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Dendroarchaeology in Europe

Willy Tegel[1,2]*, Bernhard Muigg[1,3], Georgios Skiadaresis[4], Jan Vanmoerkerke[5] and Andrea Seim[2,6]

[1] Amt für Archäologie, Kanton Thurgau, Frauenfeld, Switzerland, [2] Chair of Forest Growth and Dendroecology, Institute of Forest Sciences, Albert Ludwig University of Freiburg, Freiburg, Germany, [3] Chair of Forest History, Institute of Forest Sciences, Albert Ludwig University of Freiburg, Freiburg, Germany, [4] Chair of Silviculture, Faculty of Environment and Natural Resources, University of Freiburg, Freiburg, Germany, [5] Regional Archaeological Service, Directions Régionales des Affaires Culturelles, Châlons-en-Champagne, France, [6] Department of Botany, University of Innsbruck, Innsbruck, Austria

Human evolution was strongly related to environmental factors. Woodlands and their products played a key role in the production of tools and weapons, and provided unique resources for constructions and fuel. Therefore wooden finds are essential in gaining insights into climatic and land use changes but also societal development during the Holocene. Dendroarchaeological investigations, based on tree rings, wood anatomy and techno-morphological characteristics are of great importance for a better understanding of past chronological processes as well as human-environment-interactions. Here we present an overview of the sources, methods, and concepts of this interdisciplinary field of dendroarchaeology focusing on Europe, where several tree-ring chronologies span most of the Holocene. We describe research examples from different periods of human history and discuss the current state of field. The long settlement history in Europe provides a myriad of wooden archeological samples not only for dating but also offer exciting new findings at the interface of natural and social sciences and the humanities.

Keywords: tree rings, dendrochronology, land use, paleoecology, wood anatomy, wood technology

Edited by:
Markus Stoffel,
Université de Genève, Switzerland

Reviewed by:
Marta Domínguez Delmás,
University of Amsterdam, Netherlands
Katarina Cufar,
University of Ljubljana, Slovenia

Correspondence:
Willy Tegel
tegel@dendro.de

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INTRODUCTION

Importance of Wood

Since the beginning of mankind people have extracted and processed plant resources. Human cultural development has relied on wood, in particular, for producing tools, building constructions but also as the primary source of energy. Archaeological research, however, has a strong focus on non-biodegradable sources. This is reflected in the so-called three-age system for the rough classification of humans' pre-history into three main time-periods: the Stone Age, the Bronze Age and the Iron Age, which was established by Thomsen (1836) and is still widely used in modern archeology (Kipfer, 2000). This prevailing focus can be explained by the better preservation conditions of inorganic material. Nevertheless, wood has played an equally, if not the most important role as a raw material in all epochs up to our present time. The key role of wood as an energy source only started to diminish in the latest phase of human history, when fossil fuels became widely accessible as alternative sources of energy (Freese, 2003). The increasing use of coal, petroleum and natural gas during the modern period created the preconditions for the industrial development during the 19th century and accelerated considerably with modern chemistry at the beginning of the 20th century. As a result, forest utilization lost much of its importance since modern societies of the 19th and 20th century allegedly have been relieved from depending on renewable forest resources (Ritchie and Roser, 2017). For a great part of human history, however, the development of societies was dominated by their interaction with woodlands, since they relied on forest products for most aspects of their everyday life (Willerding, 1996).

Sophisticated supply strategies for woodland resources have been developed over time and have substantially contributed to the shaping and advance of societies and cultures. In particular, trees had numerous functions as a valuable and diverse source for construction material, fuelwood, raw material (e.g., for tools, weapons, furniture, jewelry), food (fruits, seed, fodder), tanning and coloring agent, fiber production (e.g., clothing, ropes, nets), and for resin and pitch production (Andraschko, 1996).

Dendroarchaeology

Dendroarchaeology is the study of historical and archaeological wood from various contexts and functions (**Figure 1**). These investigations are based on tree rings, wood anatomy and techno-morphological characteristics. With the application of dendrochronology [from ancient Greek: *dendron* (tree), *khronos* (time), *-logia* (the study of)], each tree ring can be precisely dated to a calendar year since annual variations in ring widths are strongly linked to annual variations in weather conditions, which allows for the alignment of ring-width patterns of different trees within a region (Douglass, 1909) (see section “Crossdating” for details on the method).

Comprehensive dendroarchaeological studies combining archeological and dendrochronological methods and data allow valuable insights into the chronological development of cultural processes, the history of ancient woodworking and construction techniques as well as into former forest utilizations and environmental conditions.

Dendroarchaeology, as a relatively young branch of research in archaeology, found its first application in Europe during the 1940s in an interdisciplinary effort to systematically investigate wooden finds from archaeologically excavated pre-historic wetland settlements of the northern pre-Alpine lakes (Rump, 2011). The combination of methods from botany, forestry, timber industry and archaeology helped to optimally process the delicate organic wooden finds (Bräker et al., 1979; Broda and Hill, 2021). For the first time, it was possible to record features and structures as well as the settlement dynamics of prehistoric lakeside settlements with chronological precision (Huber, 1941). As a consequence of the ground-breaking results, wooden remains gained greater attention in archaeological research.

History of Dendrochronological Research

The first description that trees form tree rings was done by Theophrastus (c. 371 – c. 287 BCE), a Greek philosopher and naturalist. Leonardo da Vinci (1452 – 1519 CE), followed by Montaigne (1533 – 1592 CE), were likely the first to recognize that these patterns occur in an annual sequence. The fact that tree rings are suitable for determining the life span of a tree became more generally known in the course of the 17th and 18th centuries, but it was not until the end of the 19th century that Arthur Freiherr von Seckendorff-Gudent began to "overlap" tree-ring sequences of different trees (Wimmer, 2001). Other applications of tree-ring analysis included the evaluation of how tree growth is affected by pollution (Stoeckhardt, 1871). The first attempt to examine the association between tree growth and climate was made by the Dutch astronomer Jacobus C. Kapteyn who matched tree-ring sequences from regions in the Netherlands and Germany (Kapteyn, 1914; Stallings and Schulman, 1937). However, Andrew E. Douglass, an American astronomer defined the science of dendrochronology, as he aimed at using tree rings to demonstrate a connection between the earth’s climate and the 11-year cycle of sunspots (Douglass, 1920). By using the method of crossdating (**Figure 2** and see also section “Crossdating”), Douglass was also able to determine the age of dead and decayed tree samples and in 1929, he established a continuous 1229-year long tree-ring chronology extending back to 700 CE. For the first time in history it was possible to date timber from archaeologically excavated cliff dwellings from the 13th century at Tsegi Canyon, Mesa Verde, and Canyon de Chelly with annual precision (Douglass, 1935). Inspired by Douglass’ success, several researchers from Russia, Scandinavia and Germany independently studied European tree species. The further development of dendrochronology in Europe is strongly connected with the pioneering work of the Austrian botanist Bruno Huber, who initiated research on tree rings at the former Royal Saxon Academy of Forestry in Tharandt, Germany, in the 1930s (Eckstein and Wrobel, 1983; Rump, 2011). While Douglass used extreme wide and narrow rings to cross date, Huber adjusted Douglass’ method by measuring and plotting each ring of the tree, owing to the fact that trees from temperate zones show less pronounced year-to-year variability than trees from semiarid zones (Eckstein and Pilcher, 1990). As early as 1941, Huber used this method to date several archaeological sites in eastern, northwestern, and southern Germany (Huber, 1941; Rump, 2011). Huber’s successful dating of the Bronze Age palisades at Wasserburg Buchau, southwestern Germany, marked the beginning of modern dendroarchaeology in Europe (Huber and Holdheide, 1942).

The increasing amount of dendrochronologically dated wood samples enabled further studies including the establishment of the radiocarbon calibration curve (Huber and Jazewitsch, 1958). By successfully dating three Neolithic settlements in eastern Switzerland (Thayngen Weier, Burgäschisee Süd, and Burgäschisee Südwest), Huber established their chronological parallelism and proved for the first time that the so-called Pfyn and Cortaillod cultures (ca. 3900–3500 BCE) had coexisted at the same time (Huber et al., 1963). Furthermore, Huber and his team worked on the development of reference tree-ring width chronologies for central Europe, for example, the first and well-replicated 1000-year long oak chronology for Hesse (central Germany) (Huber, 1963; Huber and Giertz-Siebenlist, 1969). This pioneering work was accompanied by further initial dendroarchaeological investigations mainly in northern parts of Europe (e.g., Kolchin, 1962; Bauch, 1968). The German dendrochronologist Ernst Hollstein played a pivotal role in further implementing dendrochronology in Europe. Since 1960,

FIGURE 1 | Wood sources for dendroarchaeological research: **(A)** Subfossil trees from a gravel pit in the Upper Rhine Valley (Leutenheim, France). **(B)** Neolithic pile excavated underwater in Oehningen-Orkopf, Lake Constance, Switzerland. **(C)** Water well lining from the Late Bronze Age, excavated in Erstein, France. **(D)** Post foundation of a Roman building in Vendresse, France. **(E)** Medieval silver mining gallery in the Black Forest (Schauinsland, Germany). **(F)** Half-timbered house in Troyes, France. **(G)** Late medieval roof truss in Langenrickenbach, Switzerland. **(H)** Modern sawmill in Many, France. **(I)** Neolithic knife with flint blade and wooden handle from Allensbach, Germany. **(J)** Late Bronze Age construction timber from Erstein, France. **(K)** Late Iron Age wooden hammer from Saverne, France. **(L)** Roman comb and **(M)** box from Troyes, France. **(N)** Modern painting and **(O)** violin.

he sampled living and historical material in western Germany, France and Switzerland and established a 2500-year long oak tree-ring width chronology (Hollstein, 1967, 1980; Rzepecki et al., 2019). Moreover, Hollstein not only introduced wood physical and technological characteristics to determine the time of tree felling, he also investigated the relationship of heartwood and sapwood rings in oaks and thus, established the commonly applied sapwood statistics, enabling more precise estimations of oak felling dates (Hollstein, 1965).

After the death of Bruno Huber, his former research associate Bernd Becker continued his work at the University of Stuttgart-Hohenheim (Germany). He further extended the existing chronologies with a strong focus on subfossil trees, deposited in fluvial gravel, and developed millennia-long tree-ring chronologies for southern Germany that covered most of the Holocene (Becker, 1982). His tree-ring chronologies still provide a crucial basis for dendroarchaeological and paleo-environmental studies in central Europe (Friedrich et al., 2004). Other millennia-long tree-ring width chronologies have also been developed since the late 1970s and 1980s, for example by Pilcher (1976), Baillie (1977), Pilcher et al. (1984), Leuschner and Delorme (1988), and Kuniholm (1994, 1996) which has led to a growing interest of archaeologists in this novel and high-precision dating method (Bannister and Robinson, 1975).

While Hollstein also worked with wood anatomical features, it was the Swiss dendrochronologist Fritz H. Schweingruber who provided the first wood anatomical atlas in three languages, a standard reference for wood identification of central European tree species (Schweingruber, 1978). Moreover, he published a first perspective on the significance of prehistoric wood samples for both archaeological and vegetation scientific studies (Schweingruber, 1976). Fundamental conceptual works for the application of dendrochronology in archaeological and (paleo)ecological research were published in the early 1980s, e.g., by Baillie (1982) and Schweingruber (1983), creating the basis for the practical implementation of tree-ring studies on archaeological wooden finds. Dendrochronology became a standard method applied in archaeological studies during the 1980s, constituting the onset of modern dendroarchaeology in various European countries (Eckstein and Wrobel, 1983).

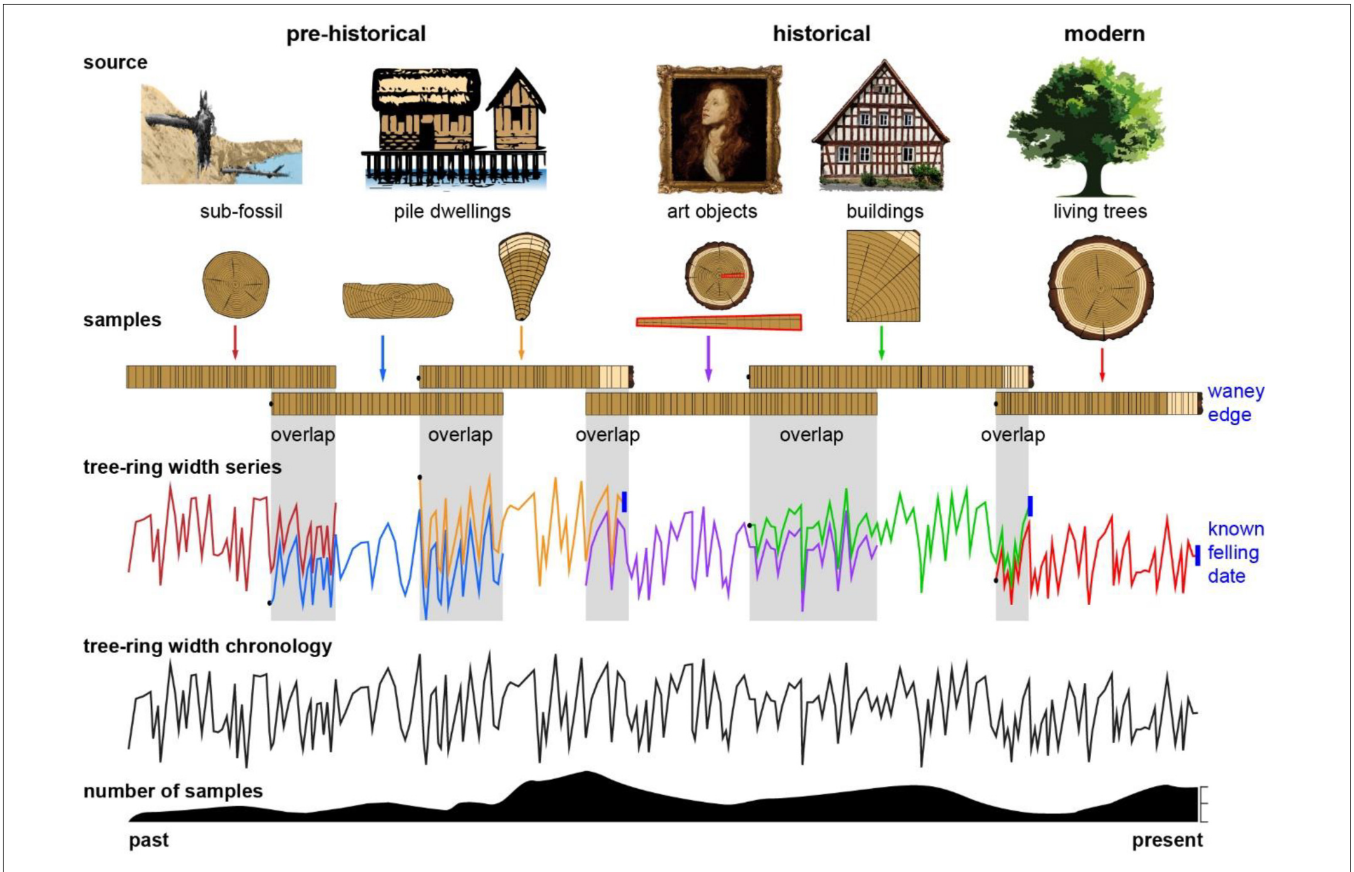

FIGURE 2 | Schematic illustration of the crossdating process. The climatic-related sequences of wide and narrow rings of the wooden samples allow the dating of wood from different sources and the development of millennia-long tree-ring width chronologies. Since the material is not evenly available through time, consequently the number of samples (replication) varies too.

This development led to the establishment of more dendroarchaeological laboratories across Europe. During this time, first large-scale archaeological projects for different periods implemented the newly established discipline. To mention only a few examples for pre-historic times, on circum-alpine lakes in France, Germany, Italy, Switzerland and Slovenia[1], for Iron Age Biskupin, Poland (Reynolds, 1985), and for medieval times in Dorestadt, The Netherlands (van Es and Verwers, 1980), Mikulčice, Czechia (Dvorská et al., 1999), Hedeby and Lübeck, Germany (Eckstein, 1978). In the context of these projects, numerous new laboratories have been founded, frequently by archaeologists who started using dendrochronology (Bernard, 1998). As a consequence, the focus on archaeological research questions intensified toward wood utilization, species selection, resource management and the technical and architectural development of settlements (e.g., Billamboz, 1988). The advances of dendrochronology provoked further interest from the fields of historical building research, however, with a stronger focus on dating and provenancing, and mainly performed by numerous newly founded laboratories all over Europe (e.g., Kuniholm and Striker, 1990; Eißing, 2005; Épaud, 2007; Hoffsummer, 2009; Kyncl, 2016; Domínguez-Delmás et al., 2018). Over the last decades, vast amounts of dendroarchaeological data have been collected from countless archaeological sites and historical constructions as well as from natural depositions in paleo-channels and from living trees all over Europe. The great number of laboratories and their interaction accelerated the development of well-replicated centennial to millennia-long tree-ring chronologies for various European regions, placing Europe in a unique position compared to the rest of the globe (Becker et al., 1985).

However, the state of dendroarchaeological research varies greatly among different countries and regions due to different research foci, political settings and administrative structures.

MATERIAL

Conditions and Forms of Preservation

Wood is an organic matter, easily biodegradable by bacteria and fungi and their enzymes (Blanchette et al., 1990; Pedersen et al., 2020), but under special conditions wooden structures and objects can be preserved for a long time (**Figure 3**). One such case of wood preservation is the lack of moisture in

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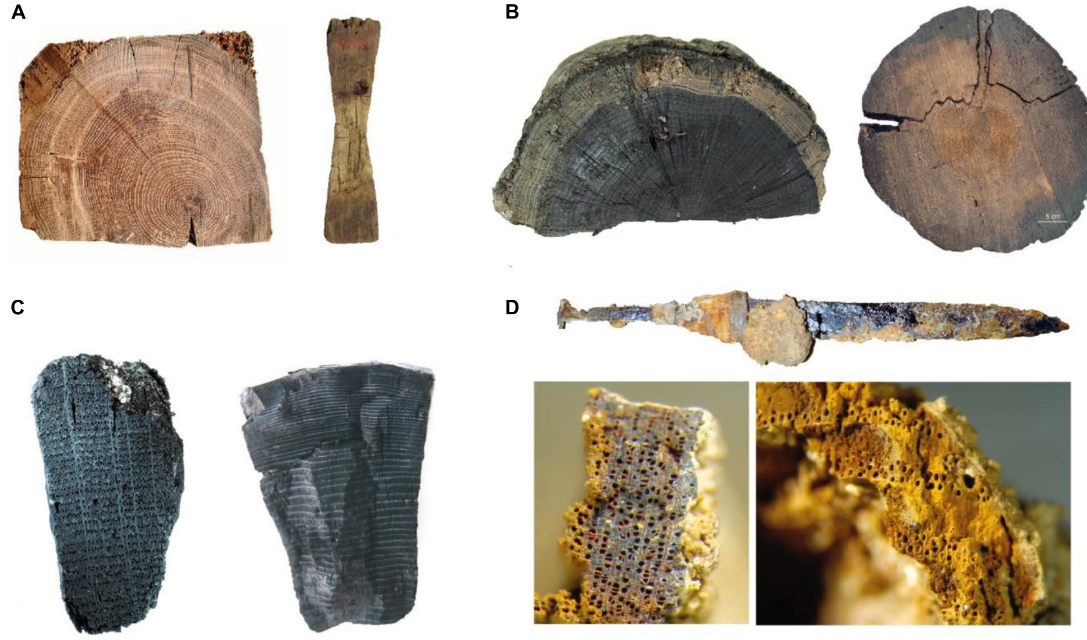

FIGURE 3 | Different types of wood preservation. **(A)** Dry preserved wood from scaffolding timber from the cathedral Notre-Dame de Reims, France (1211 CE, Tegel and Brun, 2008) and the "pagan wall" on Mont Sainte-Odile, Ottrott, France (7th century CE, Tegel and Muigg, 2015). **(B)** Wood preserved under wet conditions from a late bronze age well made of oak in Erstein, France (1208 BCE) and from a preboreal pine from gravel quarry at Pont-sur-Seine, France (^{14}C 11000 ± 60 BP). **(C)** Charcoal from oak (Cuperly, France, 133 BCE) and silver fir (Schauinsland, Germany, 1545). **(D)** Wood (alder (*Alnus* sp.; *left*) and ash (*Fraxinus excelsior*; *right*) preserved through mineralization processes on early medieval weapons, found as grave goods in burials (Tegel et al., 2016a).

constantly dry environments. Such conditions prevail mostly in arid regions, e.g., at the Syrian site of Dura Europos, but are occasionally also found in central Europe (Tegel and Muigg, 2015; Tegel and Croutsch, 2016; Baird, 2018). Another form of wood preservation is achieved when constantly low temperatures prevent biodegradation. These preservation conditions are mainly found in permafrost soils, e.g., the Kurgan graves of Pazyryk (Russia), but also in alpine glaciers (Polosmak and Seifert, 1996; Parzinger, 2006; Nicolussi, 2009). Other forms of preservation are associated with the deposition in a biotoxic environment, for example, in the famous Hallstatt saltmines, Austria (Herzig, 2009; Reschreiter and Kowarik, 2019; Haneca and Deforce, 2020; Grabner et al., 2021), and the chemical alterations of the wood tissue through carbonization and mineralization (Chabal, 1997; Tegel et al., 2016a; Haneca and Deforce, 2020). However, the most important form of wood preservation is provided by waterlogged conditions, frequently discovered at archaeological excavations, for example in water wells and other features below the groundwater level (Kretschmer et al., 2016; Croutsch et al., 2020), from pile dwellings in lakes and bogs (e.g., Bleicher, 2009; Tarrús, 2018; Benguerel et al., 2020; Hafner et al., 2021; Pranckënaitë et al., 2021), shipwrecks at the bottom of seas, lakes and rivers (e.g., Domínguez-Delmás et al., 2013; Nayling and Susperregi, 2014; Daly et al., 2021) and paleo-channels (Pilcher et al., 1977; Becker et al., 1985; Leuschner and Sass-Klaassen, 2003; Edvardsson et al., 2016b; **Figure 1**). Waterlogged wooden objects can be preserved for millennia (Thieme, 1997; Tegel et al., 2012; Rybníček et al., 2020). As wood cells and inter-cellular spaces are filled with water, freshly excavated waterlogged wooden objects display the original shape and surface. However, despite the intact surface, the cell walls are degraded, the percentage of cellulose and hemicelluloses is decreased and the proportion of lignin is increased. In this way the mechanical properties of the wood are reduced (Schweingruber, 1976; Čufar et al., 2008c; Björdal, 2012).

Wood Sources

The wooden material for dendroarchaeological analysis originates from different sources, including archaeological excavations, historic buildings, museums and private collections, natural deposits, and modern forests (**Figure 1**).

A great amount of samples is obtained from archaeological excavations and historical buildings. Archaeological excavations regularly unearth well-preserved wooden structures and everyday objects of past societies. Ever since the 19th century, various small to large-scale excavations have unearthed wooden objects. The quality of archaeological documentation and the treatment of these delicate finds varied greatly, depending on the timing of the excavation and the experience of the excavating personal. Improved technical standards for the treatment of archaeological sites and historical buildings were set in the second half of the 20th century, when most European countries passed legislations for heritage protection (Martin and Krautzberger, 2010). By the turn of the millennium, most European countries furthermore ratified international laws for the treatment of archaeological sites, defined by the International Committee for the Management of Archaeological Heritage in the Charta of Lausanne and the Charta of La Valetta (Malta) in 1989 and 1992, respectively (Hönes, 2005).

Since the beginning of modern dendroarchaeology in the 1980s, European laboratories have produced dendroarchaeological data for various regions, different species and with different chronological emphases. Within the last decades, it has become evident that areas with active and well organized departments for preventive archaeology generally show larger quantities of wooden finds than others (Laurelut et al., 2014). The same applies for other forms of physical heritage, e.g., historical buildings. The number of historical constructions and monuments studied, dated and therefore accessible for further dendroarchaeological studies strongly depends on the statutory framework and on how well-equipped and organized regional departments of heritage conservation are. Aside from historical timber, other sources of wood from historical buildings are concealed within cavities in the construction, e.g., between ceilings and floors, and occasionally studied by medieval and post-medieval archaeologists (Lohwasser, 2011; Atzbach, 2012). A special case of historical wood material is found in art objects, e.g., panel paintings, and instruments which are in most cases well-studied and safely stored in museums or private collections (Fraiture and Dubois, 2011).

Modern reference material is available from living trees in forests or recently harvested trees and is used for the development of reference chronologies and calibration with instrumental climate data to study past climate variations (e.g., Büntgen et al., 2011c; Cook et al., 2015; Tegel et al., 2020).

METHODS AND CONCEPTS OF DENDROARCHAEOLOGICAL RESEARCH

Sampling and Documentation

Dendroarchaeology combines typological analyses of surface treatments with internal features of tree growth. Size, cross-sectional shape and tool marks provide information on woodworking techniques and woodland use, whereas annual growth rates allow, besides the chronological classification of wooden objects, the study of the woodland's history. Knowledge of the utilized wood species further enables syntheses on the development of construction techniques, building history and settlement dynamics. Comprehensive and consistent sampling is a necessary precondition for conclusive results of dendroarchaeological studies. The individual sampling strategy depends mostly on the different research questions that address technological as well as ecological issues and are established in close collaboration with the excavating archaeologists or conservators. Note that any valid scientific statement regarding past forest composition, resource management or wood utilization requires extensive quantities of samples (Büntgen et al., 2012). Ideally, every excavated wooden object should be entirely removed from the soil or sampled and investigated immediately after and before any conservation treatment. Therefore, waterlogged wooden objects should be generally kept in plastic wrap to prevent that cell walls break and the wood collapses due to desiccation. *In situ* documentation of archaeological artifacts is provided by field archaeologists. Prior to the extraction of a sample, the wooden object is cleaned, if necessary, and documented (e.g., photographed and/or by creating drawings or scans) for the study of tool marks, as distinct techno-morphological features are partially only visible after the excavation (**Figure 4**). Following the careful investigation of the artifact's surface, a cross-sectional sample is extracted for tree-ring analyses. Simple preparation techniques are applied to improve the visibility of annual ring boundaries. In most cases, surface treatment with razor blades or cutters is sufficient. Powdered chalk can be used to enhance the contrast of the different cell types and therefore improve visibility of tree-ring boundaries, especially for narrow rings.

Documentation of the cross-sectional shape provides important information about the size and diameter of the trees used for timber and the woodworking process, e.g., the longitudinal splitting of trunks (**Figure 5**). To secure this information, standardized sketch drawings are prepared. The scale used depends on the size of the wooden object, a scale of 1–5 has been proven effective in most cases (**Figure 5**). It must be emphasized that the point of sample extraction on the object should be selected by the dendroarchaeologist to prevent sampling in areas of disturbed tree-ring patterns such as branches, cracks, wounds, reaction wood, etc. (Schweingruber, 1976). To maximize the obtained information, samples should ideally include the full tree-ring sequence from the pith to the bark (waney edge).

In historical buildings, documenting the location of the sample on photos or architectural plans is necessary to record the context within the construction and to combine chronological and technological information (**Figure 6**). By experience, a minimum of 6–10 samples per structural unit are needed. With the exception of art objects (i.e., paintings and sculptures), sample collection for dendroarchaeological research is performed by sawing cross-sections or by coring samples with increment borers (**Figure 6**). Dendroarchaeological analyses on art objects, instruments and furniture is conducted using either invasive non-destructive methods (i.e., cleaning with a scalpel; Edvardsson et al., 2021) to non-invasive methods (e.g., X-ray computed tomography; Daly and Streeton, 2017; Domínguez-Delmás et al., 2021).

Wood Anatomy

The study of wood anatomical features is a crucial step in dendroarchaeological studies for several reasons. Firstly, the taxonomical identification based on these features, holds information of intentional species selection of past societies (Tegel and Croutsch, 2016; Tegel et al., 2016a). Secondly, it is necessary to develop species-specific master chronologies for dendrochronological dating. Thirdly, microscopic examinations of wood anatomical anomalies (e.g., frost rings, light rings or traumatic tissue) can provide important information for paleo-ecological research (Wimmer, 2002; Schweingruber, 2007).

FIGURE 4 | Examples of the documentation of archaeological waterlogged wood (Rybníček et al., 2018) by **(A)** photos of tool marks from slashing tools (axes, adzes) and saws, **(B)** drawings (Tegel and Croutsch, 2016), and **(C)** laser scan (Tegel et al., 2012).

Wood anatomical features are studied on transverse, radial and tangential thin-sections under microscopes for taxonomical identification and to determine growth anomalies. Modern and waterlogged wood is usually investigated under a transmitted light microscope after producing thin-sections. Charcoals and mineralized wood are treated in a different way since it is usually not possible to produce thin-sections. Here, samples are broken to provide "clean" surfaces that are studied under a reflected-light microscope. Taxonomical identification can be performed using standard identification keys based on wood anatomical features (Wagenführ, 1966; Grosser, 1977; Schweingruber, 1990; Schoch et al., 2004). Distinctive features are, for example, presence of resin canals, type of rays, crossfield pits for coniferous wood and distribution and size of vessels, type of perforation plates, type of rays, type of axial parenchyma for broad-leaf wood (Schoch et al., 2004; Schweingruber, 2011). Modern equipment like digital microscopes, confocal laser scanning microscopes, improved techniques of scanning electron microscopy, multi-resolution X-ray tomography etc. (e.g., Haneca et al., 2012; Balzano et al., 2019) have significantly facilitated the identification of all categories of wood. This method enables the analyses of tiny and highly degraded samples, which are often difficult to determine by conventional microscope techniques and further provides the advantage of simultaneous photographic documentation. Non-invasive imaging techniques have been developed in recent years and offer new perspectives for the visualization of wood anatomical structures and their analysis.

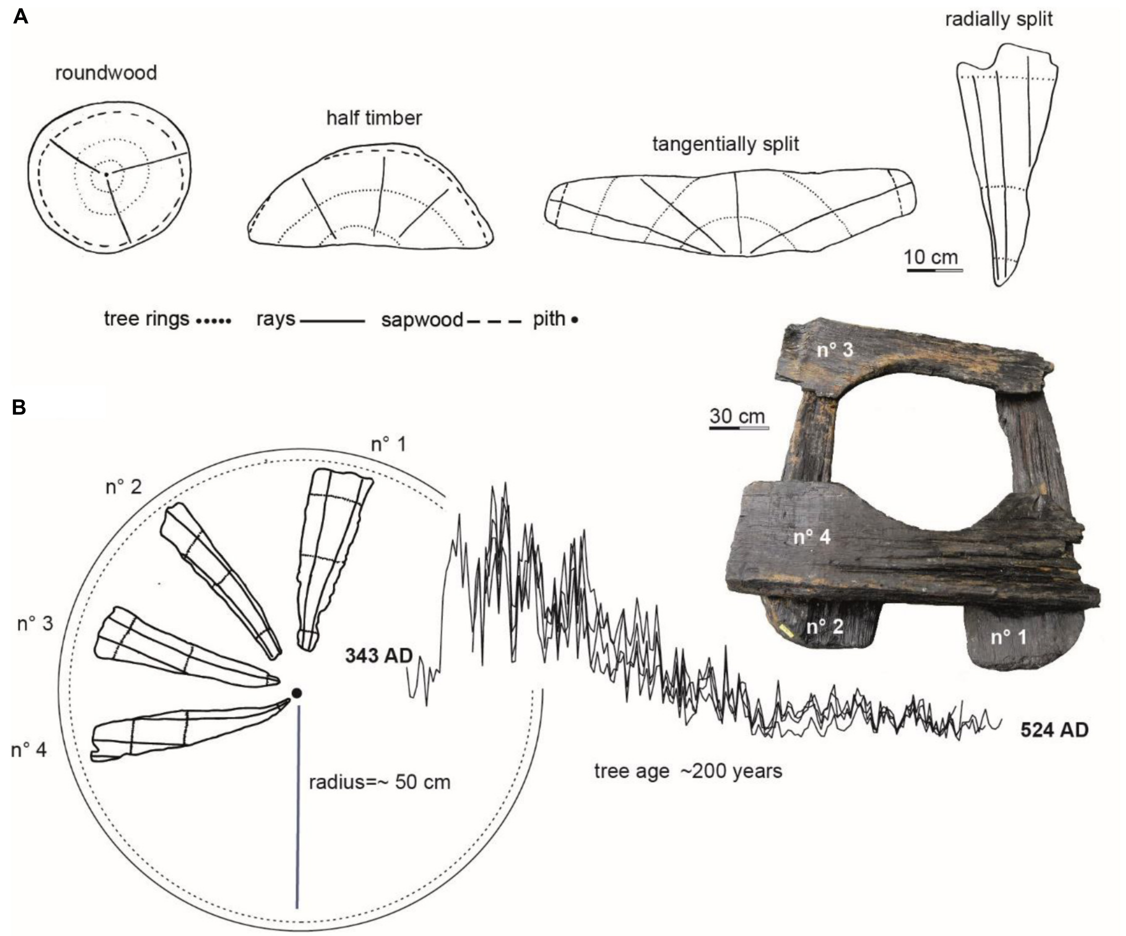

FIGURE 5 | Documentation of the used trees by **(A)** drawing the cross-sectional shape on a scale of 1:5 and **(B)** reconstruction of the origin and attribution to one individual tree trunk by using cross-sectional shapes and highly synchronous tree-ring growth patterns of the individual tree-ring curves.

Crossdating

Growth rings reflect the seasonal to annual radial growth of a tree. Such tree rings are clearly visible on the cross-section of a tree sample. By counting the annual rings, the cambial age of a tree is known. Ring widths vary due to environmental conditions, especially weather conditions, that affect the tree during wood formation but ring-width variations are also influenced by the wood species, location and position of the tree within a forest, stand dynamics, forest management practices and individual factors such as forest pests. By measuring the width of individual tree rings, a chronological sequence (tree-ring series) is obtained that is potentially characteristic for all conspecific trees within a site or even region. This is comparable to a spatio-temporal fingerprint. The method of crossdating enables the chronological placement of a tree-ring sequence, allowing the precise identification of the year in which each tree ring was formed (Douglass, 1941). Therefore, it provides the basis for all further chronological analyses such as the precise dendrochronological dating of wooden objects. Moreover, tree rings provide a valuable archive for past environmental conditions, readable from the variation in tree-ring width and wood anatomical features, such as density fluctuations, vessel sizes, and growth anomalies (Schweingruber, 1996).

Tree-ring widths are usually measured with a precision of 0.01 or 0.001 mm using semi-automatic measuring tables, e.g., LINTAB[2] or VIAS[3]. Programs like for instance Coo Recorder[4] which enable tree-ring measurement on images (manual or by automatic recognition of tree rings) are frequently used as well. The tree-ring width measurements are transformed into curves of tree-ring series showing the variation of tree-ring widths over time allowing for their visual and statistical crossdating by using statistical parameters calculated by special programs, e.g., TSAP (Rinn, 2003) or PAST (Knibbe, 2008). *Gleichläufigkeit* expresses the year-to-year agreement between tree-ring series, i.e., the percentage of synchronous growth changes (Eckstein and Bauch, 1969; Buras and Wilmking, 2015). The quality of a correlation is calculated with *t*-tests transformed after Baillie and Pilcher (1973) (TBP) and Hollstein (1980)

[2] rinntech.de
[3] sciem.com
[4] cybis.se

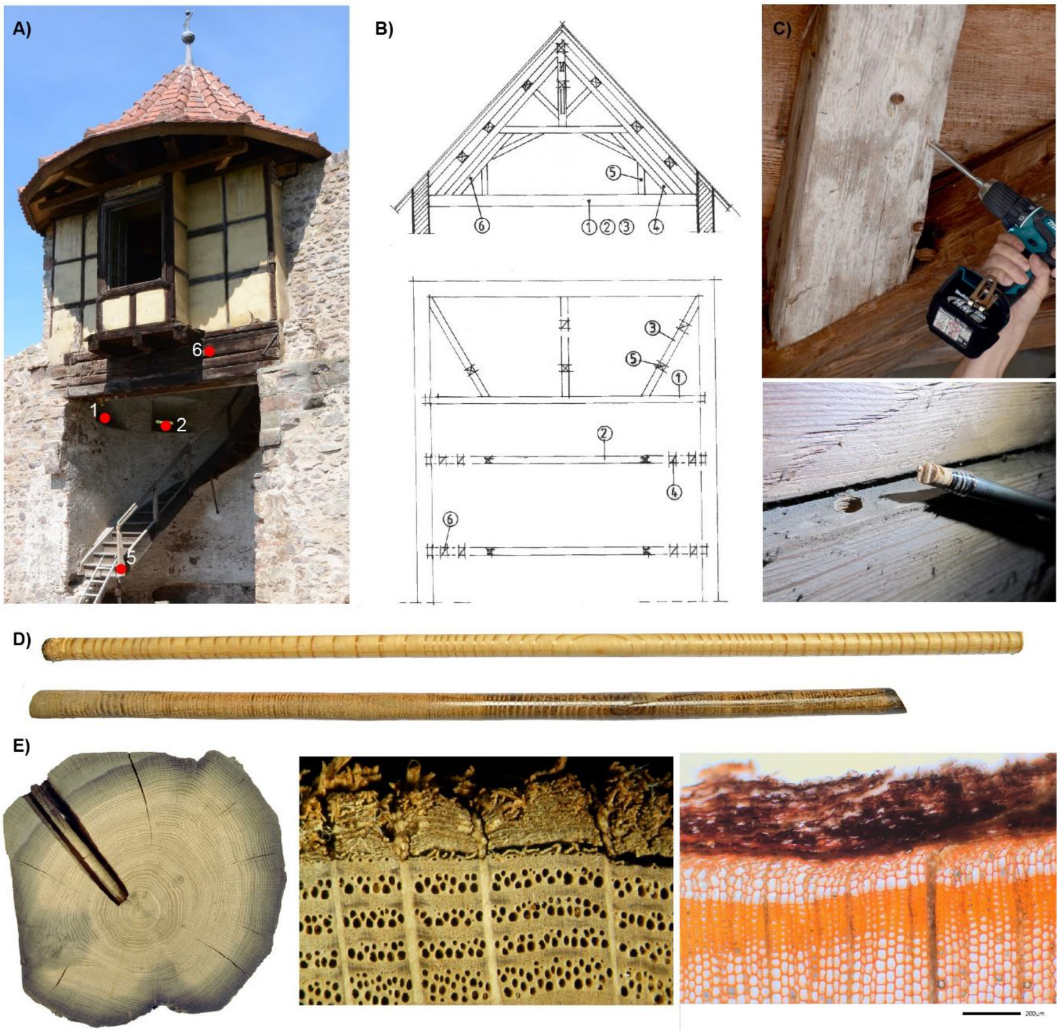

FIGURE 6 | Documentation of the location of historical timber on **(A)** photograph or **(B)** construction plans sampled with **(C)** increment borers and cordless drill. **(D)** The retrieved cores with **(E)** sapwood and heartwood (drilled oak disk; *left*) and waney edge (*center* and *right*) with parts of the bark, earlywood vessels (oak; *center*) and earlywood cells (pine; *right*) are distinguishable.

(THO) (**Figure 7**). The Pearson Product-Moment Correlation (r) (Pearson, 1895), frequently used for linear correlation between two sets of data, requires additional elimination of individual growth trends (Speer, 2010). This so-called detrending method is already implied in the t-test calculation (TBP, THO) to highlight year-to-year variations. However, it is crucial to store the raw tree-ring width data for further investigations. For this purpose, a simple ASCII text code is the best solution, as these are readable, regardless of operating systems, and data can be easily exchanged. The most frequently used file formats are Tucson (.rwl or.tuc) and Heidelberg (.fh). We recommend the use of Heidelberg-format, as this allows to include a wide range of metadata such as the information on pith, sapwood rings, waney edge etc.

Crossdating must include all statistical approaches and the visual comparison of the measured tree-ring width sequences. The comparison of the tree-ring pattern, i.e., the sequence of wide and narrow rings, between trees allows for the assignment of each tree ring to a precise calendar year. In this way, it is possible to build annual tree-ring width chronologies consisting of numerous tree-ring series from different sources with overlapping lifetimes of the trees (**Figures 2**, **7**). These chronologies cover several centuries to millennia (e.g., Becker and Giertz-Siebenlist, 1970; Hollstein, 1980; Becker, 1993; Grudd et al., 2002; Friedrich et al., 2004; Baillie, 2009; Nicolussi et al., 2009; Seim et al., 2012) and serve as reference chronologies for dendrochronological dating. The quality of a reference chronology strongly depends on high sample replication, which should ideally be equally well-distributed over time. This is necessary to generate robust estimates of past growth rates and significantly improves the dating success (Büntgen et al., 2012). The spatial extent of

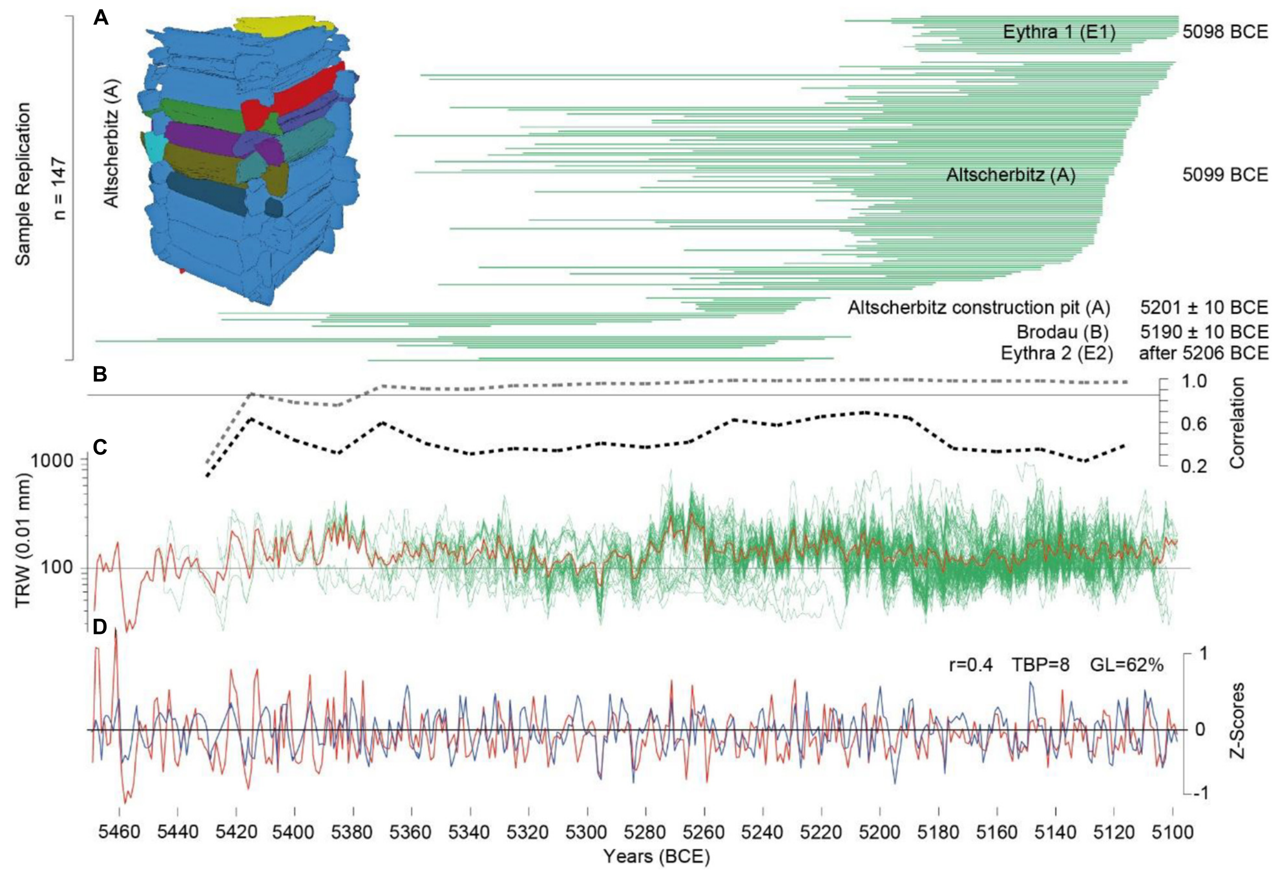

FIGURE 7 | Graphical presentation of dendrochronological results (Tegel et al., 2012). **(A)** Temporal distribution of the lengths of individual tree-ring sequences, and the youngest felling dates per construction, based on the presence of waney edges (annually precise) or sapwood estimation. The inset shows a 3D reconstruction of a wooden lining displaying each tree using a different color. **(B)** The common signal in the chronology [so-called Expressed Population Signal (dotted gray line)] and the inter-series correlation (dotted black line) calculated over 50 years lagged by 25 years along all individual samples. **(C)** Single ring-width measurements (green) and their mean (red). **(D)** Absolute dating of the new Saxon oak chronology (red) against the reference chronology from the Main River Valley (Becker, 1982) after 10-year low-pass filtering [*r*, correlation coefficient; TBP, *T*-value (Baillie and Pilcher, 1973); GL, Gleichläufigkeit].

coherent growth patterns covered by a reference chronology depends on the species and their discrete physiogeographical area and thus, cannot be clearly delimited. For this reason, it has been proven useful to produce local and regional chronologies and further combine them to supra-regional chronologies especially when working on dendroarchaeological material. The use of various dendrochronological databases assists the compilation of individual chronologies which can be (re)assembled for specific research questions. Successful dating of archaeological and historical wood is usually confirmed by several independent reference chronologies. Constant improvement of the replication allows periodic updates and improvement of reference chronologies.

The Accuracy of Dendrochronological Dating

After a successful synchronization with a reference chronology, every tree ring can be attributed to a calendar year. For information on the felling date of a tree and the construction date of a wooden building, respectively, more aspects need to be considered. (1) The state of preservation of the material, (2) the tree species (e.g., for sapwood estimation), and (3) whether the outermost ring (waney edge), i.e., the last ring formed before felling, is present on the specimen.

If the waney edge is present and the stage of its development (e.g., early- or latewood formation) is observable, the exact year and season of the felling of the tree can be determined with the so-called "waney edge dating."

If the waney edge is missing but sapwood rings are present, the felling date can be estimated for species with distinct sapwood such as oak (*Quercus* spp.) or larch (*Larix decidua*) by adding an empirically obtained number of sapwood rings to the last measured sapwood ring. In this "sapwood dating", the felling date of the tree can be estimated with a precision of approximately 10 years for oaks, for example.

In the case of absent sapwood rings and waney edge (i.e., only heartwood is present), only a *terminus post quem* (i.e., the earliest possible felling date) can be provided. In the case of oak, a certain number of sapwood rings are added to the last measured

FIGURE 8 | Stem disks of two oak piles from a late Iron Age bridge (Pont-sur-Seine, France) with heart wood, sapwood and waney edge (Leroux et al., 2018).

heartwood ring, based on the empirically obtained minimum number of sapwood rings.

Regarding the number of missing sapwood rings, different statistically based estimates exist for various regions (Eißing, 2005). For example, British oaks show 10–55 sapwood rings (Hillam and Tyers, 1995), in Western Germany oaks develop 9–33 sapwood rings (Hollstein, 1980) and in Northern Germany 10–30 (Wrobel et al., 1993). The number of sapwood rings for Poland ranges between 9 and 23 (Wazny and Eckstein, 1991), for Southern Pannonia (SI, HR, RS) 5–32 (Jevšenak et al., 2019), for Moravia (CZ) 5–21 (Rybníček et al., 2006), and for the Baltic and Southern Finland 6–19 (Sohar et al., 2012). All of these values are estimates, based on statistical averages. Hence, the exact number of sapwood rings of an individual tree remains unknown and might differ considerably (**Figure 8**). Apart from the geographical region where a tree grew, its age and growing conditions can also affect the total amount of developed sapwood rings. For example, old and slow growing oak trees generally have more sapwood rings compared to fast growing or younger oak trees (Haneca et al., 2009).

Contributions to Past Climate Estimation, Wood Utilization, Land Use, Settlement and Building History

Dendrochronological dating of historical and archaeological wood has developed into a standard method in modern archaeology and other disciplines. Nevertheless, tree rings also present a valuable proxy archive for past climate and for the estimation of past wood utilization, land use changes, settlement, and building history. In recent decades, cooperation between dendroarchaeologists and paleoclimatologists have produced various climate reconstructions (e.g., Büntgen et al., 2011c; Cook et al., 2015; Tegel et al., 2020).

Trends in the growth pattern of trees can be caused by various factors and are not attributable to a single reason. To detect or enhance certain climate signals and exclude noise several statistical methods have been introduced (Fritts, 1976; Cook and Kairiukstis, 2013). They all aim for the preservation of short-term (i.e., high frequency) and long-term (low frequency) climate information. This is essential, as low to mid-frequency trends in the tree-ring chronologies allow for the investigation of decadal to multi-centennial climate variability (e.g., Medieval Climate Anomaly, Little Ice Age), whereas high-frequency signals enhance year-to-year variability and are used for extreme year analyses (Büntgen et al., 2011b). However, it remains uncertain to which extend the climate signal is superimposed by age, site-ecological and anthropogenic factors. Since stand conditions of archaeological wood remain unknown, a high annual replication with trees from different sites eliminates non-climate-induced noise from dendroarchaeological tree-ring series (Tegel et al., 2010; Büntgen et al., 2012; Skiadaresis et al., 2021). Moreover, to improve the climate signal of tree-ring chronologies from archaeological wood, several approaches can be applied. First, high spatio-temporal replication and equal age distribution (Esper et al., 2009) of both archaeological and modern reference material can be achieved by applying a "random sampling" approach (Tegel et al., 2010). Secondly, each tree-ring series can be examined for cyclic growth patterns in the high to mid frequency domain that might be associated with insect calamities, e.g., cockchafer outbreaks (Kolář et al., 2013), or past forest management, e.g., coppice-with-standards (Muigg et al., 2020).

To statistically preserve and detect climatic information at different frequencies in tree-ring chronologies, an array of standardization methods is available that can remove non-climate-induced noise such as biological age trends from each individual tree-ring series. Such standardization methods include different statistical models, e.g., smoothing splines, negative exponential curves or regional curve standardization (RCS) (Briffa et al., 1996).

The resulting detrended (i.e., age-trend free) tree-ring chronologies can be correlated with instrumental climate data (in most cases starting from the 20th century), demonstrating the direct relationship between climate conditions and tree growth in a region. Several methods for tree-ring based climate reconstructions have been applied within the last decades including reverse modeling, scaling and regression models (Esper et al., 2005; Büntgen et al., 2021a). Every climate reconstruction is based on the assumption that the climate-growth relationship is stable over time (Fritts, 1976).

Dendroarchaeological material with its species composition, tree age and size as well as abrupt growth changes, vessel size and formation also provides valuable insights into processes of human-woodland-interaction. For example, models of fire clearance, slash-and-burn farming, woodland degradation and forest management concepts, e.g., coppice and coppice-with-standards, have been established in spatio-temporal dimensions (Tinner et al., 2005; Bernard et al., 2006; Conedera et al., 2009; Billamboz, 2014b; Bleicher, 2014; Muigg et al., 2020). The technical evolution of tools and woodworking practices can be studied on artifacts and species selection for their development over time (e.g., Épaud, 2007; Hoffsummer, 2009; Tegel et al., 2016a). Detailed investigations of individual wooden structures allow to develop *chaînes opératoires* for their construction (e.g., Tegel et al., 2012).

Chronological classification and the identification of felling date clusters are crucial prerequisites for regional to supra-regional studies of settlement dynamics, building activities and demographic development that can be associated with general economic developments and crises (e.g., Thun and Svarva, 2017; Ljungqvist et al., 2018; Seifert, 2018). The combination of quantitative dendroarchaeological research and Geographic Information Systems (GIS) enables spatio-temporal syntheses from local settlement dynamics to large-scale demographic developments (Nicolussi et al., 2013; van Lanen et al., 2016).

SOURCES AND CURRENT STATE OF DENDROARCHAEOLOGY IN EUROPE

Chronologies

Annually resolved and absolutely dated millennia-long tree-ring width chronologies from living and relict wood have been developed in Europe for the Austrian Alps (9111 years; Nicolussi et al., 2009), northern Germany (8000 years; Leuschner et al., 2002), Ireland (6939 years; Baillie, 2009), northern Sweden (7400 years; Grudd et al., 2002), and Finish Lapland (7519 years; Eronen et al., 2002). The initial "Holocene Oak Chronology" by Becker (1993), has been revised and extended by the "Preboreal Pine Chronology" (Spurk et al., 1998; Friedrich et al., 1999, 2004). This composite dataset covers 12.460 years and reaches back to the Late Glacial Period with a continuous coverage, which is unique globally.

Despite the continuous temporal coverage of European chronologies, it has to be noted that there are significant differences regarding regionality, tree species and sample replication. For most regions, at least millennium-long chronologies are available for economically relevant species, but a large number of chronologies have not been comprehensively published so far. In northern and central Europe long chronologies are available for oak (*Quercus* spp.), silver fir (*Abies alba*), beech (*Fagus sylvatica*), spruce (*Picea abies*), pine (*Pinus sylvestris*), larch (*Larix decidua*), and stone pine (*Pinus cembra*) (e.g., Hollstein, 1980; Jansma, 1995; Neyses-Eiden, 1998; Grabner et al., 2001; Čufar et al., 2008b; Nicolussi et al., 2009; Tegel et al., 2010; Büntgen et al., 2011c, 2013, 2014; Kolář et al., 2012; Edvardsson et al., 2016a; Prokop et al., 2016; Sochová et al., 2021).

For southern Europe, multi-centennial long chronologies exist for oak (*Quercus* spp.), beech (*Fagus sylvatica*), fir (*Abies* spp.), juniper (*Juniperus* spp.), larch (*Larix decidua*), black pine (*Pinus nigra*), bosnian pine (*Pinus heldreichii*), and mountain pine (*Pinus uncinata*) (e.g., Panayotov et al., 2010; Seim et al., 2012; Szymczak et al., 2014; Tegel et al., 2014; Shindo et al., 2017; Nechita et al., 2018; Sangüesa-Barreda et al., 2018; Belingard et al., 2019; Esper et al., 2021; Roibu et al., 2021).

Many of these chronologies have been developed using living trees from old-growth forests or in combination with samples from historical timbers (**Figure 2**). Preserved buildings from modern and medieval periods can provide data for the last millennium. Preserved dry wood from older timber structures is extremely rare. To go further back in time, waterlogged wooden finds from archaeological excavations and subfossil trees from gravel pits and paleo-channels are of fundamental importance to extend tree-ring width chronologies. Several periods with low sample replication exist during the Holocene. Some can be linked to regional research gaps, while others are related to supra-regional phenomena, caused by changes in demography, changes in settlement systems during cultural transition periods (e.g., 5th century BCE, i.e., the onset of the Late Iron Age, and 5th century CE, i.e., the transition from Late Antiquity to Early Middle Ages). Such phases can often be linked to crises, whereas times of socio-economic prosperity are associated with increasing amounts of wooden finds (Ljungqvist et al., 2018). In phases of low replication, subfossil trees from natural deposits provide important additional specimens. In some regions, subfossil material even provide the most important source of tree rings (Brown et al., 1986; Eronen et al., 2002; Baillie, 2009).

Subfossil Wood

Trees from past forests can be preserved in natural deposits and can be found in gravel pits, peats and bogs as well as in glacier forefields. The deposition occurs as a result of natural processes, most importantly, erosion. Such trunks allow the establishment of long tree-ring chronologies and provide important information for the history of fluvial and glacial dynamics, the evolution of treelines, peats and riparian forests as well as possible anthropogenic impacts (e.g., Becker, 1982;

Krąpiec, 2001; Leuschner et al., 2002; Leuschner and Sass-Klaassen, 2003; Baillie, 2009; Edvardsson et al., 2016b). Due to the generally better preservation of subfossil trees compared to archaeological wood, they have been used for developing the radiocarbon calibration curve and are frequently used for its enhancement (Reimer et al., 2020).

Combined dendrochronological and radiocarbon evidence provide on the one hand, high resolution proxy archives for the investigation of climate variability during the Late Glacial Period and on the other hand, high-precision dating of environmental events such as earthquakes and volcanic eruptions (e.g., Nicolussi et al., 2015; Büntgen et al., 2017), particularly during periods of high climate variability but low data availability, for instance the Younger Dryas cold spell (∼11700 and 12900 cal BP) (Reinig et al., 2018, 2021).

Early to late Holocene glacial and tree line dynamics in high alpine areas have been investigated on regional to global scales (Nicolussi and Patzelt, 2000; Holzhauser et al., 2005; Nicolussi et al., 2005; Le Roy et al., 2015; Solomina et al., 2016).

Subfossil tree trunks preserved in alluvial infills of European rivers are of great interest to document the formation, evolution and destruction of riparian forest vegetation (Pukiene, 2003; Carozza et al., 2014; Vitas, 2017). Significant temporal accumulations of post-glacial trees deposited in river sediments indicate repeated phases of substantial floods and changes of river courses and provide insights into anthropogenic influences and destructions (Becker, 1982).

Subfossil trees from peatlands are important proxies for Holocene palaeohydrology and palaeoclimate, essential to our understanding of long-term changes in hydroclimate and the terrestrial carbon cycle (Edvardsson et al., 2016b). Even though the anthropogenic impact on subfossil trees is limited in most cases, they are substantial data sources that need to be considered for dendroarchaeological studies.

Archaeological Wood

Wooden remains from past human societies are unearthed during archaeological excavations. The oldest man-made artifacts discovered in Europe are ca. 300.000 years old hunting spears from Schöningen, Germany (Thieme, 1997; Conard et al., 2020). Substantial amounts of wooden finds, however, only appear in periods of sedentary cultures, starting from the mid-6th millennium BCE, when first farming societies settled in the fertile loess regions of Europe and systematically used large amounts of timber. Their settlements consisted of longhouses, sometimes over 40 m in length, for year-round habitation that required large timber sizes and technical innovations in carpentry (Tegel et al., 2012). First intensive anthropogenic influence on the natural environment happened during this time when forests were cleared to create agricultural areas. Within the last decades, several water wells from settlements of the 6th millennium BCE have been excavated in Europe. Technological studies revealed the impressive woodworking skills of Europe's first farmers. Hundreds of timbers from these water wells enabled the development of different tree-ring chronologies and are the oldest dendrochronologically dated archaeological features in Europe so far (Tegel et al., 2012; Rybníček et al., 2018, 2020).

Extraordinary preservation conditions in pile dwellings lead to the excavation of vast amounts of archaeological wood. Early examples from the 6th millennium BCE are restricted to southern Europe (e.g., López-Bultó and Piqué Huerta, 2018; Naumov, 2020; Fermé et al., 2021). In central Europe, pile dwellings appeared in the circumalpine lakes during the 5th millennium BCE and are listed as a UNESCO world heritage "Prehistoric Pile Dwellings around the Alps" since 2011, protecting a total of 111 archaeological sites in six countries[5]. Here, absolutely dendrochronologically dated structures exist from around 4200 BCE onward providing large amounts of waterlogged woods for dendroarchaeological studies (Billamboz and Schlichtherle, 1982; Lambert and Lavier, 1997; Billamboz and Unz, 2006; Cichocki and Dworsky, 2006; Billamboz, 2014b; Martinelli, 2014; Čufar et al., 2015; Bleicher and Harb, 2017). The combination of archaeological, archaeobotanical and dendroarchaeological data provide detailed insights into pre-historic socio-economies including their social networks, husbandry and forest management (e.g., Billamboz, 2014b; Menotti, 2015; Bleicher and Harb, 2017; Hafner et al., 2020). Pre-historic pile dwellings occurred in several waves, most likely in periods of favorable climate conditions, from the Late Neolithic until the Iron Age period at around 500 BCE (Billamboz, 2003). The documentation and dendrochronological dating of piles enables detailed investigations of settlement structures and development with high temporal precision (Bleicher and Harb, 2018). Many wetland sites are characterized by multiphase occupations with thousands of piles. Therefore, ground plans of single structures are often only recognizable after dendrochronological dating, the identification of wood species and typological studies of cross-sections (e.g., Benguerel et al., 2020). Moreover, wetland sites yield various kinds of wooden objects for every-day purposes, e.g., vessels, tools, weapons, and provide detailed insights into the material culture and technology (e.g., Müller-Beck and Boessneck, 1965; Capitani et al., 2002; Fermé et al., 2021). Outside of wetland areas, such finds are only preserved in single structures with waterlogged conditions like water wells (Croutsch et al., 2019, 2020). In recent years, large-scale excavations of preventive archaeology have also discovered extensive settlement areas with waterlogged conditions in large river valleys with high groundwater levels (Donnart et al., 2019). In particular, for the Roman period the number and quality of archaeological sites increased significantly. Political and administrative efficiency led to high building activities and consequently to large amounts of archaeological wood for the 1st to 3rd century CE for many central European laboratories (Hollstein, 1980; Nicolussi, 1998a,b; Herzig and Berg-Hobohm, 2010; Benguerel et al., 2012; Herzig et al., 2013; Bernard et al., 2014; Čufar et al., 2014; Jansma et al., 2014; Tegel et al., 2016b; Jansma, 2020). The highly developed trade networks and the rising urban development triggered new dimensions of forest resource exploitation (Bernabei et al., 2019). Socio-economic decline at the end of the Roman Empire is reflected by a decrease in building activity and therefore, a limited number of

[5] https://whc.unesco.org/en/list/1363

dendroarchaeological evidence in the late 4th and 5th centuries CE (Rzepecki et al., 2019).

In the majority of archaeological sites in Europe, no organic tissue is preserved. Here, dendroarchaeological studies are limited to chemically modified wood, e.g., charcoal or mineralized wood. These highly fragmented finds rarely show traces of the original object surface and hardly provide a sufficient number of tree rings. In most cases, they are not suitable for technological or dendrochronological analyses. However, taxonomical identification is still possible and often the minimum diameter of the used trunk can be estimated. With large charcoal datasets it is possible to answer research questions of local vegetation cover, anthropogenic land use and forest exploitation as well as dendrochronological dating (Cichocki, 2007; Nelle et al., 2010; Deforce, 2017; Blondel et al., 2018; Dufraisse et al., 2018; Moser et al., 2018; Oberhänsli et al., 2019). Mineralized wood provides distinct information regarding wood utilization and selection due to mechanical properties for specific purposes, e.g., weapon production (Tegel et al., 2016a; Haneca and Deforce, 2020).

Wood From Historical Buildings

Large amounts of historical timber, e.g., roof trusses, ceilings joists, buttresses and basement pillars, have survived under dry conditions in buildings that are in many cases still intact, enabling insights into the building history of the last millennium (e.g., Hollstein, 1980; Kuniholm and Striker, 1987; Crone and Fawcett, 1998; Büntgen et al., 2006b; Seiller et al., 2014; Bernabei et al., 2016). In particular, sacral buildings (e.g., churches), but also public and private secular architecture from medieval to modern periods are valuable data sources for dendroarchaeological studies (e.g., Hoffsummer, 2009; Seim et al., 2015; Domínguez-Delmás et al., 2017; Haneca and van Daalen, 2017; Christopoulou et al., 2020b).

The dating of historical constructions is primarily initiated by departments of heritage conservation or heritage inventorization for the protection of architectural monuments or for their documentation in the context of renovation, restoration, re-use or demolition (Gomolka, 1992; Marshall et al., 2004; Harzenetter et al., 2016; Withalm, 2018). It is important for research on building history as well as for studies on urban and rural development (Schmidt et al., 2001; Eißing, 2015; Werlé, 2017; Vitas, 2020).

The position of timbers within their larger constructive context allows to investigate the evolution of new types of constructions and innovative technical solutions. Vernacular architecture shows distinct construction details (e.g., floor plans, room division), often typical for certain periods and regions and therefore, reveals local technological developments and regional differences in building traditions (e.g., Schmidt et al., 1990; Épaud, 2007; Houbrechts, 2007; Susperregi et al., 2017).

The tree species used for historical timbers vary among different regions and within each construction according to their functional purpose. For structural elements with soil (i.e., moist) contact, oak (*Quercus* spp.) was used almost exclusively. Other species regularly used for timber framework and roof constructions are silver fir (*Abies alba*), spruce (*Picea abies*), pine (*Pinus sylvestris*) and larch (*Larix decidua*). Sophisticated knowledge of mechanical properties and other characteristics of various tree species by historical craftsmen can be expected (Blau, 1917). The regional preference of a species is strongly affected by its natural distribution (Kolář et al., 2021; Shindo and Giraud, 2021; Sochová et al., 2021; Solomina and Matskovsky, 2021). For example, in the lowlands of western Europe oak was regularly used for all components of vernacular buildings due to the rare occurrence of conifers (Haneca et al., 2009; San-Miguel-Ayanz et al., 2016). Northern Europe's vernacular architecture was dominated by pine, whereas fir and spruce are more frequently found in central European constructions (Becker and Giertz-Siebenlist, 1970; Eißing and Dittmar, 2011; Seim et al., 2015; Thun and Svarva, 2017; Kolář et al., 2021). Larch is restricted to high elevation areas in the Alps and parts of the Tatra Mountains, where it was also preferentially used (Büntgen et al., 2006a, 2013). Larch (from the Alps) was massively used also in the areas dominated by the Venetian Republic Serenissima (e.g., Levanič et al., 2001). The most frequently used species in the Mediterranean region are oak (*Quercus* spp.), chestnut (*Castanea sativa*), pine (*Pinus* spp.), fir (*Abies* spp.), juniper (*Juniperus* spp.), and cedar (*Cedrus* spp.) (Bernabei et al., 2016; Christopoulou et al., 2020a). In the sparsely wooded regions of the Mediterranean, timber import played a particularly significant role (Domínguez-Delmás et al., 2018; Bernabei et al., 2020; Christopoulou et al., 2020a).

There are chronological and regional differences regarding the data basis of historical timber constructions in Europe. Many modern towns and rural villages were just established during the consolidation of high medieval political structures in the 12th-13th century and those urban settlements that had existed before ca. 1200 CE have been affected largely by structural changes during the 13th century and later extensive reorganizations (e.g., Bartlett, 1994; Westphal, 2002; Mitchell, 2013). Therefore, the early centuries of the last millennium are generally underrepresented. The vast majority of all studied timbers are from towns, typically small ones in rural settings that in many cases have lost their importance in modern times. Because of that, old buildings were more likely to survive the destruction caused by later wars and urban renewal in the 19th and 20th centuries than buildings in major cities. Rural farm buildings pre-dating the 17th century are rarely preserved and are therefore only represented to a limited extent. For large parts of central Europe, the Thirty Years' War (1618–1648) might have greatly decimated older buildings in rural areas (Ljungqvist et al., 2018).

Wood From Objects of Art History, Instruments, and Furniture

Dendroarchaeological analyses can also be applied on wooden art objects like panel paintings, sculptures, furnishing items and musical instruments. The most important research questions for these high-quality objects are precise dating and provenance of the wood and is mainly initiated by art historians in museums or art dealers. As the actual origin of the wood for the highly specialized art sector is unclear in many cases, these sources are not included in paleoclimatological studies. However, wooden art objects provide information on historical species selection and woodworking techniques.

The first dendrochronological analyses of panel paintings in Europe were conducted on works by German medieval painters in the 1960s and ‘1970s by the German biologist Josef Bauch (1968). In the mid-1970s, J. M. Fletcher followed and dated panel paintings done by 15th- to 17th-century English and Flemish artists (Fletcher, 1975). From this point on, dendrochronology has been commonly applied to art objects (Bauch and Eckstein, 1970, 1981; Bauch, 1978; Bauch et al., 1978; Klein, 1986, 1998; Klein and Wazny, 1991; Hillam and Tyers, 1995) and musical instruments (Klein, 1985, 1996; Topham and McCormick, 1998; Beuting and Klein, 2003; Topham, 2003; Beuting, 2009; Bernabei et al., 2010, 2017; Čufar et al., 2017). For musical string instruments, the material is carefully selected, such as spruce trees with hazel growth, an uniformly finely striped texture, which were found to produce the best sounds (Buksnowitz et al., 2007; Brandstätter, 2016; Bucur, 2016).

Non-invasive methods are applied and the tree-ring widths of the planks are measured either directly on the planks of the panel or instrument or on macro-photos (of ca. 5 cm segments) which are taken from the cross section of the panels (Myhr et al., 2007). Even more modern technologies using an industrial CT scanner or X-ray technology allow the analysis of tree rings non-invasively (van den Bulcke et al., 2014; Stelzner and Million, 2015; Daly and Streeton, 2017; Domínguez-Delmás et al., 2021a). Dendrochronological analyses on furniture are less common but similarly important as they highlight woodworking and stylistic changes in the society (Pickvance, 2012, 2015; Klein et al., 2014; Allen, 2015; Domínguez-Delmás et al., 2021b).

APPLICATION AND MULTIDISCIPLINARY FIELDS IN DENDROARCHAEOLOGY

Evolution of Woodworking Technology

Since the Paleolithic, wood has been an important raw material for various purposes, e.g. hunting weapons (Thieme, 1997; Lozovski et al., 2016; Conard et al., 2020). Mobile hunter-gatherer communities of the Upper Paleolithic (50–12 ka BP) and Mesolithic (ca. 15–5 ka BP) periods used wood for the production of tools, weapons and short-lived housing. First important innovations in woodworking technology are recognizable during the Neolithic period (ca. 6000–2200 BCE) when the establishment of a sedentary lifestyle required the processing of larger timber for permanent buildings, which are suitable for year-round habitation. Water wells from this period provide evidence for the utilization of large oak trees, frequently split for the use in block constructions, and sophisticated carpentry techniques for surface treatment and corner joints (Tegel et al., 2012; Rybníček et al., 2018, 2020). Analyses of toolmarks on the preserved timber provide evidence for the use of different tools for specific working steps (Elburg et al., 2015). Different types of construction produced by Neolithic carpenters illustrate the impressive woodworking skills of Europe’s first farmers (Rybníček et al., 2020). In the further course of the Neolithic period, large-scale constructions consisting of hundreds of mature oaks suggest the collaboration of larger communities and provide evidence for socio-economic developments (Donnart et al., 2019). Oak remained the preferred species for construction timber throughout the pre-historic and proto-historic periods in Europe.

New impulses for carpentry techniques were provided with the occurrence of new materials for the production of tools. Bronze first occurred in large parts of Europe during the late 3rd millennium BCE and the technology of iron production spread in the early 1st millennium BCE. The use of metal tools enabled the development of new woodworking techniques and novel types of constructions. Important innovations are the development of new tools, e.g., wood borers and saws that together with other inventions further accelerated the civilization of Europe. Improvements in iron technology in late Iron Age and Roman Europe allowed the development of large saws suitable for longitudinal cutting of trunks, which facilitated the production of planks and boards (**Figure 9**). This, together with the invention of the carpenter’s plane in Roman times, revolutionized furniture making (Goodman, 1963; Schadwinkel et al., 1986). The use of hydro-power as a mechanical labor force for grain mills was first applied in European Antiquity and further developed in different regions of early medieval Europe (Wikander, 1984; Spain, 2008; Rynne, 2015; Muigg et al., 2018). The mechanics of watermills are entirely made of wood and require extensive mechanical knowledge and high-precision carpentry. These first complex mechanical machines were also adapted for cutting wood, with first sawmills appearing in central Europe around 1200 CE (Finsterbusch and Thiele, 1987; Berthold, 2009). The milling technology spread throughout medieval Europe in the 12th and 13th century and was a main driver for changing economic structures (Jeute, 2015). During the late medieval and early modern periods, the development of craft guilds and the diversification of woodworking professions lead to a great variety of specialized tools (Goodman, 1963; Schadwinkel et al., 1986; Finsterbusch and Thiele, 1987; Greber, 1987).

Trade of Woods and Goods

As a consequence of the sedentary lifestyle, developed in large parts of Europe during the Neolithic period, forest areas in the vicinity of settlements were intensively exploited, which successively led to a shortage of timber. Therefore, wood had to be harvested from further away and transported to the settlements. Prehistoric settlement patterns are frequently found on lakeshores and riversides, which enabled effortless transport on water by towing or rafting of construction material. Timber from the same forest stand that was found in different dwellings on the northern and southern shore of Lake Constance provides indirect evidence for timber transport (Benguerel et al., 2020).

First proof for local timber transport on water is provided by a Neolithic palisade from La Villeneuve-au-Châtelot (Aube), dated to 3232 BCE, where characteristic recesses in various timbers suggest the assemblage of rafts (Donnart et al., 2019; **Figure 10**). In contrast to transportation on water, overland transport was a much more tedious process. Since the Neolithic, large amounts of wood were used for road building to enable

FIGURE 9 | Longitudinal sawing of planks and boards. **(A)** Oak board with a characteristic "V" saw mark from the Roman harbor in Reims, France (1st century CE) and **(B)** sawing marks with a characteristic "V" mark on a beam from a historical building in Le Val-d'Ajol, France (18th century CE). **(C)** Historical postcard from La Baconničre, France, depicting the sawing process.

land transportation in marshy areas (Hayen, 1990; Fansa, 1992; Endlich and Lässig, 2007). First evidence for chariot wheels from Europe date to the late 4th and early 3rd millennium BCE (Höneisen et al., 1989; Velušček and Čufar, 2009; Schlichtherle, 2010). Around 2000 BCE the domesticated horse spread throughout Europe, providing a new type of working animals suitable for faster transportation (Anthony, 1995), which led to the development of new chariot and wheel types during the early Bronze Age (Heussner, 1985; Tegel and Croutsch, 2016). The bronze-age invention of steerable front axles had an impact on the size of wooden roads, which were built narrower than in Neolithic times (Fansa, 1992). During the Bronze Age, chariots were not exclusively used for transportation but also became objects of prestige. The prestigious image of wheel chariots continues through the Iron Age and is visible in elite graves furnished with chariots (Biel, 1995; Laurent et al., 2002).

Besides chariots, ships were the most important means of transport for timber. These vehicles themselves were entirely or predominantly made from wood and played a pivotal role for the transportation of various other goods.

Simple monoxyle log boats are known in Europe as early as the Mesolithic period and were in use until post-medieval times for fishing and short distance transport in certain regions (Arnold et al., 1995; Lanting, 1997; Kröger, 2014). The oldest archaeological evidence of a raft of combined logs was found in 1922 at the "Wilden Ried" in Upper-Swabia, Germany, dating to the Bronze Age (Ellmers, 1972). However, it can be assumed that such rafts were already used in earlier periods (cf. Donnart et al., 2019). Larger vessels both for inland and maritime navigation required more complex constructions. The oldest examples for such ships found in Europe date to the Iron Age, e.g., from Hjortspring, Denmark (Crumlin-Pedersen and Trakadas, 2003). Archaeological evidence of ships with laced planking for the 6th century BCE in Massalia (Marseille), France, and for the 3rd century BCE in Ljubljana, Slovenia, illustrate the influence of the Mediterranean maritime ship building traditions on European inland navigation vessels (Pomey, 1996; Teigelake, 1998). Different types of ships have developed since the Roman era (Arnold, 1992; Bockius, 2002, 2006) and further technological innovations can be recognized for medieval and post-medieval times (Bridge and Dobbs, 1996; Hakelberg, 1996; Crumlin-Pedersen et al., 1997; Hoffmann and Schnall, 2005; Lemée, 2006; Jansma et al., 2014; Englert and Crumlin-Pedersen, 2015). For all these mobile wooden vessels, their excavation site might differ considerably from their site of construction (Bonde, 1998; Domínguez-Delmás et al., 2019), making them important objects of research

FIGURE 10 | (A) Oak posts from a Neolithic palisade (3231 BCE) with recesses on the basis used for timber floating or over land transport (Donnart et al., 2019). **(B)** Recesses on construction wood frequently found in roof trusses (Colmar, Alsace, France, 18th century CE) typical for timber rafting. **(C)** Detail view on the raft assemblage of a modern reconstructed raft.

for dendroprovenancing (Daly, 2007; Daly and Nymoen, 2008; Bridge, 2012; Domínguez-Delmás et al., 2013).

The same applies for wooden barrels, used as containers for various trading goods and frequently re-used in well linings or latrines at their final destinations in Roman and post-Roman settlements (Ulbert, 1959; van Es, 1972; Greig, 1981; Clerici, 1983; Marličre, 2002; Falk, 2003; Hagendorn and Bouchet, 2003; Bauer, 2009; Robben, 2009; Čufar et al., 2019; Mille and Rollet, 2020). Barrels are elaborately crafted objects that reveal detailed information about the precise wood technology and manufacturing as well as trade systems (Marličre, 2002; Tamerl, 2010). Moreover, brand marks and graffiti found on barrels provide information for epigraphic and other studies (Frei-Stolba, 2017).

Wood itself was an important trading good. First indication for long-distance timber transport was found during the Antiquity for silver fir (*Abies alba*) for the construction of Roman harbors and bridges in regions outside the natural habitat of the species, e.g., in Mainz and Cologne (Bauer, 2001; Tegtmeier, 2016). Further evidence for Roman long-distance timber transport was found in Voorburg-Arentsburg, Netherlands (Domínguez-Delmás et al., 2014). New dendroarchaeological research shows a combined river and sea transportation of oak planks from regions north of the Alps for a construction in the city of Rome, further illustrating the necessary advanced logistic infrastructure (Bernabei et al., 2019). In post-roman Europe (after the first Millennium CE), growing population and fast urban development accelerated the decline of regional forests (Kaplan et al., 2009; Deforce, 2017) and led to the development of intense timber trade on the continental waterways through sea trade and river systems (Ellmers, 1985; Eißing and Dittmar, 2011). First historical evidence for medieval timber rafting on various large and smaller rivers date from the 12th and 13th centuries (Neweklowsky, 1952; Irsigler, 1992; Henne, 2005; Eißing and Dittmar, 2011), demonstrating the rising importance of timber transport on rivers (Delfs, 1985; Heussner, 2015). The development of extensive rafting infrastructures in mountain regions led to progressive exploitation of new forest areas for both, fuelwood and timber (Neweklowsky, 1959). Proto-industrial glass and salt production emerged to major consumers for fuelwood (Lamschus, 1993; Goldammer, 1998; Grabner et al., 2018). The prevalence of coniferous species in the timber material from historical buildings in large parts of central Europe, noticeable from the 14th century onward, provides strong evidence for extensive timber transport on a continental scale. Occasionally, traces of rafting can be found on timber elements in historical buildings (e.g., Eißing and Dittmar, 2011; Zunde, 2011; Shindo and Claude, 2019; **Figure 10B**). Regional differences of technical solutions for combining logs, varying for different river systems, hold information on the origin of timber (Eißing et al., 2012).

Selected, high quality timber, especially from oak, for art objects was in high demand also after local old forests were depleted in some regions in western and central Europe already by the 10th century (Deforce, 2017). Consequently, from the mid-14th century, increasing amounts of long-lived, straight-grained oak trees were imported from Poland and the other states around the Baltic Sea (Wazny, 1992, 2002; Bonde et al., 1997; Haneca et al., 2005; Fraiture, 2009). The Baltic timber trade was actively practiced by the Kingdom of Sweden and the Polish–Lithuanian Commonwealth with England and the Low Countries in the 14th to 18th century (Kirby, 2014). The transport was done on ships and mainly with prepared planks, boards, deals etc. (Johansen, 1983; Belasus, 2017).

Forest History

Comprehensive dendroarchaeological datasets established by European laboratories provide information on the anthropogenic impact on forest environments. The natural composition of species in European forests depends on various factors, including soil properties, environmental and climate conditions, the ecological amplitude of different tree species, the timing of species occurrence as well as the inter-species competition within a forest ecosystem (Ellenberg, 1996). However, human societies have influenced the natural forest composition in large parts of Europe throughout the Holocene. First indirect human impact on post-glacial forests might have already happened in the Mesolithic period through hunting pressure on large herbivores as well as facilitating the distribution of species through gathering, e.g., hazelnuts (Küster, 1996). Distinct human impact on forest compositions started at least with the emerge of sedentary societies during the Neolithic period that extracted construction timber and cleared forest areas for agriculture and settlements. Growing populations and successive colonization of suitable areas throughout the pre-historic and historical periods were accompanied by increasing forest exploitation. Hence, there are hardly any natural forests left in the western parts of Eurasia (Malzahn, 2011).

For millennia, people have been using forest resources for various purposes of their everyday life. To cover a constant demand of wood, e.g., for fuel and timber from the same forest areas, local communities had to develop strategies for sustainable resource availability. Large amounts of dendroarchaeological data from pile dwellings at Lake Constance suggest cyclic utilization of local forest stands as early as the late Neolithic period (Billamboz, 2014b). After a first phase of clearing primary forests, several different forms of forest treatment can be postulated from dendrotypological studies on timber size, individual tree age and growth patterns during the Neolithic occupation (Billamboz and Köninger, 2008; Billamboz, 2014a). Coppice-like forest structures are documented for the 36th century BCE in phase IB at the Neolithic pile dwellings at Hornstaad-Hörnle (D), yet without evidence for systematic management (Billamboz and Unz, 2006). Alternating phases of over-exploitation of local forests through harvesting and grazing, subsequent degradation, change of utilized forest area, natural reforestation and clearing display the complex interaction of natural and anthropogenic factors. First evidence for successive use of the same forest stands by local communities is provided by the dendroarchaeological data from Sipplingen-Osthafen (D), where continuous building activities between 2915 and 2864 BCE confirm coppice-like forest management (Billamboz and Köninger, 2008). Similar forest management systems have been studied for Bronze Age and Iron age settlements (e.g., Reynolds, 1985; Andraschko, 1996; Billamboz and Schöbel, 1996). Other possible silvicultural systems, for example coppice-with-standards-like forest structures cannot be ruled out for pre-historic communities. However, such management practices, presupposing intensive large-scale forest clearing and the absence of alternative regional wood sources, require certain demographic conditions, which probably did not occur in most regions of Europe before the Roman period (Lo Cascio, 1994).

The first historical evidence for coppice-with-standard forest management in Europe appear at the beginning of the 13th century CE (Hausrath, 1982). As a result of population growth and urbanization, this silvicultural system was necessary to secure the constant supply of timber and fuelwood for medieval central Europe. Improved administrative structures, crucial for such long-term regulations that required planning by local authorities, led to a surplus of historical evidence, i.e., written sources, during late medieval and early modern periods (Hausrath, 1982). New dendroarchaeological studies, however, provide strong evidence for the existence of this more sophisticated silvicultural practice as early as the 6th century CE and therefore throughout a ca. 1400-year long period from early medieval to modern times (Muigg et al., 2020). Coppice and coppice-with-standards management has played an important role during medieval and early modern times until the use of fossil fuels provided alternatives to fuelwood and allowed the transformation of economic forests to modern high forests (Schmidt, 2002). Before that, countless historically recorded disputes and conflicts of interests illustrate an intensification of resource scarcity in many parts of Europe (Epperlein, 1993; Warde, 2006, 2018). Similar conflicts have to be assumed also for densely populated areas in earlier periods/pre-historic times but cannot be verified due to the lack of historical records. Nevertheless, dendroarchaeological parameters, i.e., changing annual growths, tree age classes and species might display long-term spatio-temporal changes in European forest management regimes (e.g., Haneca and Beeckman, 2005; Deforce and Haneca, 2015; Deforce et al., 2020).

Environmental History (Climate, Anthropogenic Land Use, Deforestation)

Interannual variability in growth increment is one of the fundamental features of dendroarchaeology. Inter- and intra-annual tree ring parameters such as variability in wood density, stable ($\delta^{13}C$ and $\delta^{18}O$), and unstable ($\delta^{14}C$)

isotopes are also highly suitable natural proxy data for environmental reconstructions, in particular climate, as they provide information with high temporal and spatial resolution. Today, they form the primary basis for palaeoclimatology of the last centuries to millennia (Stocker, 2014). In Europe, dendroclimatological studies have mainly focused on temperature reconstructions based on coniferous species of the high altitudes in the Alps (Büntgen et al., 2006b; Corona et al., 2010), the Pyrenees (Büntgen et al., 2008), the Carpathians (Popa and Kern, 2009; Kaczka et al., 2016), and the boreal forests in Scandinavia (Grudd, 2008; Helama et al., 2009; Esper et al., 2014). Annual tree growth at such treeline sites is primarily controlled by temperature during the short growing season (June–August) and thereby a distinct temperature signal in series of both tree-ring width and maximum latewood density is present (e.g., Esper et al., 2016). Aside from hydroclimatic reconstructions from extreme sites such as the eastern Mediterranean (Akkemik et al., 2008; Klippel et al., 2018) and North Africa (Esper et al., 2007), coniferous species from southern Scandinavia (Helama et al., 2005; Seftigen et al., 2013), Slovenia (Čufar et al., 2008a), Moravia (Brázdil et al., 2002; Büntgen et al., 2011a), and southern Germany (Wilson et al., 2005) provide precipitation reconstructions for central and northern Europe. For hydroclimate-sensitive broadleaf tree species at low elevations in Central Europe, however, only a few studies are available so far (Kelly et al., 2002; Čufar et al., 2008a; Büntgen et al., 2010, 2011c, 2021b; Scharnweber et al., 2019; Tegel et al., 2020).

Information relevant for forest ecology can be obtained from the distribution of species in archaeological material. Local to regional differences over time indicate changes in natural woodland societies. Long-term changes of forest ecosystems can be studied in conjunction with palynological records and yield important information on the migration history of species and establishment and consolidation of forest communities (Tinner and Lotter, 2006).

Other wood anatomical characteristics of archaeological wood provide further information to study past ecological conditions. Defoliation leads to growth reactions visible in the anatomical structure of trees, for example abnormal earlywood zones, irregularly shaped, small vessels or slightly thickened latewood tissue cells (Schweingruber, 1996). There are various possible reasons for defoliation events, for example anthropogenic (pollarding, management) or natural (floods, storms, insects) (**Figure 11**). Even though it is not always possible to attribute an anatomical feature to a specific event, the combination of wood anatomical observations and tree-ring patterns allow further interpretation. For example, a larger earlywood section combined with characteristic tree-ring patterns observable in archaeological wood samples has been attributed to insect calamities (Büntgen et al., 2009; Kolář et al., 2013; **Figure 11A**). Massive cockchafer outbreaks follow a 3–5-year cycle depending on the region. They occur during the early vegetation period and result in significant defoliation, which is accompanied by a reduced radial growth in combination with a higher amount of earlywood vessels (Kolář et al., 2013; **Figure 11A**). This leads to a distinct cyclic tree-ring pattern, occasionally found in subfossil trees and archaeological timber (Rohmer and Tegel, 1999; Herzig and Seim, 2011). Distinct growth reduction and vessel anomalies can also be associated with pollarding and flood events, causing partial defoliation (**Figure 11B**). However, a differentiation is only possible in combination with dendrochronological studies and strongly depends on an attributable tree-ring pattern. Several other wood anatomical features (e.g., frost rings, physical injuries and overgrowth, reaction wood, traumatic resin duct) can be found in archaeological and subfossil material, albeit their specific interpretation relies on the amount of data and the overall context.

Dendroarchaeology and Radiocarbon Dating

Another fundamental method for dating in archaeology is based on the partial decay of radioactive isotopes (radiocarbon, $\delta^{14}C$) contained in organic finds. The atmospheric radiocarbon content varies because of changes in upper atmosphere production and global carbon cycling. Therefore, radiocarbon dating and dendrochronology are strongly interconnected, as tree rings provide an important source for calibrating the radiocarbon variability over time. The calibration curve, used as a worldwide standard for radiocarbon (14C) dating over the past ca. 50.000 years, is continuously improving toward a higher resolution and replication (Reimer et al., 2020). Tree rings from dendroarchaeological sources contain high-precision data throughout the Holocene. Recent studies have shown the significance of tree-ring-based calibration also for the Late Glacial Period (e.g., Reinig et al., 2020, 2021).

The interconnection of the two methods of dendrochronology and radiocarbon dating also allows the calibration of millennia-long dendrochronological records. Improved inter-annual radiocarbon measurements enable to observe sudden and anomalous activity shifts, such as significantly increased atmospheric production rates of cosmogenic radionuclides on a global scale (Miyake et al., 2012; Usoskin et al., 2013; Jull et al., 2014; Büntgen et al., 2018). The detection of such events enables to independently validate tree-ring chronologies on both hemispheres and can furthermore contribute to connecting synchronous events with other long-term proxy records, for example isotopes from corals and ice cores (e.g., Liu et al., 2014; Mekhaldi et al., 2015).

Annually resolved chronologies are paramount to precisely date past volcanic eruptions not recorded in historical documents (Büntgen et al., 2017; Hakozaki et al., 2018). Starting from a distinct and well-known event, e.g., the 774/775 CE ^{14}C spike (Miyake et al., 2012), the dating of an unknown event can be established by counting the number of rings to the waney edge. An other prominent example is the precise dating of Viking activity in Newfoundland in 1021 CE by making use of the rapid ^{14}C excursion at 993 CE (Kuitems et al., 2021). In this way, all wooden finds worldwide, which show such rapid ^{14}C excursions, can be accurately dated. This is all the more important for regions lacking dendrochronological reference chronologies.

However, it is paramount for multi-proxy synchronization that the independent dating results from tree rings and

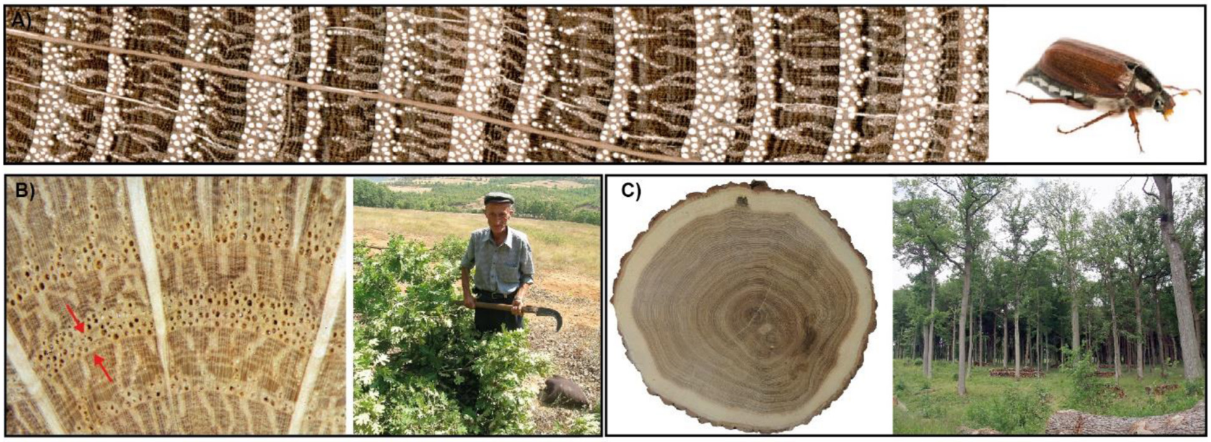

FIGURE 11 | Tree-ring anomalies. **(A)** Cockchafer outbreak pattern on a recent oak from Diesenhofen, Switzerland, with cyclic growth reductions every three years combined with higher early wood production. **(B)** Two years reduction in tree-ring width (red arrows) by pollarding of oak (*Quercus cerris*, Albania). **(C)** Stem disk from an oak standard (Welbhausen, Germany) with periodical growth release pattern induced by coppice-with-standard forest management practice.

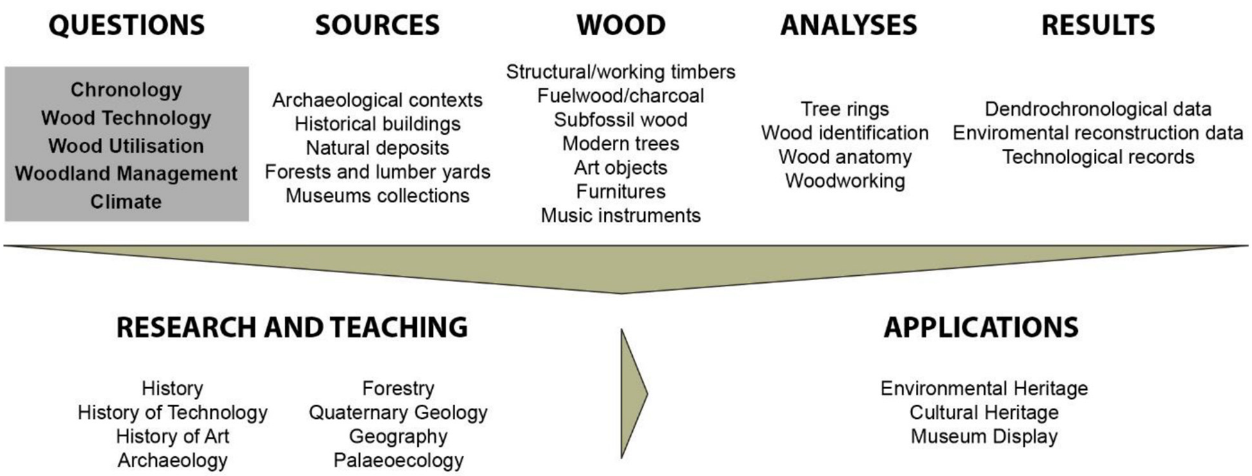

FIGURE 12 | Overview of the research discipline dendroarchaeology including research questions, wood sources, analyses and results that are relevant for different research fields and applications.

radiocarbon are compared on the annual scale, as the common decadal or semi-decadal resolution of radiocarbon dates can lead to misinterpretations (Jull et al., 2021). So far, verified spikes in ^{14}C activity could be observed for 993/994 CE, 774/775 CE, 660 BCE, 813 BCE and 5480 BCE (Mekhaldi et al., 2015; Miyake et al., 2017; Park et al., 2017; Jull et al., 2018; O'hare et al., 2019). Given the great success of recent investigations in identifying and precisely addressing such events, it is to be expected that further intensified research might reveal additional atmospheric ^{14}C spike excursions.

CONCLUSION

Dendroarchaeology is a remarkably wide research field, which can offer essential contributions to a variety of disciplines and should not be restricted to delivering absolute dating (**Figure 12**). Wooden remains can be found from almost all epochs. Therefore, dendroarchaeologists should generally be open to interdisciplinary approaches and need to stay open-minded toward all areas of palaeosciences. A major prerequisite for dendroarchaeological studies is a comprehensive data base, well-replicated over time. The amount of high-quality tree-ring data varies greatly for different regions of Europe, especially south and south-east of the Alps. The development of millennia-long tree-ring chronologies for the main European tree species is an ongoing process and needs to be further developed constantly for more regions within the Old World (Nechita et al., 2018; Christopoulou et al., 2020a; Roibu et al., 2021). Therefore, all available sources of wood should be used: subfossil trees, archaeological finds, historical buildings, art objects and modern trees are essential to build and improve dendroarchaeological records.

The diversity of sources requires active cooperation between experts of dendroarchaeology as well as beyond disciplinary boundaries. So far, the most fruitful and close interdisciplinary cooperation have been implemented with archaeologists, historians, physicists, climatologists, geologists and palynologists, providing important contributions to dating, history of technology, radiocarbon calibration, palaeoclimate reconstructions, volcanic activities and vegetation history, just to name a few.

Considering the recent advances in studies of ancient plant DNA, the field of aDNA holds a great potential for combined studies on postglacial migration and climatic adoption of tree species as well as provenancing wooden objects (Wagner et al., 2018; Saleh et al., 2021). Different fields of dendro-sciences have developed various novel approaches, for example by studying density fluctuations, earlywood/latewood ratios and variances of vessel size, allowing to extract further information on the inter- to intra-annual regimes and to combine these different parameters (e.g., Wilson et al., 2017; Mann et al., 2018; Akhmetzyanov et al., 2019; Björklund et al., 2019).

However, these innovative approaches are only partially transferable to archaeological wood. Large differences in quality and type of wood preservation, combined with the inherent lack of stand and tree level information, pose limits to a generalized inclusion in dendroarchaeology. Therefore, total tree-ring width provides the most accurate, most widely used and consequently the most valuable parameter for dendroarchaeological tree-ring studies.

AUTHOR CONTRIBUTIONS

WT, BM, and AS searched and reviewed the literature and wrote the manuscript with input from JV and GS. All authors provided critical discussion, helped writing the manuscript, and approved its submission.

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