. In north-western Europe, it is the building material par excellence. The density and the mechanical qualities vary greatly depending on the proportion of latewood in the total width of a ring (Zobel and Van Buijtenen, 1989). The thick annual growths are of high density and are best suited to resist the static and dynamic forces experienced. These woods are difficult to work and have large shrinkages. In contrast, medium annual growths (less than 2 mm) correspond to mechanically weaker and softer woods, which are easier to work and have small shrinkages. Trees with such wood have even and straight trunks that are ideal for obtaining long beams (C.T.B.A., 1989; Rameau et al., 1989; Sell and Kropf, 1990).

At La Hersonnais, oaks with slow growth were used. This was the case within any given architectural group, with a great similarity between timbers from the building and the enclosures. There was no significant difference according to the Student t-test, except for group B where the average widths are clearly greater in the fences (Sokal and Rholf, 1981). The trees with narrow rings, and probably with long, straight and regular trunks, were probably chosen owing to the large size of the buildings.

3.1.3. Catchment areas

For La Hersonnais, we systematically analysed the distribution of oak ring widths wherever possible. Owing to this method, it was possible to assess the homogeneity or heterogeneity of the sample as well as the supplier areas (Fig. 13).
The histogram of classes drawn up for building A shows a very well classified normal distribution, which is unimodally centred on the value 1.25 mm ($M = 1.30$ mm, $\sigma = 0.49$, $N = 486$ charcoals and 5193 rings). The oaks used come from a single homogeneous population (Fig. 13A).

At Saint-Symphorien (Paule, Côtes-d'Armor), the sediments filling the underground passage (P1555) during the second half of the 5th century BC contain charcoals of oak with a large average ring width ($M = 2.78$ mm, standard deviation $= 1.41$, $N = 59$ charcoals and 363 rings), showing a scattered and multimodal distribution from 1.01 to 7.25 mm (Fig. 13B). The woods of these mixed fires came from different areas with different growing conditions.

In the Carolingian settlement of Talvassais at Montours (Ille-et-Vilaine) (Cattedu, 2001), oak charcoals corresponding to the first stage of the use of the domestic kiln (St. 629) have ring widths with a strongly scattered distribution from 1.71 to 7 mm (Fig. 13C). The average width is 3.32 mm with a standard deviation of 1.12 mm, calculated on 74 charcoals and 327 rings. This sample contains seven charcoals with very high growth rate. In this case, charcoals seem to have come from different areas or from the middle of a dense forest out to its open edge.
3.2. Palaeo-environmental information

In forest ecology, incremental variations in wood may be interpreted using a complex series of parameters: adaptation of the tree to the location, availability of water and nutrients, tree spacing, attack by pathogenic organisms and climate (Gassman, 1999; Otto, 1994; Schweingruber, 1988; Wilson and White, 1986; Zobel and Van Buijtenen, 1989). In 1983, Heinz carried out a palaeo-dendroclimatological analysis by measuring the widths of tree rings on charcoals of Juniperus (Heinz, 1983).

Along with environmentally induced variations in wood formation, we consider the effect of spacing within communities on wood properties, as shown by the examples given below. Differences in spacing have a considerably effect on competition between trees, such as through the availability of moisture and nutrients (Otto, 1994). Recently, Carrion (2003) carried out a dendrological analysis of charred material from the wooden support structure of the Neolithic dolmen of Tres Montes (Navarra, Spain). This author measured tree growth rings in charcoals of Juniperus, thus highlighting the exploitation of two different stands as well as the impact of climatic variations and human activities around the site.

Following many studies in the north-western France covering the postglacial period, during which climatic variations were too weak to modify clearly the average radial growth of the trees, we conclude that the average annual growth rate provided by the dendrological analysis of charcoals above all reflects the density of the stands.

At the Neolithic site of La Hersonnais, the different settlement complexes were not contemporaneous. The stratigraphic study carried out during the excavation, as well as the typological criteria and the relative dating of the structures, all suggest that the oldest building was structure A, followed in order by B, C and D (Fig. 11).

In this case, anthracology may provide information about the environmental context and the structure of surrounding woodlands. The increase of the average ring width over the studied time interval reflects forest degradation and the
evolution of woodland potential around the site. It seems that a single forest was exploited throughout the occupation of the site. Following the same pattern, buildings became smaller and the walls, previously made of big oak posts, were replaced by thinner wattle walls.

The samples of oak charcoal have an average ring width measured on 1501 fragments that varies between 1.26 and 1.94 mm. This average value increases from group A to group D (Fig. 14). The Student t-test shows that the difference between A and B is not significant and that oaks used for the construction of these two groups probably came from the same ecosystem. Between the groups A and C, and between B and C, the average values are significantly different at a 99% confidence level.

The narrowness of oak rings in groups A and B indicates the existence of dense supplier forests. Then, the increase of the average width observed during the development of occupation over the next century informs us about the opening up of the forest, leading to a damaged formation of scattered and isolated large trees.

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From woods designated for the construction of buildings, we can interpret the dendro-anthracological data in terms of palaeo-ecology. The growing proportion of heliophilic species (birch, hazel, maple, broom, etc.) used during the different phases of occupation of the site follows the clearing of the environment and the greater availability of these species around the settlement (Fig. 12).

In north-western France, the average width of the growth rings in oak charcoal from domestic hearths, coming from about 40 sites and 55 samples, shows a significant increase from the Neolithic to the end of the Iron Age. Linear regression analysis gives a relationship between time (t years) and ring width (y mm) that can be expressed as $y = 0.0028t + 1.2682$ ($r = 0.57$) (Fig. 15A).

The graph shows the average width of growth rings observed, along with the standard deviation. Two sets of samples are quite clearly contrasted:

- width of about 1.5 mm during the middle Neolithic period, corresponding to narrow rings,
- width of about 2.4 mm during the Iron Age, with a large dispersion of values, corresponding to wide rings in general.

The increase in oak ring width and the greater dispersion of the values suggests a clearing of the forest between these two periods. This observation supports the increasing taxonomic richness and abundance of recorded heliophilic taxa among the charcoals from domestic fires, some of which are characteristic of heathland (Fig. 15B). This phenomenon is the result of an increasing exploitation of the forest (Gaudin, 2004). At the same time, there is evidence for the development of heliophilic vegetation over time. During the establishment of Neolithic peoples in north-western France, trees with low growth
were the first to be felled or collected as deadwood within dense forest. With the considerable growth of human population in north-western France during the Late Iron Age (Audouze and Buchsenschutz, 1989), wood collection led to significant deforestation and people made use of numerous different varieties including many heliophilic species. However, the Iron Age corresponds to a period of development of regressive heathland in Brittany. Similarly, we can observe more frequent use of oak firewood of small diameter from branches or young trees.

The dendrological analysis of various samples of Medieval and post-Medieval charcoals from the Anjou region, near Angers (Fig. 4), reveals large variations in the average ring width. We were unable to detect any chronological trend. The charcoals collected from the fireplaces of the Dark age sarcophagus quarry of Doué-la-Fontaine yield an average ring width of 2.33 mm (standard deviation = 0.96, N charcoals = 93). By contrast, oak charcoals from the mortar of the abbey church of Fontevraud (early 12th century) have an average width of 1.20 mm (standard deviation = 0.43, N charcoals = 197). The various results in space and time over this region point out a Medieval landscape where dense forests coexisted with over-exploited open zones.
4. Conclusion

The application of dendrochronological methods supplements the analysis of charcoals. We can interpret the results of dendrology applied to charcoal analysis through a convergence of criteria, without taking into account the small variations found in some of the parameters. This new tool in charcoal analysis is more than just an identification of the species or genus used, since it provides fundamental data on gathering modes, fuel economy, types of supplier areas, timber selection, catchments areas and, of course, the environment. By considering these extrinsic criteria in association with the analytical results, we can obtain palaeo-ethnographic and palaeo-environmental information.

In north-western France, our work in this field over many years has led to information of an ethnographic and environmental nature on a local and regional scale.

In the study of fuel used in domestic and craft combustion structures, dendrology provides us with information about the calibre and state of the wood chosen for combustion. These studies of kilns show that craftsmen chose their wood fuel according to the wood’s technical characteristics. Similarly, detailed examination of woodwork from the Neolithic site of La Hersonnais allows us to assess its provenance, initial calibre and rate of growth. On wood with porous zones, such as oak, growth rate confers the particular technical properties that would be appreciated by Neolithic builders.

From a palaeo-environmental point of view, the information obtained at La Hersonnais, based on measurements of the average radial growth rate of oaks used in the various construction phases, concerns the evolution of the forest environment exploited around the site and its progressive degradation. From the systematic measurement of the average ring-widths of oak charcoals on forty sites in north-western France, we are able to distinguish two states of the forest environment: tree cover remained dense during the Neolithic, but was degraded and varied during the Late Iron Age.

Palaeo-environmental interpretations based on the measurement of growth-ring width in charred and fragmented material are only valid only when applied to large charcoals (with weak ring curvature) belonging to the same taxon in the same geographical area and ecological setting, while also coming from the same archaeological context (i.e. domestic fire places) and size of wood.

The next step in this application of dendrology to anthracology will be to increase the precision of the wood anatomy observations. It is important to distinguish the phenomena responsible for a given width of ring. The morphometric analysis provides valuable information on the conditions affecting growth, such as climate, local conditions, cultural uses, domestication, tree treatments, etc.
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