frontiers in Ecology and Evolution

MINI REVIEW
published: 04 March 2022
doi: 10.3389/fevo.2022.823968

Taming Trees, Shaping Forests, and Managing Woodlands as Resources for Understanding Past Societies. Contributions and Current Limits of Dendro-Anthracology and Anthraco-Isotopy

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OPEN ACCESS

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Specialty section:
This article was submitted to Paleoecology, a section of the journal Frontiers in Ecology and Evolution

Received: *28 November 2021*
Accepted: *02 February 2022*
Published: *04 March 2022*

Citation:
Dufraisse A, Coubray S, Picornell-Gelabert L, Alcolea M, Girardclos O, Delarue F and Nguyen Tu T-T (2022) Taming Trees, Shaping Forests, and Managing Woodlands as Resources for Understanding Past Societies. Contributions and Current Limits of Dendro-Anthracology and Anthraco-Isotopy. Front. Ecol. Evol. 10:823968. doi: 10.3389/fevo.2022.823968

In many societies, livelihood strategies are based on a combination of economic strategies, including natural resources such as trees for wood, leaves, and fruits. Archeological wood charcoals are residues of human activity related to fire. They provide evidence of fuelwood and, in some contexts, timber, handcraft activities, and fruit production. They represent a detailed record of the way ancient woodlands were exploited. However, charcoal analyses are often confined to the study of taxa and their relative frequency, and socio-economic interpretations are thus limited. In the last two decades, dendro-anthracological studies have been developed. Tree-ring widths, radius of curvature, and carbon isotope contents are increasingly used as indicators of wood gathering practices, woodland management and climate. Nevertheless, in the absence of standards, measurement procedures and data processing are very diverse. The challenge for archeological charcoal analyses is thus to improve analytical tools, especially on dendro-anthracological and isotopic aspects, in order to improve the interpretation of archeological assemblages and advance the discipline. As an example, we present a new approach for taxa growing in Western Europe combining (i) different dendro-anthracological parameters, (ii) an anthraco-typological approach based on modern-day wood stands, (iii) identification of anatomical signatures revealing particular forestry practices, and (iv) stable carbon isotopes. This opens the discussion on methodological perspectives and the associated scientific questions focusing on woodland exploitation and climate, and on the interest of a systemic approach for the analysis of charcoal in archeological contexts.

Keywords: archaeological charcoal assemblages, dendro-anatomy, isotope, wood gathering, woodland management, climate

RETHINKING WHAT WOOD MANAGEMENT PRACTICES CAN TELL US ABOUT PAST SOCIETIES

Natural Wood Resources: An Underestimated Key for Studying Past Societies

In archeology, reflection about wood gathering practices for fuel and timber is mainly based on a list of taxa and their frequency and thus often reduced to concepts of selection or opportunism. However, many ethnographic examples show much more complex relationships between societies and the living world. In many societies, livelihood strategies are based on a combination of economic strategies, including wild plant resources (Testard, 2012). Highly sophisticated systems of natural wood resource exploitation linked to different degrees of woodland management have been described in ethnography (see e.g., Kialo, 2007; Michon, 2015; Rostain, 2016). At the tree scale, strategies include harvesting or incipient management such as tolerance (preserving plants) and protection (eliminating competitors) (González-Insuasti and Caballero, 2007). Additional practices, such as coppicing and pollarding, lead to an increase in wood biomass, favoring the production of wood with a specific morphology and the management of edible fruit production (Mosquera-Losada et al., 2012). At the forest ecosystem scale, societies transform their living space by the interweaving of natural silvigenetic dynamics and socially driven actions favoring particular wood resources and their associated products such as fruits and roots (Michon, 2015). Forests have been shaped by societies into humanized, valuable, nourishing spaces in as many different ways as the societies themselves, depending on social organization, know-how and techniques, food strategies and environment (Descola, 2004). Various spatial configurations, from the simplest to the most complex, result from this articulation between forest and society, and particularly from different forestry practices. Therefore the forest can be understood as part of the social space of a community, both shaping and shaped by communities (Paschalis, 2003). Our challenge is to identify such practices and reconstruct the resulting landscape. Furthermore, woodland management practices may constitute a key and as yet underestimated tool for studying the trajectories of past societies. Charred wood preserved as charcoal in archeological sites is the most frequent and informative record of past woodland exploitation. These residues of wood gathered and transported by people are also valuable artefacts reflecting social actions depending on techniques, economic strategies, and the environment (Asouti and Austin, 2005; Picornell-Gelabert et al., 2011; Dufraisse, 2012, 2014; **Figure 1**).

The Memory of the Tree and Charcoal Fragments: Tree-Ring Parameters

To characterize natural and anthropic woodlands four parameters are needed: composition (dominant and secondary species), stand density (number of stems per hectare), structure (distribution of age and diameter classes of trees), and modes of regeneration (seeded or vegetative regeneration) (Rondeux, 1999). The factors influencing growth are therefore multiple, highlighting environmental events and human practices that affect the tree throughout its life. These are recorded within the wood tissues i.e., tree-ring anatomy and density, chemical and isotopic wood composition, and depend on age and tree organ (trunk or branch). To extract information recorded in tree-ring widths from ecological records on living trees or archeological wood remains, different tools from dendrochronology, dendroarchaeology, dendroclimatology, etc., are used (Cook and Kairiukstis, 1990; Schweingruber, 1996; Payette and Filion, 2010).

While carbonization preserves the wood anatomy, allowing the taxonomic identification of wood remains, it also leads to fragmentation, shrinkage and mass loss as charcoal fragments are partially reduced to ashes. Besides, fragments deriving from trunks and/or branches, or even roots, present few rings, often without pith and/or bark, resulting from the exploitation of many indistinguishable individuals. Consequently, in the absence of adequate tools to explore the information contained in charcoal tree-rings, the first dendro-anthracological developments started at the beginning of the 20th century (for a review, see Marguerie et al., 2010).

METHODOLOGICAL ADVANCES IN DENDRO-ANTHRACOLOGY

Methodological Developments During the Last Two Decades

Dendro-anthracological methods have undergone a decisive expansion in the last two decades. Lundström-Baudais (1997) and Ludemann and Nelle (2002) presented a semi-quantitative estimation of the wood diameters guided by a graduated target. Marguerie and Hunot (2007) proposed a systemic approach using large pieces of charcoal, based on a combination of the measurements of tree-ring width, a qualitative approach of ring-curvature, and the presence of bark, pith or reaction wood, and fungal hyphae. But the most outstanding advances involved the development of quantitative tools and significantly benefited from the use of image analysis software. This led to the development of (i) quantitative anatomy, applied to specific problems such as the management and cultivation practices of the olive tree in the western Mediterranean (e.g., Terral and Mengual, 1999; Limier et al., 2018); and (ii) quantitative dendro-anthracology, focusing on estimating the charcoal-pith distance independently of ring morphology variations (Dufraisse and Garcia-Martinez, 2011; Paradis-Grenouillet et al., 2013), or to specific approaches on entire pieces of round wood (Deforce and Haneca, 2015; Out et al., 2020).

From Practices to Paleoenvironmental Reconstruction: Dendro-Anthracological Applications and Current Limitations

The application of dendro-anthracological parameters to archeological charcoal assemblages gives access to valuable information both on wood gathering practices (selection criteria,

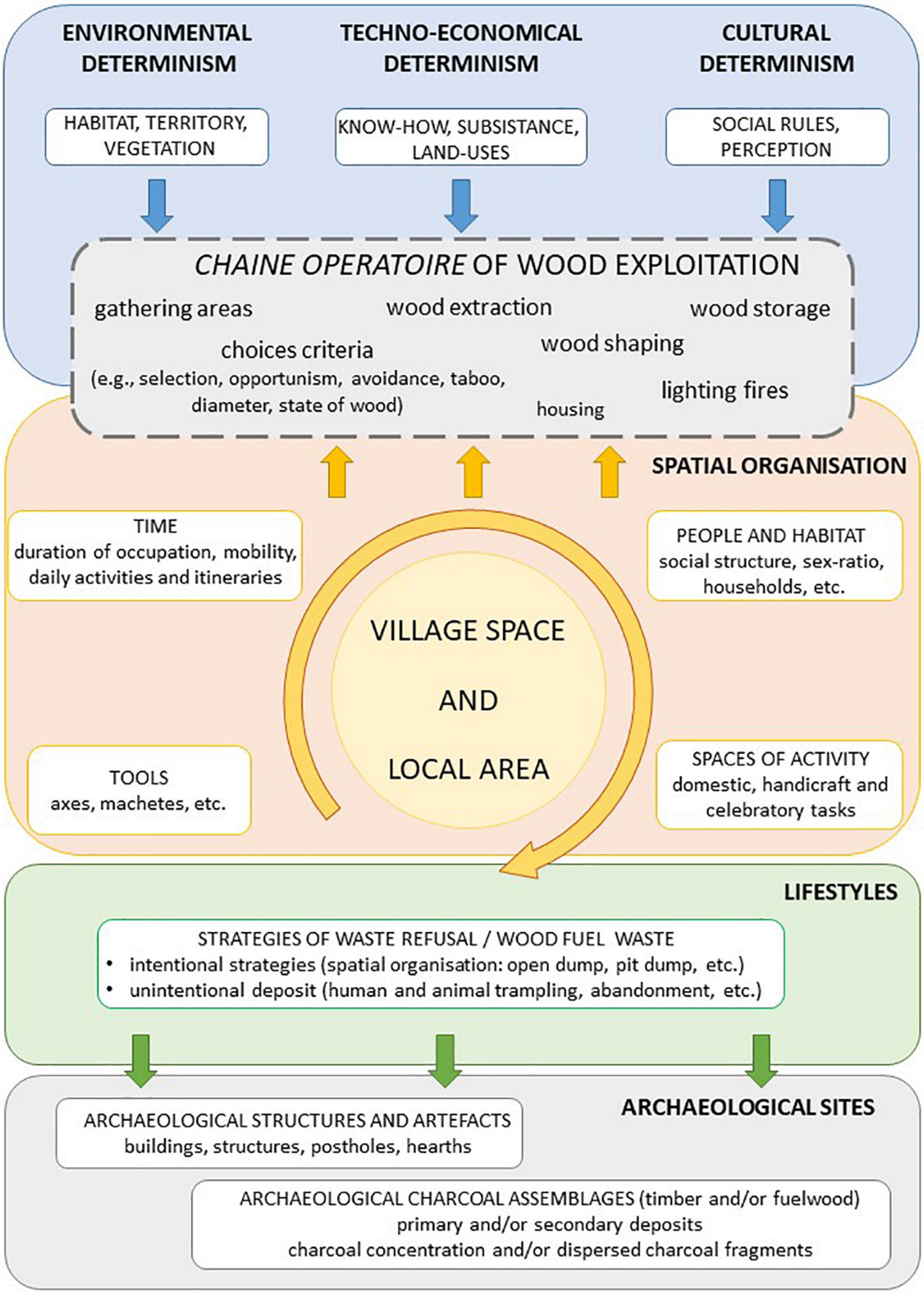

FIGURE 1 | Archeological charcoal fragments as valuable artefacts reflecting socio-economic organization and environment.

extraction methods, wood shaping), and woodland management (supply areas, pruning practices). In Western Europe, mainly in France and Germany, dendro-anthracology was developed and applied in different contexts. Ludemann and Nelle (2002) and Paradis-Grenouillet et al. (2015) characterized past wood uses through the study of numerous historical wood charcoal kilns, respectively in the Black Forest and Mont-Lozère. Marguerie and Hunot (2007) systematically added the measurement of ring widths to the identification of charcoal to assess woodland density during the Holocene in Northwestern France. Dufraisse (see e.g., Dufraisse and Leuzinger, 2009; Schlichtherle et al., 2010) studied firewood gathering and woodland management as an indicator of the social organizations and economic contexts of Neolithic societies living along alpine lakeshores. In arid environments, in Turkey, Kabukcu (2018) and Marston et al. (2021) applied dendro-anthracology to describe wood uses and assess their environmental impact. Finally, the production of new datasets combining dendro-anthracology and entomology has revitalized the field of anthracological research (Bouchaud et al., 2021; Toriti et al., 2021).

All the above studies point out that the measurement procedures and data processing lack a methodological standard. In general, the morpho-anatomical characteristics cited in the literature (ring width, radius of curvature, tyloses, etc.) are used without regional and/or specific standard references. For example, the presence of tyloses in vessels occurring with aging and heartwood formation can be used to estimate a minimum logging age for oak (*Quercus robur/petraea)* through a quantitative approach (Dufraisse et al., 2018a). However, the application of this proxy on other taxa requires modern references, since tyloses are not systematically associated with heartwood formation in all woody species (Tyree and Zimmermann, 2002). Furthermore, specific qualitative or quantitative procedures have to be implemented to apply this approach to archeological charcoals. In other cases, multivariate analyses give a very good overview of the identified taxa and their associated dendro-anthracological parameters and their other attributes (the condition of the wood and the ecophysiological tree-ring attributes). However, they cannot process the combined dendro-anthracological information at the fragment scale. When dendro-anthracological analyses are reduced to one parameter, for example ring curvature, interpretations are limited, in this case to the distinction between small and large diameters, without distinction between branches and stem, whereas the social and economic organizations derived from these two modes of exploitation are quite different.

The challenge for anthracology is thus to improve analytical tools, i.e., modern references, measurement procedures and data processing, especially on dendro-anthracology, that will allow advances in the interpretation of archeological charcoal assemblages.

Example of a Quantitative Dendro-Anthracological Approach to Taxa Growing in Western European: Anthraco-Typology

The objective of the anthraco-typological approach is to improve the use of dendrochronological methods by proposing a battery of quantitative dendro-anthracological tools and transposing them to anthracology's "dendroecological growth models" (Girardclos et al., 2012) established from modern wood stands, which was previously impossible (**Figure 2**). In that way, we developed a systematic approach conducted for taxa growing in Western Europe, based on modern-day wood stand references and combining (i) quantitative dendro-anthracological parameters, and (ii) an anthraco-typological approach, capable of processing the information at the fragment scale.

Tree-ring width is easily measured from wood charcoal. The main methodological problem is that we do not know where the charcoal fragment was located in the tree (trunk or branch) or the wood section, i.e., the distance from the center of the stem. The first tool developed was therefore the measurement of the charcoal-pith distance [review in Dufraisse et al. (2020)], which consists in repositioning the charcoal fragment in relation to the missing center of the stem, allowing us to better analyze tree-ring widths. This parameter can also help to estimate the diameters of the wood exploited with mathematical models, taking into account charcoal fragmentation (Dufraisse, 2006).

The second tool deals with the sapwood-heartwood distinction, tested on European temperate deciduous oaks (*Quercus robur/petraea*). As the heartwood of this taxon is formed around 21 $\pm$ 18 years according to Lambert (1996), its presence or absence can be a valuable proxy to estimate the age of the wood harvested (Dufraisse et al., 2018a). These two parameters were tested on uncarbonized and carbonized wood to evaluate margins of error, establish correction factors and define discriminating thresholds (Garcia-Martinez and Dufraisse, 2012; Blondel et al., 2018; Paradis-Grenouillet and Dufraisse, 2018).

A protocol for archeological applications was proposed considering charcoal fragment size (from 2 mm transversal section), number of charcoal fragments and charring effects, such as shrinkage, which depends on the carbonization temperature that varies with the archeological context. These quantitative approaches have led to new developments based on combining these dendro-anthracological parameters, now quantified, and therefore on the possibility of mobilizing current or past dendroecological growth models established from current wood stands or archeological uncarbonized woods (Dufraisse et al., 2018b).

An interpretative grid can therefore be established on modern wood stands characterized by dendrochronology. Dendrochronological data are then converted into dendro-anthracological parameters (e.g., tree-ring width *vs.* age transformed into mean tree-ring widths *vs.* charcoal-pith distance), considering branches, trunks, and the whole tree separately. First developed on deciduous oaks (Dufraisse et al., 2018b), this approach was successfully extended to pines (*Pinus halepensis* Miller and *Pinus sylvestris* L.) (Picornell-Gelabert et al., 2020; Alcolea et al., 2021), in which branch shedding also occurs by natural pruning, since tree-ring widths vs. pith-charcoal distances in branches do not overlap with those in trunks.

TAMING TREES: IDENTIFICATION OF PARTICULAR GROWTH PATTERNS

Trimming Practices and Identification of Ancient Ecological Knowledge

The trimming practices of the trees are determined by the uses to which the trees are put: timber, firewood or fruit production, livestock feed. They also reflect the know-how, tools and cutting techniques, uses and customs of past societies. According to Bernard et al. (2007), the tree is "*a technical support for agroforestry practices, an architectural element in the landscape that drives innovation and adaptation [...].*" These practices are of obvious interest in understanding the development of wooded areas, whether

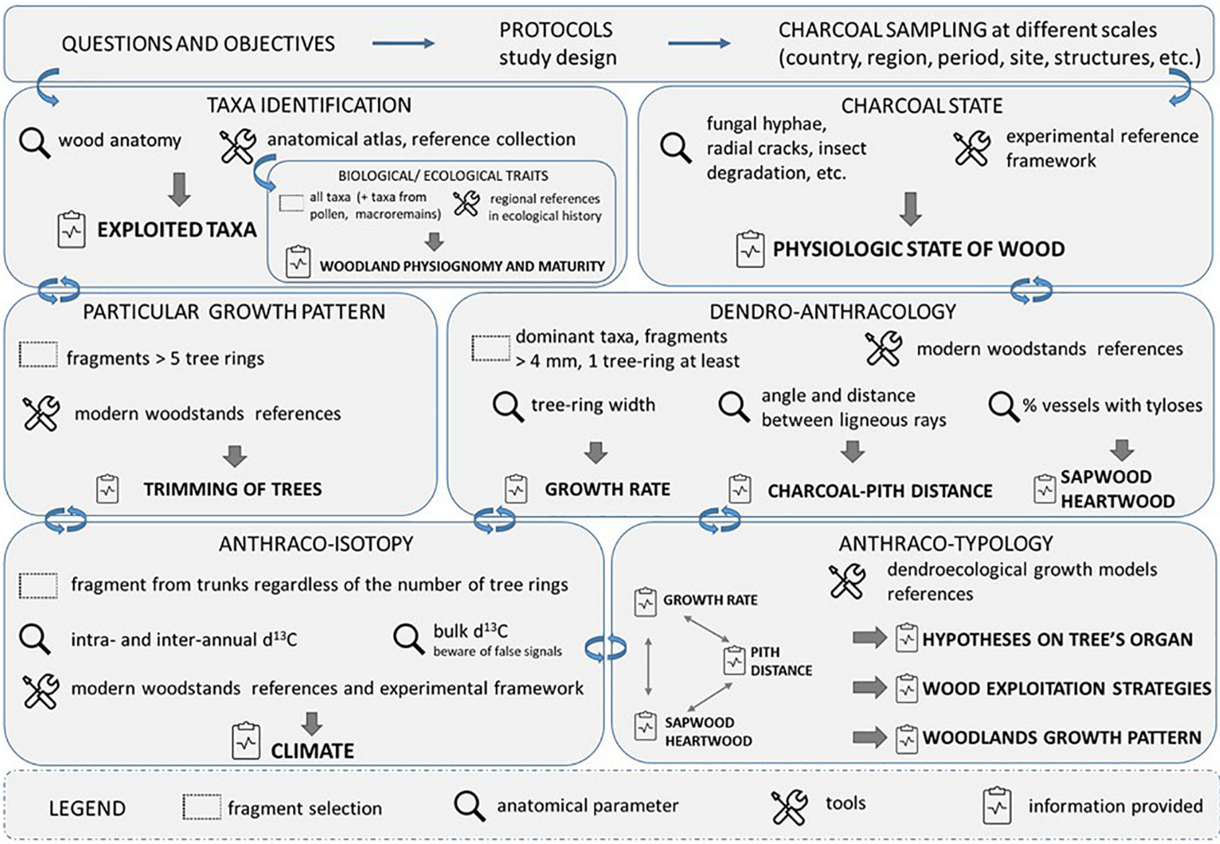

FIGURE 2 | From taxa identification to anthraco-typology and anthraco-isotopy: contribution of dendro-anthracological analysis of archeological charcoal assemblages to characterize wood exploitation practices, woodland management and climate.

they are systems built for gathering, crafts or for agro-sylvo-pastoral activities. The identification of such practices contributes more widely to the identification and conservation of ancient ecological knowledge.

Many forest management strategies carried out in order to guarantee or increase the availability of resources rely on the natural ability of many tree species to regenerate when cut. To create new shoots and attempt to increase wood and/or fruit production, two main techniques exist: coppicing and pollarding. Coppicing consists in cutting trees close to ground level to promote vegetative propagation by stump shoots. Pollarding consists in cutting back the tree crown in order to produce a close head of shoots (high coppice or branch coppice). Identifying such trees relies on an examination of particular growth patterns.

While the search for particular growth patterns linked to coppicing and pruning is relatively well developed in dendroarchaeology (see for example Bleicher, 2014), very few studies have been conducted in the field of anthracology.

Coppicing and Charcoal Analysis

Coppicing patterns are characterized by a particularly strong juvenile growth in the first 5–10 years followed by a rapid decline (Haneca et al., 2005; Girardclos et al., 2012). Similar growth patterns are sometimes identifiable on charcoal fragments but require the observation of a series of 5–15 rings (Deforce and Haneca, 2015). However, wide rings around the pith cannot always be considered as a fingerprint of coppice (Copini et al., 2010), due to complex criteria such as age and size of the root system (Salomón et al., 2013). To complement this approach, a comparative study between sessile oak stump sprouts and seedlings of the same age and dimensions was undertaken to identify markers appropriate for anthracology and dendroarchaeology (Girardclos et al., 2018). The study showed that the combination of ring width, proportion of earlywood and charcoal-pith distance can be effective on fragments with less than 5 rings.

Pollarding

Only one study focusing on identifying anatomical markers of tree fodder for ash (*Fraxinus excelsior*) (Haas and Schweingruber, 1993) and one on oak related to fuelwood and timber harvesting (Bernard et al., 2007) exist. The last one showed specific anatomical markers at a scale of 3–5 rings that repeat cyclically during the tree's life, reflecting cutting rotations. The combination of the tree's morphological characteristics and the anatomical characteristics of the wood enable these signals to be attributed to human activity (Bernard et al., 2007).

In anthracology, only specific patterns at a scale of 3–5 rings are potentially recognizable. Indeed, "not all anatomical elements of the ring react simultaneously" (Bernard et al., 2007), which would allow the differentiation of leaf/branch removal from simple narrow rings on charcoal fragments. Therefore, the characterization of traumatic growth related to pollarding relies on quantitative anatomy in earlywood and latewood; successive narrow rings are not sufficient to characterize a pollarding signal.

THE DEVELOPMENT OF ANTHRACO-ISOTOPY TO ASSESS PAST CLIMATE

Recent Advances in $\delta^{13}C$ Applied to Archeological Charcoal

The development of dendro-anthracology has made it possible to describe wood gathering practices and woodland management and to reconstruct past woody landscapes and assess human impact. However, the main challenge is to disentangle the explanatory factors, which can be anthropogenic (variations in the degree of competition) and/or natural (climate change). Stable carbon and oxygen isotopes have been used in dendroclimatology to reconstruct past environments (Daux et al., 2018). In the field of anthracology, pioneer studies by Jones and Chaloner (1991), February and Van der Merwe (1992), and Vernet et al. (1996) revealed the potential of charcoal carbon isotope compositions to reconstruct past environments, notably paleo-precipitation. Ten years later, Ferrio et al. (2006) proposed a methodological framework to constrain the effect of carbonization and apply stable carbon isotopes to investigate aridity changes.

Since then, archaeobotanical paleoenvironmental studies using $\delta^{13}C$ values determined on wood charcoal fragments have proliferated (review in Fiorentino et al., 2015). The only studies combining dendro-anthracology and stable carbon isotopes were carried out in Syria by Deckers (2016) and in France by Baton et al. (2017). In Baton et al. (2017), we tested the relevance of a seasonality index in a well-documented archeological context: $\Delta^{13}C_{seasonality} = \delta^{13}C_{earlywood} - \delta^{13}C_{latewood}$. As we showed in an experimental context that the carbonization is not significantly different at the scale of a tree-ring (Baton, 2017), this appears to be a promising climate indicator, independent of carbonization intensities.

Charcoal Isotopes and the Effect of Carbonization: A Sufficient Methodological Framework?

Wood carbonization involves morphological, physical and chemical modifications [review in Bird and Ascough (2012)]. While in dendro-isotopy, stable oxygen and carbon isotopes are usually measured on wood cellulose, carbonization does not allow the extraction of cellulose which disappears progressively with increasing temperatures, leading to a progressive decrease in the charcoal ^{13}C content toward that of wood lignin (Jones and Chaloner, 1991; Czimczik et al., 2002; Ferrio et al., 2006).

As the charcoal carbon content (%C) progressively increases through carbonization, Ferrio et al. (2006) suggested correcting the effect of charring on $\delta^{13}C$ by using this parameter. However, such a correction may be questioned. First, it is worth noting that %C does not evolve above 500°C (Ascough et al., 2011), whereas domestic hearth fires typically reach temperatures of 600–800°C (Cohen-Ofri et al., 2006), and even higher for charcoal from burned timber (building fires, Deldicque and Rouzaud, 2020). Second, this approach relies on the hypothesis that %C is conserved through time, excluding post-depositional oxidation that potentially yields (i) a higher oxygen concentration in charcoals (Wiedner et al., 2015) and (ii) a relative decrease in %C. Consequently, %C cannot be applied indifferently in all archeological contexts as is currently the case.

Current Limitations and Future Challenges to Apply $\delta^{13}C$ on Archeological Charcoals

Besides potential issues related to the determination of carbonization temperatures and/or the effect of post-depositional processes described above, the use of $\delta^{13}C$ as a climatic proxy also faces challenges related to wood anatomical parameters. Recent studies in anthraco-isotopy are in most cases conducted without taking into account the heartwood/sapwood, organ, and age while ^{13}C contents differ according to wood composition (Loader et al., 2003) and organs (Leavitt and Long, 1986).

Charcoal sampling can also be considered as a limiting factor. Up to fifteen fragments, each with several rings, per stratigraphic level are often pooled to obtain an average signal, possibly biasing climatic information by smoothing the $\delta^{13}C$ variability recorded at the scale of each growth ring (see e.g., Aguilera et al., 2009; Caracuta et al., 2016). In the near future, investigating $\delta^{13}C$ at the scale of the individual growth ring should be a way to recover a proper climatic signal provided the carbonization degree and post-depositional processes are constrained. However, comparison with dendro-isotopy references is still not possible so that only relative values can be considered. Given these current limitations, we suggest combining $\delta^{13}C$ with anthraco-typology to better constrain the $\delta^{13}C$ signal in archeological charcoal (**Figure 2**). This approach aims (i) to avoid branch measurements whose $\delta^{13}C$ variations are less controlled by climate than those of the trunk (Heaton, 1999), (ii) to analyze heartwood and sapwood separately as their ^{13}C content may differ significantly (Baton et al., 2017), and (iii) to combine tree-ring width (and latewood/earlywood width) and carbon isotopes for past climate reconstructions.

DISCUSSION AND PERSPECTIVES

Beyond Botanical Identification: Contribution of Dendro-Anthracology to Characterize Wood Gathering Practices

Recent advances based on a systemic approach combining quantitative tools, anthraco-typology, particular growth patterns and anthraco-isotopy, have pushed back the limits of anthracology. This systemic approach applied to different archeological contexts enables easy reading between dendro-anthracological parameters (Dufraisse and Coubray, 2018; Picornell-Gelabert et al., 2021). Interpretations of tree-ring widths have been refined and hypotheses on the tree organs used have been proposed. It also becomes possible to characterize gathering practices, particularly when forms of wood degradation are integrated (Moskal-del Hoyo et al., 2010). Hypotheses related to social organization, technical systems and subsistence modes can be suggested for Neolithic societies (Coubray and Dufraisse, 2019). Beyond taxonomic identification and dendro-anthracology, the use of diversity indexes and biological/ecological traits of the identified taxon, especially the use of "Ancient Forest Species," allow hypotheses on the physiognomy of the woodland in terms of maturity, opening, or fragmentation (principles in Hermy and Verheyen (2007); anthracological application in Dufraisse (2014), Coubray and Dufraisse (2019). Subsequently, the state of transformation of these social and humanized forests can be better assessed.

Anthraco-Typology: Perspectives for Future Paleoenvironmental Approaches

The anthraco-typological approach, which aims to be collaborative and open access,[1] requires a specific methodological adjustment for each new taxon in terms of both analysis protocol and interpretation (for charcoal-pith distance, Dufraisse et al., 2020). Anthraco-typology is also constrained by the establishment of dendroecological growth models according to taxa, regions and archeological questions. This dataset allows the establishment of thresholds in tree-ring width, heartwood/sapwood, and charcoal-pith distance. Based on this reference data frame, the distinction between trunk and branches becomes possible. While the principle of this approach was validated on only a few taxa (*Quercus*, *Pinus*), the reference dataset has now to be enlarged both on new taxa and new wood stands.

When using wood charcoal, this distinction is the first necessary step when considering paleoenvironmental studies based on tree-ring width or isotopes. Thus, anthraco-typology opens up new perspectives in terms of paleoenvironmental analyses on charcoal, allowing the selection of the most appropriate fragments, for example to investigate past environmental conditions (e.g., by excluding fragments from branches or the 1st years of a tree's life) or for radiocarbon dating to avoid old wood effects (selecting sapwood fragments). Combined with anthraco-isotopy, it is possible to identify potential explanatory factors, especially climatic ones, to interpret woodland evolutions. Moreover, due to the fragmented and incomplete nature of charcoal fragments, combining tree-ring width and carbon isotopes might allow the discrimination of specific growth patterns between climate and human factors.

[1] https://dendrac.mnhn.fr

The Question of Intentional Woodland Management and Perspectives for Anthropological Interpretations

While wood exploitation practices of past societies can be described by wood studies (uncarbonized and charred), some particular growth patterns suggest woodland management since the Neolithic and even the Mesolithic period (Warren et al., 2014; Billard and Bernard, 2016). However, caution must be applied to distinctions made between "opportunistic" collection and "promotional strategies" (Zvelebil, 1994) such as "in-place encouragement" (Smith, 2011), i.e., the distinction between adventitious woodland management (natural regeneration) and formally managed woodland management in the interpretation of archeological material. It remains to be determined, therefore, whether it is a question of using what nature offers (cut down a tree, it grows back from the stump, the stump's offshoots are exploited) or of setting up a management system to create an ecological niche within which humans are a decisive force (Descola, 2015). Pollarding, which consists in adapting coppicing in height to protect the leaves from livestock or to maintain a tree whose bark is exploited, may be considered as a sign of intentionally managed woodland (Coubray and Dufraisse, 2019).

The characterization of Holocene woodlands by anthracology, until now essentially approached in terms of human and climate impact, can be characterized from another point of view. The tree is "socialized," landscapes are shaped by human practices and wood charcoal macro-remains constitute the archeological record of these processes. The history of the forest itself is as much about trees as about people. Addressing forest issues necessarily involves an explanation of the human and social dimension of forests. However, there are very few hypotheses for tracing wood harvesting strategies to a higher level of technical, economic or even ancient social function. For example, how should one interpret individual wood collection organized by domestic unit (Schlichtherle et al., 2010)? Was there a gendered division of labor of wood collection as reported in many ethnographic studies (Testard, 2014) and was it determined by the tools and their prohibitions? These anthropological perspectives on forest management have given rise to new approaches, in particular ethnographical references (Zapata Pena et al., 2003; Dufraisse et al., 2007; Picornell-Gelabert, 2020).

AUTHOR CONTRIBUTIONS

AD: conceptualization, methodology, modern reference data curation, archeological data curation, writing – original draft preparation, supervision, and DAO. SC: conceptualization, methodology, archeological data curation, writing – original draft preparation, supervision, and DAO. LP-G: modern reference data curation, archeological data curation, writing – original draft preparation, and DAO. MA: modern reference data curation, archeological data curation, and proofreading. OG: methodology, modern reference data curation, and proofreading. FD and T-TN: isotopic development supervision, and proofreading. All authors contributed to the article and approved the submitted version.

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