Wood Charcoal Analysis in Archaeology

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1 Introduction

In the great majority of archaeological sites plant macro-remains are preserved by carbonisation. Wood charcoal is amongst the most abundant and ubiquitous of these remains, providing ample opportunities for the investigation of past woodland vegetation dynamics and human impacts on the landscape. The aim of this chapter is to briefly outline the historical development of wood charcoal analysis (anthracology) as applied in archaeological research and present and discuss more recent methodological developments in this field. The primary concern here is to evaluate how anthracology as a field of inquiry has changed in recent years to address research questions relating to palaeoecology, woodland growth conditions in the past and woodland management practices.

2 From Its Beginnings to 'Anthracology as Palaeoecology'

Charcoal analysis (anthracology) involves the identification and examination of carbonised wood remains relying on the observation of the three-dimensional anatomical structure of wood. The earliest known identifications of wood macrofossils were carried out in the nineteenth century by Unger (1849) and later by Heer and Passerini (in Pigorini 1865) (see also commentaries by Castelletti 1990; Paysen 2012). In the following decades through to the early twentieth century, macrobotanical identifications, including carpological and anthracological remains, became more widespread

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(Maby 1932). In the first half of the twentieth century, methods of wood and charcoal identification were becoming more efficient. Initially, specimens were impregnated with resin, and thin sections were obtained from resin blocks for examination using transmitted light microscopy. However, some researchers (e.g. Maby 1932; Grimes and Hyde 1935) had started using less time-consuming techniques, whereby charcoal fragments were not resin-treated; instead they were hand-sectioned to obtain a fresh, clean break and examined with a hand lens or under a low power, binocular microscope, which also reduced the cost of analysis and enabled the identification of several fragments with ease. By the second half of the twentieth century, this technique had become a standard, and (with the adoption of darkfield, reflected light microscopy) much higher numbers of wood charcoals from a range of sites and contexts could be analysed as a result (cf. Couvert 1968; Western 1969, 1971; Leney and Casteel 1975; Vernet et al. 1979). In addition, the increasing number of archaeobotanical reference collections around this time, such as the Cecilia A. Western Wood Reference collection established in the late 1960s with a specific focus on the identification of archaeological wood charcoal macro-remains, significantly facilitated future anthracological research (Asouti 2017, Charcoal Analysis Web).

Alongside these methodological developments and the first publication of comprehensive wood anatomy atlases in Europe (e.g. Greguss 1955, 1959), interest in vegetation history and pollen analysis also increased, fuelled in part by an increasing awareness of human impacts on the environment (Godwin 1956; Smith 1970). One of the earliest studies to explore the potential of wood charcoal assemblages for inferring prehistoric vegetation dynamics was the publication of the wood charcoal assemblage from Maiden Castle (Dorset) in Britain (Salisbury and Jane 1940). Salisbury and Jane (1940) combined species identifications with the examination of growth ring morphology (i.e. average growth ring width and estimated log dimensions) and argued that the proportions of species observed in the assemblage, mostly deriving from fuel wood, reflected to some degree prehistoric woodland composition around the settlement. Their particular emphasis was on the issue of fuel wood availability and selection. Based on the evidence for the presence of a majority of branch wood and twigs in the charcoal assemblage, they argued that fuel wood was collected in the environs of the settlement and that it was 'non-selective' (i.e. collected without regard to the burning properties of the different species of wood). Their interpretations were heavily criticised by Godwin and Tansley (1941) who stressed the importance of cultural parameters determining the selection of wood for fuel and argued that anthracological assemblages, as a result of selection bias, could not reflect prehistoric vegetation accurately. Thus, one of the enduring debates in anthracology started and continues to this day: how representative are the remains of fuel wood debris with regard to past vegetation cover? In addition, Godwin and Tansley touched upon three important concepts in the interpretation of charred fuel wood macro-remains: collection (selective vs. non-selective), the impact of taphonomic processes and their quantification potential.

One of the most influential concepts addressing the issue of quantification of wood charcoal macro-remains was the 'law' (process) of fragmentation proposed by Chabal (1988, 1992), based on the statistical analysis of archaeological assemblages. The author observed that charcoal fragments from archaeological sites, independent of their wood anatomical and/or chemical characteristics (i.e. independent of species), tend to fragment in a way that produces a high number of smaller fragments and a low number of large fragments, resulting in a log-normal size and weight class distribution. Chabal argued these observations on fuel waste taphonomy reflect the random nature of impacts on charcoal fragmentation resulting from the combined effects of mass loss during burning, fuel waste discard in midden-like areas, post-depositional weathering and burial of the charcoal fragments. In the archaeological case studies, Chabal established that the random nature of taphonomic impacts renders anthracological samples suitable for subsampling utilising a rarefaction (or taxon diversity saturation) curve and, furthermore, can be evaluated for their representativeness in terms of taxon composition by a close examination of taxon abundance values in stratigraphic sequences. Methodologically, these findings formed the backbone of present-day anthracological analysis concerned with reconstructing fuel use practices, which rely on wood charcoal fragment counts obtained from deposits containing long-term accumulations of fuel waste (e.g. middens; see also the terms *synthetic* cf. Théry-Parisot et al. 2010a; *charbon de bois dispersés* cf. Chabal et al. 1999).

These developments in wood charcoal quantification were closely matched with a more palaeoecological research trajectory in anthracology, stemming from the influence of the principle of least effort (PLE) in the interpretation of wood fuel use. PLE, proposed by Zipf (1949) argued that all human behaviour is explained by the general rule that the least amount of effort is spent to obtain maximum returns. It has greatly influenced anthracological interpretation with its central assumption that fuel wood collection would take place close to the settlement and that all available woody species would be universally collected in direct proportion to their availability in the past vegetation (cf. Prior and Price-Williams 1985; Tusenius 1989; Chabal 1992; Shackleton and Prins 1992). More specifically, Shackleton and Prins (1992) proposed that in high-density woodland environments, fuel economies tend to be selective towards preferred wood fuel species and are characterised by the routine collection of readily available dry deadwood in close proximity to habitation sites. By contrast, under conditions of wood scarcity, fuel economies would be non-selective, targeting all available species. Based on this theoretical foundation, PLE-inspired interpretations of anthracological datasets have proposed that archaeological wood charcoal taxon frequencies may represent an accurate reflection of local woodland composition and its changes through time. They can thus be used as a source of evidence for palaeoenvironmental reconstruction in a manner similar, if not identical, to that of pollen analyses (Chabal et al. 1999).

While there has been debate concerning whether or not fuel wood collection is determined by cultural selection (i.e. culture-specific definitions of 'good fuel') or functional motives (i.e. maximising calorific and energy returns), this has not resulted in systematic theoretical approaches in this field, with some exceptions (e.g. Asouti and Austin 2005; Dufraisse 2008, 2012; Picornell et al. 2011). Proponents of culturally determined fuel selection (e.g. Heizer 1963; Godwin and Tansley 1941; Smart and Hoffman 1988) have argued that wood collection reflects the preferences of prehistoric communities that depend on sociocultural value systems, as opposed to purely functional, optimal behaviour patterns. Thus, it has been argued that archaeological fuel wood remains cannot provide a sound inference on the local (or regional) availability and distribution of woody plants. A further expression of this argument is that data based on quantified charcoal datasets cannot accurately reflect the entire spectrum of wood fuel use (e.g. Willcox 1974, 2002; Zalucha 1982; Smart and Hoffman 1988; Brady 1989; Piqué 1999). Therefore, any reconstructions of species availability and/or use would be at best partial. More recent anthracological investigations, aided by ethnographic and ethnoarchaeological investigations of fuel use and selection, have stepped away from such a polarised view of the palaeoecological significance of anthracological research.

Ethnoarchaeological work on fuel use by Picornell et al. (2011) in the Fang villages of Equatorial Guinea demonstrates the importance of economic and cultural parameters in determining fuel collection areas and the selection of fuel species. The authors report that fuel wood collection takes place not only within the immediate vicinity of the settlement but rather in areas that are 'socialised' spaces. These areas (*tsií*, orchards; *ekot*/*mbut*, fallow land) are spaces in which the spirits of the animals, the plants and the ancestors do not roam. By contrast the rainforest (*afán*) is never used for fuel wood collection as it is considered to be the home of the spirits. The authors argue that even though a concept of 'good fuel' exists (woods that are dense, burn slowly and produce little smoke) this does not translate in habitual preference for, and use of, such taxa. The 'good fuel' property is invoked only when extraordinary circumstances (short-term fuel shortages or requirements for special events) necessitate additional labour for wood procurement. Instead, the byproducts of agricultural activities (woodland clearance for the establishment of new tree groves) are regularly used as a source of domestic fuel wood. Several wood species are never collected (even from cleared fields) because they are deemed to be 'bad fuels' due to cultural restrictions. This case study and several other ethnographic accounts demonstrate that while fuel needs and patterns of use develop in response to everyday subsistence activities, at the same time, they are also the results of locally determined strategies of fuel use and cultural perceptions.

Functional or cultural perceptions of the qualities of individual species may sometimes outweigh practical necessities. For instance, the Erenk of Siberia reportedly avoid using birch wood as fuel, as they believe it to be harmful to humans; instead they use larch in various states (green, dead, rotting) for most fuel needs (Henry 2011). Therefore, selective pressures may not always be exerted equally on the most abundant species in the landscape. In some cases, cultural distinctions of fuel preference may act as markers or ethnic, communal or socio-economic boundaries, regardless of species availability. Along these lines, the Erenk (Siberia), for example, choose the location of their settlements partly based on the availability of standing dead larch trees in the vicinity. To view such cultural norms of habitation and resource use in a purely functional way (i.e. settlement location chosen based on the availability of particular wood species in the natural vegetation) would be misleading and simplistic. If this was the case, and energy returns rather than cultural factors were the driving factor behind fuel use and settlement location, the same group of people would not have a problem burning shrub species and birch wood.

In sum, fuel selection (or more correctly procurement) cannot be considered as predominantly functional, cultural or technologically and environmentally optimal. From an anthropological perspective, all such considerations (and perhaps several more not necessarily amenable to direct empirical investigation) contribute to the decision-making strategies of individuals and social groups about how, when, where and which fuels to use for a wide range of purposes. In the end, what we find in the archaeological record are the material residues of fuel procurement and consumption representing the end product of complex *chaînes opératoires* of fuel use (Dufraisse et al. 2007; Dufraisse 2012). As a result, anthracological assemblages, along with the residues of other fuel types, reflect not only the vegetation accessible to (and used by) the communities in any given settlement but also the ways in which such resources were perceived, adapted to local conditions and technologies and finally incorporated into daily life (and by extension, subsistence economies).

3 Recent Methodological Developments

The focus of more recent anthracological work has been on refining our understanding of wood charcoal taphonomy, particularly in relation to residues derived from fuel waste. Several experimental and ethnoarchaeological investigations (Sect. 3.1) have addressed depositional and post-depositional processes impacting charcoal fragmentation in relation to species, the nature of post-depositional disturbances and the estimation of log diameter. In addition to taphonomic concerns, considerable effort has been expended on understanding wood condition (i.e. green wood vs. deadwood) and the diameter of the logs used in fires (Sect. 3.3). These developments are largely inspired by ethnographic evidence highlighting the importance of dry deadwood availability and log size in fuelwood collection (Sect. 3.2). Additionally, the detection methods for the identification of woodland management practices in archaeological wood charcoals have become increasingly important (Sect. 3.4).

3.1 Wood Charcoal Taphonomy

The processes impacting the preservation of wood charcoal remains deriving from fuel waste debris relate to practices of primary deposition (e.g. hearth type), redeposition (discard) and post-depositional weathering (e.g. soil moisture, surface exposure and freeze-thaw cycles) and trampling by people and animals. More recent advances in the study of wood charcoal taphonomy come from numerous experiments by Théry-Parisot et al. (2010b), Lancelotti et al. (2010), Chrzazvez (2013) and Chrzazvez et al. (2014). These were conducted for testing Chabal's hypotheses regarding the observed patterning in charcoal fragmentation, particularly in relation to fragmentation during burning and weathering following the discard of fuelwood waste. Théry-Parisot et al. (2010b) conducted fire experiments using a single species in each fire experiment to test whether species-specific wood anatomical features have any significant impact on the rate of charcoal fragmentation and/or the number of fragments produced. The carbonised wood fragments were collected at the end of each experiment, sieved into different size fractions (>4 mm, 4–2 mm, <2 mm) and counted to assess the fragmentation indices for each species. The purpose was to evaluate whether fragment counts reflect the original quantities of wood placed in the fire and the effects of taxon-specific properties on rates of fragmentation (e.g. wood density, chemical composition, anatomy, etc.). The authors found no significant correlation between species-specific variables and the fragmentation rates of wood charcoal. When the entire experimental assemblage was quantified based on fragment counts (295,688 fragments of >2 mm charcoal, produced from 110 controlled fire experiments), the results confirmed the original relative proportions of species used as fuel for 6 out of the 11 species selected for these experiments (Théry-Parisot et al. 2010b: 86 & Figs. 4–6 therein).

Chrzazvez (2013) conducted a different series of repeated experiments testing the post-depositional fragmentation of wood charcoals. She used equal numbers of wood charcoal fragments from each taxon, with the aim of evaluating the rates of fragmentation of different species under surface weathering conditions, freeze-thaw cycles, mechanical pressure and wet-dry cycles. She reported that of all the species tested, oak and beech charcoal produced the highest number of fragments, especially in <2 mm fractions (Chrzazvez 2013: 293–298 & Figs. 152–155). As a result of trampling, surface weathering, freeze-thaw cycles and mechanical pressure, a majority of >2 mm fragments broke down into smaller size classes for all the species included in the experiments. In most archaeological wood charcoal assemblages, <2 mm fragments rarely preserve enough anatomical features to permit botanical identification. Conditions of repeated wet-dry cycles resulted in a very high proportion of <1 mm charcoal fragments. Chrzazvez concluded that overall mechanical pressure produces the highest fragmentation rate; all experiments resulted in higher fragmentation rates amongst size fractions <2 mm (Chrzazvez 2013: 306–312).

Théry-Parisot et al. (2010b) and Chrzazvez (2013; see also Chrzazvez et al. 2014) found that >4 mm size fractions were more representative with regard to the relative proportions of the wood originally burnt as fuel and the quantities of wood charcoal fragments subjected to post-depositional fragmentation, respectively. However, occasional differences were also evidenced: Of all the taxa included in the experiments conducted by Chrzazvez (poplar, hazel, pine, ash, oak, beech, maple, birch, juniper, hornbeam), oak charcoals produced the highest number of >4 mm fragments, while poplar produced the least. Yet both sets of experiments demonstrated that the taxa most intensively used as fuel still emerged as the most abundant ones in the resulting wood charcoal assemblages. Thus, as originally suggested by Chabal et al. (1999), focusing on the analysis of fragments >2 mm and especially >4 mm provides the most reliable reconstruction of the relative proportions of the woody taxa used as fuel. Regardless of any discrepancies that may be observed in the carbonisation stage, depositional and post-depositional processes appear to impose a random and even filter on charcoal fragmentation for all the tested species.

The detailed ethnoarchaeological investigations at the village of Sarakini (Thrace, Greece) by Ntinou (2002) demonstrated that the wood charcoal fragments contained in fire features (hearths, ovens) contained either the remains of the most recent burning event and/or a very small amount of residual fuel waste accumulated over longer periods. Ntinou also observed that more expedient fire features (e.g. open fires next to seasonal work sites or those on the edges of agricultural fields) contained fuel waste debris reflecting the vegetation in the immediate vicinity of the hearth. As these tend to be features with minimal pyro-technological requirements and less labour investment, the fuel used in them is likely to reflect a resource maximisation scenario (Ntinou 2002: 115–120). On the other hand, more permanent and complex fire features, such as outdoor ovens and domestic hearths, contained a mix of preferred fuel sources and easy to collect ones. Ntinou reports that these features are cleaned on a regular basis and their debris deposited in designated midden areas. The author's analysis of midden charcoals demonstrated that they represented a composite picture of fuel use in contemporary fire features. These observations provide further support to the preferential selection by analysts of specific context types containing charcoal scatters accumulated over long periods of time (e.g. midden and midden-like deposits) as the most suitable proxies for reconstructing long-term trends in fuel collection and consumption.

Until recently, charred plant remains were thought to be composed of mostly inert carbon, which would render them durable to further decomposition. Instead, more recent research demonstrated that the major components of woody tissues (cellulose, hemicellulose and lignin) are converted into benzenoids, known to be unstable in alkaline conditions (Cohen-Ofri et al. 2006; Braadbaart and Poole 2008; Braadbaart et al. 2009; Huisman et al. 2012). Burnt plant remains are therefore subject to further decomposition after carbonisation, quite independently of other depositional and post-depositional variables. Such alkaline conditions could be prevalent in archaeological contexts if burnt plant debris was discarded together with the accompanying ash from fires (ash is predominantly alkaline, containing a significant amount of calcium and potassium oxides). Similarly, Rebollo et al. (2008) demonstrated through experiments under controlled pH conditions that soil alkalinity results in the degradation and fragmentation of wood charcoals, while acidic soils might also result in the accumulation of mineral deposits on charcoal particles. Further evidence for decomposition and degradation of carbonised remains is provided by Scott (2010) and Ascough et al. (2011) who report that, as a result of oxidising conditions, the graphitic components of wood charcoal degrade with time into materials chemically and macroscopically similar to humic acids.

3.2 Fuel Selection and Use

As already discussed, ethnographic work has highlighted the significance of dry-deadwood availability and size of logs as important criteria in fuelwood collection. Thus, recent anthracological work has sought to incorporate studies of patterns of

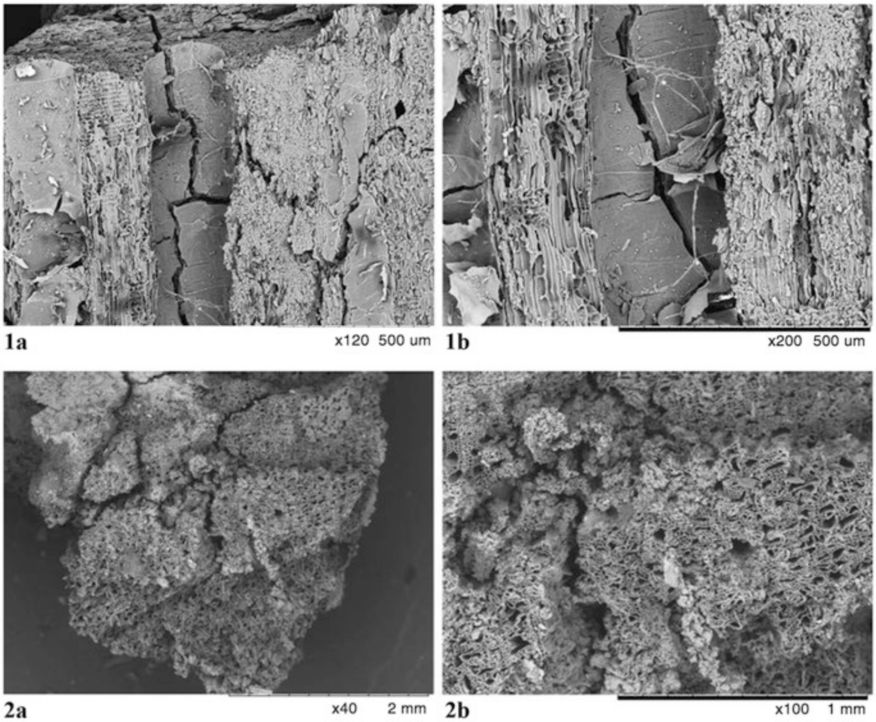

Fig. 1 Fungal decay preserved in archaeological wood charcoal specimens. 1a, 1b: *Quercus* (Çatalhöyük), fungal mycelia preserved in vessel walls. 2a, 2b: Salicaceae (Boncuklu), collapsed vessels, fibres and parenchyma tissue, most likely as a result of fungal decay

wood decay and reconstructions/estimations of log diameter into anthracological analyses which had previously relied solely on botanical identification. Experimental charring of fungi-affected wood by Moskal-del Hoyo et al. (2010) and Théry-Parisot (2001) has provided new evidence on the preservation of remnants of fungal hyphae and spores in wood charcoal (see also Fig. 1). The alterations observed in wood anatomy as a result of fungal attacks, as well as the mycelium and deposits of crystal oxalate salts in vessel elements, can be readily observed in wood charcoals. Previously, microscopic observations of fungal hyphae were interpreted as post-depositional attack on the charcoal (Heiss and Oeggl 2008), whereas only imprints of fungal mycelia on vessel walls were considered to be reliable indicators of fungal infestation prior to charring. However, experimental work by Moskal-del Hoyo et al. (2010) demonstrated that fungal hyphae can also be preserved in charcoal, and the use of this criterion alongside other anatomical effects of fungal rot (e.g. collapsed vessel walls, crystal oxalates) may confirm the use of deadwood as fuel. The same authors suggest that preserved hyphae attached to cell walls can be safely interpreted as evidence of fungal attack prior to charring (Moskal-del Hoyo et al. 2010: 211).

More recent work on the identification of different states of decay in conifer wood by Henry and Théry-Parisot (2014) confirms that the various stages of fungal decay and rotting can be detected through the detailed study of the wood anatomical features of charcoal specimens. These authors report that the degree of cell deformation and the frequency with which such features occur in a charcoal fragment could be indicative of the degree of fungal and/or microbial decay of the wood before charring. In the most severe cases, the dominant presence of fungal hyphae is accompanied by severe cellular deformation (collapsed and/or thin cell walls dominating the transverse section, alongside the occurrence of gaps and cavities in wood grain). Such features could be interpreted as indicators of whether deadwood was collected in earlier stages of decay or in the rotting stage. More experimental work is necessary for establishing reliable signatures of fungal decay stages in hardwoods that are more common in temperate and semiarid regions.

Estimates of minimum log diameter of fuel wood harvested have been applied in anthracology in a variety of ways since the 1970s (Willerding 1971) and were later developed further by other researchers (Hillebrecht 1982; Marguerie 1992; Marguerie and Hunot 2007; Ludemann and Nelle 2002; Dufraisse 2002, 2006; García Martínez and Dufraisse 2012; Paradis et al. 2013). As mentioned earlier, the size of wood can be as important as species availability in what concerns fuel selection. Therefore, considerable emphasis has been placed on improving wood calibre estimation methodologies over the last two decades. There are two main approaches currently employed in anthracology: (1) qualitative estimation of growth ring curvature and (2) quantitative calculation based on growth ring curvature and the angle between rays.

The qualitative ring curvature estimation criteria developed by Marguerie (1992) and Marguerie and Hunot (2007) classify growth rings into three groups (Fig. 2): curvature degree (CD) 1, weakly curved rings; CD 2, moderately curved rings; and CD 3, strongly curved rings. The definition of curvature classes is based on the observation that small branches and twigs have strongly curved growth rings while moderately large trunks are classified as CD 2 and large trunks as CD 1.

Quantitative methods of calibre estimation made using a transparency printed with growth ring perimeters of different diameter classes provide a visual estimate of growth ring morphology (cf. Willerding 1971; Lundström-Baudais 1986; Ludemann and Nelle 2002; Dufraisse 2002, 2006). Another variant is the use of the 'circle tool' in microscope imaging software to provide a good fit of a circle or arc on the largest visible growth ring of a specimen (Ludemann 2006; see also Fig. 2). Both methods have shortcomings when it comes to measurements on specimens with growth anomalies (e.g. wavy growth rings resulting from climatic or mechanical stress).

Trigonometric methods of quantitative diameter estimation use the angle of the rays together with the outermost growth ring boundary (Fig. 2, Paradis et al. 2010, 2013). These authors conducted repeated measurements on collected wood of known diameter (both freshly cut and carbonised) to test the reliability of various techniques of wood calibre estimations, comparing trigonometric estimation methods with the circle tool (Paradis et al. 2013). They report that measurements made using the circle tool produce a much larger error margin (nearly 1/3 of the measurements resulted in >60% error) because they seek to calculate the perimeter of the original

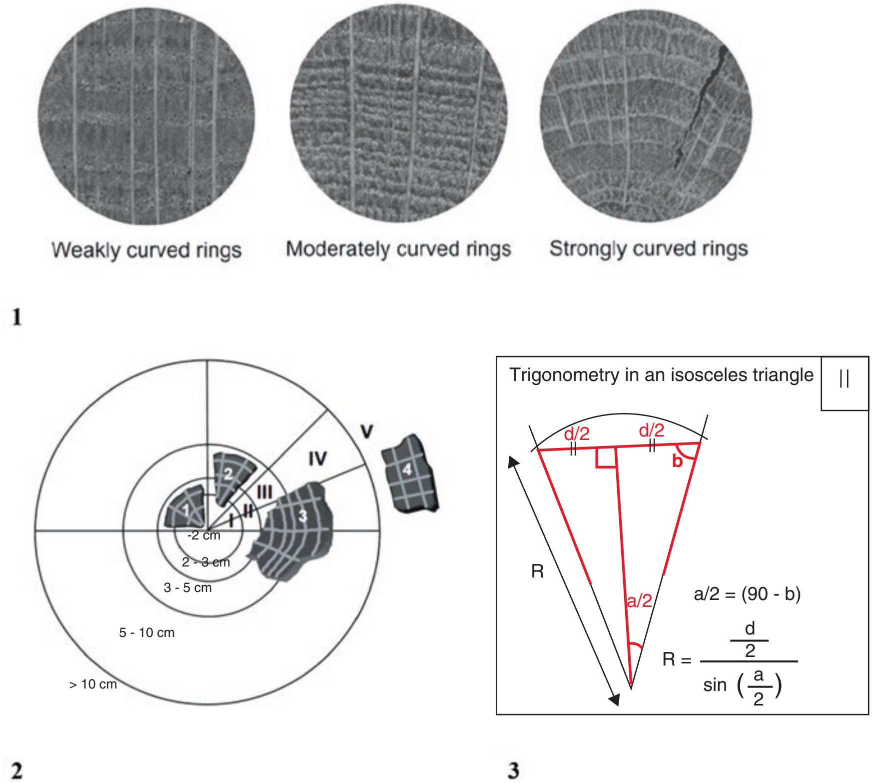

Fig. 2 Diameter estimation methods. 1. Test card for qualitative evaluation of tree-ring curvature degree (After Marguerie and Hunot 2007). 2. Circle tool used for the estimation of wood diameter size classes represented in an anthracological assemblage (After Ludemann 2006). 3. Method of calculation of estimated radius of curvature (R) using the trigonometric method; minimum estimated diameter = 2 × R (After Kabukcu 2017)

log rather than its diameter. By contrast, techniques which rely on geometric and/or trigonometric measurements using the angle of the rays and the distance between two rays to calculate the radius of curvature produce a much smaller margin of error. This is because several anchor points are used thus accounting for variability in curvature. It is also noted, however, that it is often difficult to make accurate diameter measurements of twigs (≤1 cm in diameter) due to the acute angle of the rays close to the pith (Paradis et al. 2013).

On a theoretical basis, Dufraisse (2008: 203) has proposed that fuel waste debris comprises wood charcoal fragments that are representative of the calibre of the logs originally put into fires. In the same paper, Dufraisse also argues that the majority of the preserved charcoal fragments likely derive from the largest diameter portions of the logs originally put into fire. For example, the burning of a log of 15 cm diameter will produce wood charcoal fragments most of which when measured with the trigonometric tool will generate diameter estimates approximating 10–15 cm. Recent burning experiments by Théry-Parisot et al. (2016) conducted on wood of known diameter have provided new insights into the preservation of diameter size classes. Following repeated burning experiments with uniform diameter logs and whole branches/trunks, these authors found significant differences in charcoal diameter classes compared to the proportions of wood diameter classes originally put into fire. While burning experiments have been limited with regard to the different possible combinations of log sizes (i.e. mixtures of larger and smaller logs, log-splitting, etc.), this particular study suggests that when a log is placed into the fire, the outer portions of the log (i.e. those in immediate contact with the fire) are more likely to burn completely and/or preserve as small charcoal fragments. In the case of large diameter logs of uniform diameter (e.g. 15–20 cm), the results of diameter estimation indicate a greater number of fragments in the 5–10 cm and 10–15 cm diameter classes. In the case of fires using predominantly 7–10 cm diameter logs, diameter estimations indicate a far greater number of fragments falling in the 0–5 cm diameter class. When a whole trunk, with all branches and twigs, is burnt, the resulting wood charcoal diameter classes are similarly dominated by small diameters (Théry-Parisot et al. 2016: 492–493). These findings, if tested further with additional fuel use scenarios and under diverse burning environments (e.g. ovens, hearths, outdoor fire features), hold distinct potential for improving current understandings of log diameter representation in archaeological wood charcoal assemblages.

3.3 Woodland Growth Conditions: Ecophysiological Attributes on Charcoal Wood Anatomy

One of the greatest concerns with diameter estimations applied to archaeological wood charcoal remains is to ascertain whether smaller-diameter specimens derive from the inner portions (e.g. the heartwood) of large trunks or from twigs/branches. This necessitates identifying the occurrence of heartwood and sapwood in charcoal fragments. For conifers such determinations may prove difficult, as the main difference between the sapwood and heartwood relates to colour, which is unobservable in carbonised wood remains. On the other hand, in hardwood species that form tyloses (e.g. oak), these are usually absent from the sapwood. Tyloses are overgrown parenchyma cells which spread through pitting on vessels filling out the vessel cavity (Fig. 3). In the heartwood, groups of tyloses often become lignified and block vessel cavities completely thus increasing the resistivity of wood to the spread of fungal hyphae (Wilson and White 1986: 207–211; Taylor et al. 2002). Thus, recording the presence of tyloses provides a useful means of assessing which part of the stem charcoals are likely to have derived from (Dufraisse et al. 2017). However, when trees are felled during their active growth season, tyloses may develop in the sapwood as well. Tyloses may also form when wood is cut during dormancy and

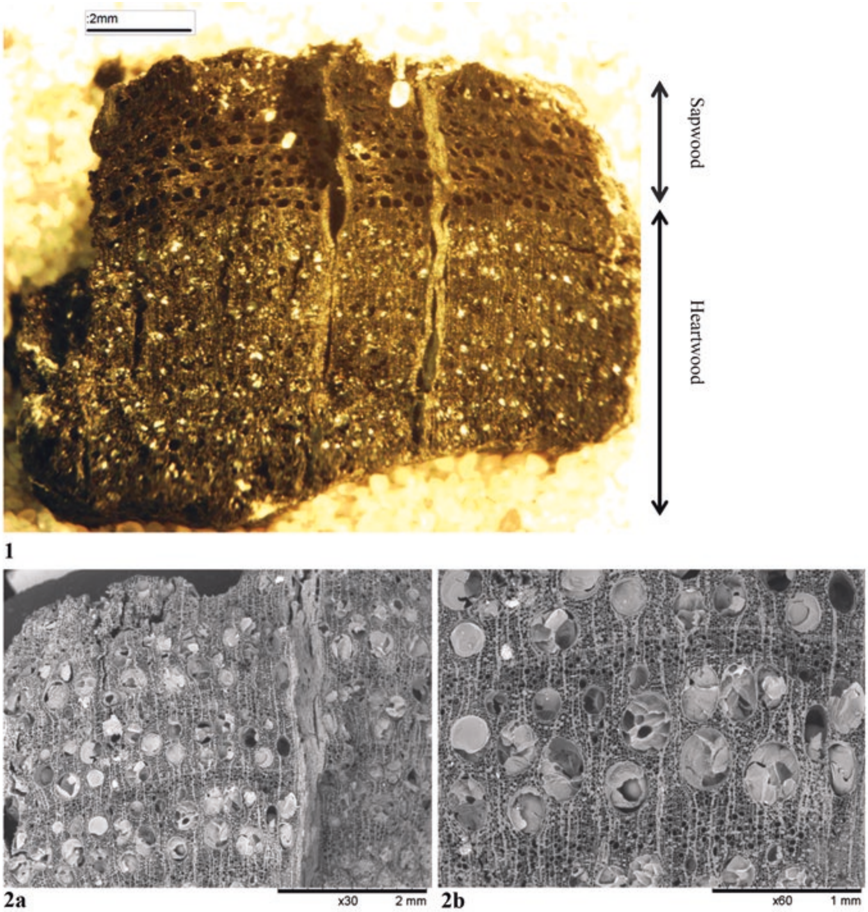

Fig. 3 1. *Quercus* (Çatalhöyük), transition zone from heartwood (with tyloses) to sapwood (without tyloses) (Stereo-zoom microscope digital image). 2a, 2b: *Quercus* (Çatalhöyük), tyloses in earlywood vessels

then stored for a period of time or as a result of other kinds of physical injury (trauma) (Murmanis 1975; Schweingruber 2007).

Several wood anatomical features can provide evidence of woodland growth conditions, environmental stress, damage to the bark and cambium by exogenous factors or anthropogenic impacts (Kabukcu 2017, see Fig. 4). Open wounds (e.g. from bark stripping) cause increased cell formation and cell wall thickening, as well as a change in fibre direction, all resulting in scar tissue formation. Callus formation can be caused by numerous factors including bark and cambium scarring caused by lightning, fire, bark stripping, frost and hail damage, the shedding of twigs and/or needles, etc. (Schweingruber 2007: 188). Traumatic resin canals in conifers and traumatic gum ducts in hardwoods can also form in response to factors such as

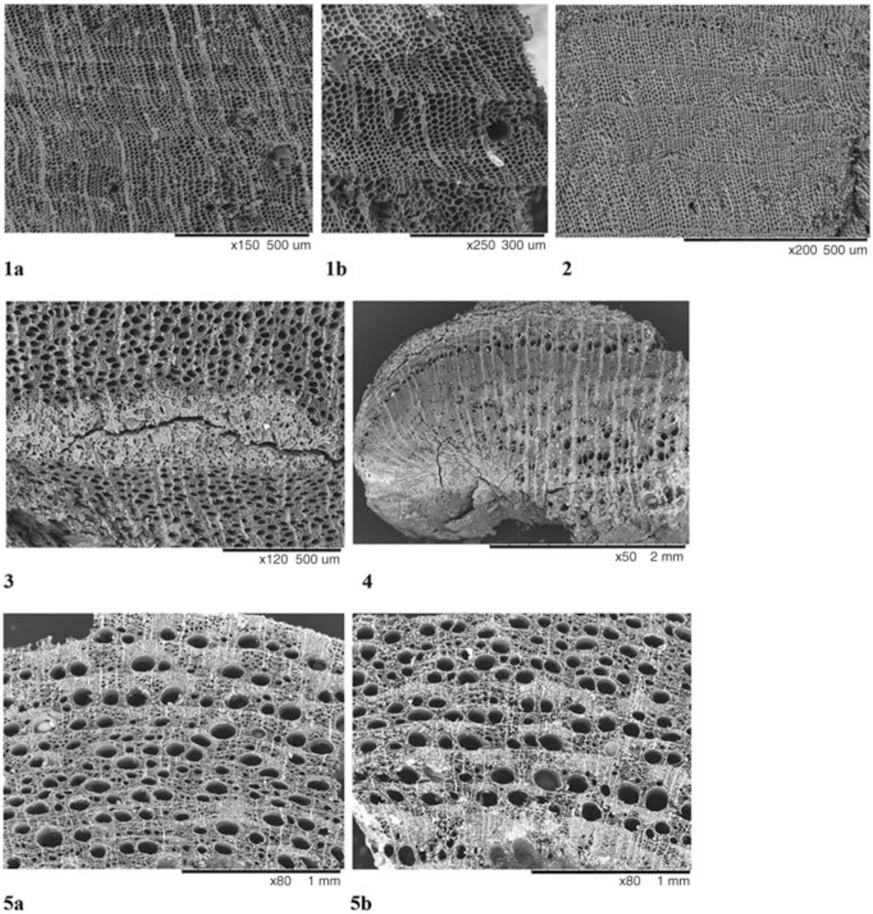

Fig. 4 Qualitative wood anatomical features associated with tree ecophysiology, examples from anthracological remains. 1a, 1b: *Juniperus* (Çatalhöyük), deformed tracheids, narrow and discontinuous rings. 2: *Juniperus* (Pınarbaşı Epipaleolithic), narrow and discontinuous growth rings, deformed tracheids (right). 3: Maloideae (Çatalhöyük), callus tissue. 4: Ulmaceae (Çatalhöyük), scar tissue (wound or damage occurred shortly after initial earlywood formation, radial overgrowth continued during the latewood and earlywood of the following year). 5a, 5b: *Quercus* (Çatalhöyük), round wood fragment with narrow and discontinuous rings

spring frost and other extreme weather conditions and defoliation (Schweingruber 2007: 85, 182, 187). Conditions of severe ecological stress (drought, widespread defoliation) may also lead to the formation of very narrow (<0.2 mm) and/or false growth rings (Schweingruber 2007: 98–99). Increased competition in the understorey (for light and/or nutrients and water) and browsing pressures can result in the formation of series of narrow and/or discontinuous growth rings, resulting from reduced growth rates.

3.4 Woodland Management

Woodland management entails the creation and maintenance of anthropogenic woodland habitats, whereby the density of woodlands stands, their species composition and cycles of regeneration are controlled, to a great extent, by people. These practices can range from more established silviculture systems (e.g. coppicing and pollarding) to the protection of woodland stands and clearance of invasive herbaceous plants and shrubs (Asouti and Kabukcu 2014). In most cases, woodland management relies on the capacity of trees to regenerate from dormant buds on the trunk/stump or from root suckers. In anthracology, particularly in relation to people-environment interactions and palaeoecology, the reconstruction of ancient woodland management, especially the identification of the prehistoric use of coppicing/pollarding practices, has become an important research area. Several recent archaeological applications, including dendrochronology (e.g. Billamboz 2008; Bleicher 2014) and dendroanthracology (e.g. Ludemann and Nelle 2002; Nelle 2002; Dufraisse 2006; Deforce and Haneca 2015), have addressed the question of past woodland management activities through observations on archaeological wood (including carbonised and waterlogged remains). In anthracology woodland management is studied through the application of log/wood diameter estimations (discussed earlier) alongside observations on average growth ring width (e.g. Ludemann and Nelle 2002; Nelle 2002; Dufraisse 2006, 2008; Wright 2017). Such methods may indicate, for example, the predominant presence of more uniform (and small) diameter classes in anthracological assemblages and/or growth improvement patterns, both of which may reflect past woodland management practices. Approaches relying on diameter classes can be problematic due to the differential rates of diameter preservation in archaeological wood charcoal specimens (see discussion earlier; also Théry-Parisot et al. 2016). Additionally, practices such as coppicing, pollarding or bark shredding do not always produce wood logs of uniform diameter. In fact, if coppicing is carried out for the purpose of fuel wood production, then stems of variable sizes will be harvested comprising a mixture of trunk wood, branches and twigs. On the other hand, if management is predominantly aimed at leafy fodder production or building poles, then more uniform diameter classes would have been selected.

Furthermore, it is often difficult to differentiate between the impacts on wood anatomy of management strategies (such as coppicing, pollarding, lopping, etc.) and other environmental factors. Several ecological and anthropogenic factors impact on the growth conditions of managed or unmanaged stands. This situation is further accentuated by the vast amount of intraspecific variability observed in the wood anatomical characteristics of seedlings, long and short shoots and stems. Various studies of managed woodlands (e.g. Rozas 2003, 2004; Corcuera et al. 2006; Copini et al. 2010; Altman et al. 2013; Deforce and Haneca 2015) have demonstrated that management strategies impact wood anatomy either by enhancing or hindering radial growth (hence growth ring width). Generally, shoots growing from cut-down coppice stools have larger vessel diameter and wider growth rings compared to seedlings (see Fig. 5). After a cycle of thinning, involving either the cutting of a patch of coppice stools or the thinning of standards, the remaining trees experience a period of improved growth conditions characterised by an abrupt increase in ring width (referred to as growth release period) (Fig. 5; also Schweingruber et al. 1990; Corcuera et al. 2006; Altman et al. 2013; Schweingruber 2007). Growth release is sustained for 5–10 years, with ring width substantially higher than average growth years. In the years leading up to a cycle of cutting, most sprouts and stems on coppice stools display reduced growth rates, due to competition for light and nutrients caused by increased canopy density (referred to as growth suppression period) (see Fig. 5; also Schweingruber et al. 1990; Rozas 2004; Bleicher 2014). On the other hand, pollarding, pruning and browsing result in a sudden reduction in growth rate, due to trauma and subsequent radial overgrowth (Fig. 5; also Thiébault 2006; Schweingruber 2007: 139).

In rare instances where large numbers of small-diameter wood with pith and bark preserved have been recovered at archaeological sites, these applications can be refined to follow a more dendrochronological methodology (i.e. involving continuous ring-width measurements and comparisons across populations in the same phase; see Deforce and Haneca 2015). In such cases, growth dynamics observed in individual specimens can shed light on management practices with greater accuracy. Recent applications of such methods, by Kabukcu (2017) on the anthracological assemblage from the prehistoric site of Çatalhöyük in central Turkey, highlight the potential of combining diameter estimation methods with continuous growth ring-width measurements and recording of indicators of ecological stress, for characterising woodland management and other environmental impacts on tree growth conditions. In deciduous oak charcoals, diameter classes and curvature degree estimates, proportion of tyloses (indicating presence/absence of heartwood) and continuous ring-width measurements were used to evaluate in detail temporal changes in woodland growth dynamics. Specimens with pith and bark preserved were rare. For this reason, the analysis focused on evaluating average radial growth and rates of change in radial growth observed for each specimen (i.e. the difference between the widest and the narrowest ring width per specimen). Based on these observations, it was argued that deciduous oak charcoals at Çatalhöyük originated mostly from a mixture of coppice shoots, branches and twigs, alongside fragments derived from mature trunk wood.

With the exception of annual growth ring-width measurements, applications of quantitative wood anatomy on archaeological wood charcoal remains have been limited to date. Studies of wood anatomical variation in wild, feral and domesticated olive populations (cf. Terral 2002; Terral and Durand 2006; Terral and Arnold-Simard 1996; Terral and Mengüal 1999) have indicated that variations in vessel density, vessel diameter, total vessel area and growth ring width might signal the effects of different climatic conditions or the impacts of management practices. For instance, lower vessel density has been reported for wild olives growing in conditions of higher moisture availability resulting from irrigation and competing vegetation clearance (Terral and Arnold-Simard 1996).

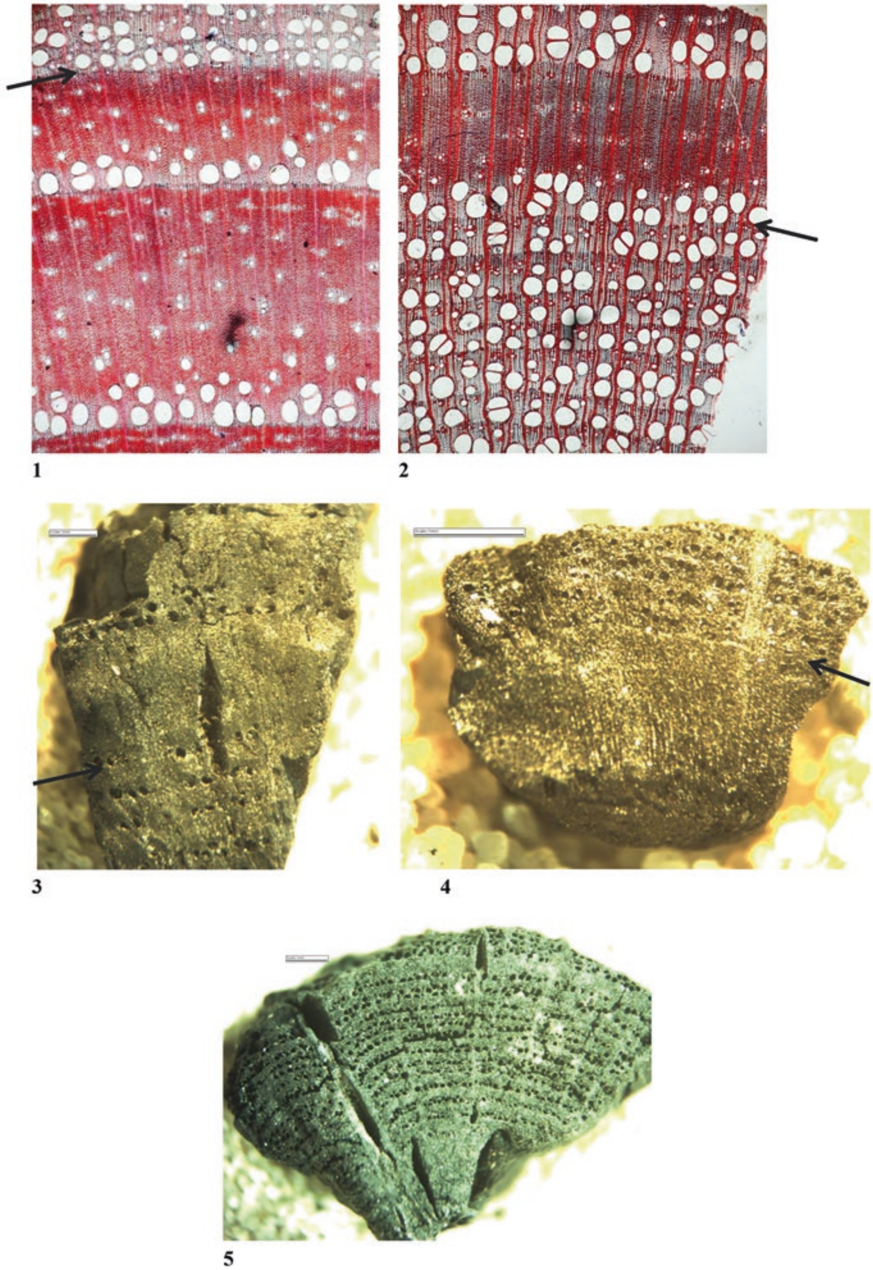

Fig. 5 Growth variability under woodland management. 1. *Fraxinus excelsior*, crown lopping (e.g. pollarding), results in successive growth reduction indicated by arrow. 2. *Fraxinus excelsior*, coppiced stem; arrow indicates growth release period. 3. *Quercus* (Çatalhöyük), arrow indicates growth release. 4. *Quercus* (Çatalhöyük), arrow indicates growth suppression. 5. *Quercus* (Çatalhöyük), suppressed/dwarfed sapling or shoot with brief periods of growth improvement (1–2: images by author, reference material kept by the WSL, F.H. Schweingruber; 3–5: images by author)

4 Conclusions

The aim of this chapter was to summarise the main methodological and interpretative developments in the field of charcoal analysis (anthracology), defined as the study of wood fuel remains derived from archaeological sites. Following the development of charcoal analysis predominantly as a method for reconstructing past woodland composition and its changes through time, more recent applications emphasised the complexities of palaeoecological and cultural signals preserved in archaeological fuelwood remains. It is now well established that anthracological remains (when analysed following strict protocols regarding sample choice and subsampling laboratory procedures) can provide a representative picture of the relative proportions of fuelwood species used by past societies. Anthracological assemblages represent the material residues of people-woodland interactions. Carbonised wood fuel remains embody the signatures of the growth conditions and life histories of the individual trees and shrubs collected as fuel and of the woodland ecologies they have derived from. Thus, not only species composition but also the form, ecological function and environmental setting of past woodland vegetation, and the ways in which these were impacted by management activities, should also be studied. Anthracology provides a unique set of analytical tools with which to disentangle the varied phases of the complex feedback cycles between vegetation, climatic conditions and past woodland management and landscape use practices. For these reasons, archaeological wood fuel remains represent a category of archaeobotanical data that are exceptionally well suited for reconstructing the evolution and long-term histories of anthropogenic landscapes.

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