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Seeing the forest for the trees: New approaches and challenges for dendroarchaeology in the 21st century

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ABSTRACT

The application of tree-ring research to the study of cultural heritage has seen important conceptual and methodological developments in the 21 st century. Following the breakthrough discovery in the 1980s of the importation of timber from the south-eastern Baltic to the Low Countries for panel paintings, the historical timber trade acquired paramount relevance in European dendrochronology. The improvement of methods and tools to locate the area of origin of the wood has since become a focal line of research. Reference chronologies of different variables (ring width, earlywood, latewood, earlywood vessel size in oak, latewood density in conifers, stable isotope chronologies of $\delta^{13}C$, $\delta^{18}O$) are now being developed in areas formerly (and currently) exploited for timber production, and isotopic signatures of $^{87}Sr/^{86}Sr$ are being mapped to provide a geochemical reference. In parallel, novel techniques to identify wood species (automated wood identification, chemical biomarkers, DNA barcoding) and their application on historical and ancient wood are being explored, given that this could sometimes help narrow down the timber source area. Modern technology is playing a key role in the study of wooden objects through non-invasive methods, and collaboration with (art) historians, mathematicians, engineers and conservators has proven essential in current achievements. Tree-ring series can now be retrieved from high resolution X-ray computed tomography images, allowing the research of otherwise inaccessible pieces. This paper reviews recent advances in those fields (tree-ring based dendroprovenancing, wood species identification, chemical fingerprinting, use of genetic markers, isotopic signatures, and non-invasive methods), and discusses their implementation and challenges in dendroarchaeological studies.

1. Introduction

Dendroarchaeology is a subdiscipline of dendrochronology that was defined by Hollstein (1984) as "system of scientific methods used to determine the exact time span of a period during which timber has been felled, transported, processed, and used for construction" (Kaennel and Schweingruber, 1995). Objects subject to dendroarchaeological scrutiny include (pre)historical dwellings and structures, shipwrecks, historic buildings, artefacts, art objects, furniture, musical instruments and any other object made of wood species that produce tree-rings with annual resolution. The pillars of this subdiscipline rely on the factors underlying tree growth (Fritts, 1976; Schweingruber, 1996), having the principle of crossdating, i.e. finding the exact cross-match between two growth series, at its core (Douglass, 1941; Fritts, 1976). Crossdating methods have not changed from those described by Pilcher (1990), but the concept and methods to approach dendroarchaeology have seen noteworthy changes and advances in the first two decades of the 21st century.

Throughout the 20th century, dendroarchaeology focused in the development of chronologies to date timber from (pre)historic sites, and to provide absolutely dated wood for improving the calibration of the radiocarbon curve, and reconstructing climatic variables in the past (see Nash, 2002). In the new millennium, the focus has shifted from establishing dates to providing entire narratives around the selection and use of timber for different purposes (Houbrechts and Fraiture, 2011), analysing the behavioural and environmental aspects of wood utilization (Čufar, 2007; Bleicher, 2014a). Nowadays, we seek to understand the context surrounding the choice of a particular species or tree for a specific use, as this informs not only the availability of species and timber resources in certain places at an exact moment in time, but also about ancient craftsmanship that might have been transferred through time and space. We also want to know how the trees grew in the forests (were they managed, or perhaps guided); when were they cut (year and season); how and where were they processed (at the

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forest, at a sawmill, at the construction site; before or after transport); how were they transported (as logs, lumber, boards, planks, and on land or over water); and how the supply of timber was organised until the final product (a building, a ship, a cabinet, a sculpture, etc.) was made. Wood from cultural heritage objects offers a unique archive of such information, even when it remains undated. The phrase "seeing the forest for the trees" conveys all these aspects of dendroarchaeological research in the 21st century, both literally and metaphorically.

Such a holistic approach to the study of wood utilisation is facilitated now by the collaboration between scientists from different disciplines, and more importantly, by the knowledge and the data built up during the 20th century, for which Kuniholm (2001), Nash (2002), Baillie (2002), and Sass-Klaassen (2002) provide insightful reviews. Other reviews particularly focussed in dendroarchaeology include that of Kuniholm (2002) and Čufar (2007), who presented the advances in dendroarchaeology at the turn of the millennium. Čufar (2007) emphasised the raise of this discipline in Asia and the new focus on human-environment interactions and also highlighted the need for international multidisciplinary collaborations to tackle the subject of historical timber supply, which has gotten momentum in recent years. Bridge (2012) recapped the principles, potential and limitations of dendroprovenancing based on ring-width chronologies, and Bleicher (2014a) examined the impacts of different natural and anthropogenic events on tree-growth, grouping them in four descriptive categories to allow inferences from archaeological and historical samples. Recently, Pearl et al. (2020) reviewed the applications of dendrochronology with an emphasis in climatological and ecological studies, presenting some examples from archaeological studies.

In recent years, a bulk of studies have been published that explore novel techniques and methods to pinpoint the origin of modern and historical timber, to identify wood species, and to enable non-invasive research of cultural heritage objects. Those studies are scattered through different fields, from forensic, molecular, and palaeoenvironmental disciplines to computer and imaging sciences, among others. This review aims at i) reflecting on the conceptual changes that are shaping dendroarchaeology in the 21st century, and ii) compiling scattered literature to review the most recent advances in the methods and techniques for dendrochronological dating, provenancing, and for non-invasive research of cultural heritage made of wood. Focus is given to the use of novel tree-ring based chronologies, multivariate approaches, refined statistical methods, identification of wood species through visual methods, chemical fingerprinting, genetic markers, isotopic signatures and X-ray computed tomography. Their application in dendroarchaeology is discussed, and future research lines are proposed.

2. Long-distance timber transport and the key question: where did the trees grow?

Since prehistory, the consumption of timber resources has been related to the development of human society. While Neolithic communities relied on resources relatively close to their settlements and exploited them until they would relocate (e.g. Billamboz, 2011, 2014; Čufar et al., 2013; Caruso Ferme and Piqué i Huerta, 2014), further developed societies in the ancient Mediterranean established trade networks that facilitated the access to distant timber resources (Meiggs, 1982). Such networks expanded during Roman times and Middle Ages throughout Eurasia, culminating in a world-wide trade network during the Early Modern Period (Parry, 1967; Sarnowsky, 2015). As a result, depending on the time period and geographical location, the distance from the site where the wood is found to the original woodland may vary from a couple dozen meters, to hundreds of kilometres inland, or even thousands of kilometres overseas. This notion resulted in the inception of *dendroprovenancing* as a subdiscipline of dendrochronology (Eckstein and Wrobel, 2007), and led to the quest to develop methods for establishing the provenance of historic timbers. Such an exciting turn in tree-ring science deserves special consideration, and a brief retrospect is presented in this review.

The earliest evidence of long-distance timber transport is probably the cedar in Egypt (Kuniholm et al., 2007, 2014). In addition to having religious significance, cedar (*Cedrus* sp.) was highly desired as a construction material for shipbuilding, palaces, and furniture (Meiggs, 1982: 63). In this case, dendrochronology is not needed to prove that the wood has an allochthon origin in Egypt, as this genus is endemic elsewhere in Asia (*C. deodara* in the Himalayas), the south-western Mediterranean (*C. atlantica* in northwest Africa), and the north-eastern Mediterranean (*C. brevifolia* in Cyprus, and *C. libani* in Anatolia, Syria or Lebanon) (Rich, 2017).

In Europe, however, oak species (e.g. *Quercus robur* or *Q. petraea*) have an extensive longitudinal and latitudinal distribution, and are commonly found in cultural objects and sites of all time periods due to their abundance and the quality of their wood (Haneca et al., 2009). In the mid-1980s, Dieter Eckstein and co-authors reported in the journal *Nature* that wood from Poland had been used in different cities of western Europe for the production of panel paintings during the 16th and 17th centuries (Eckstein et al., 1986), a suspicion already raised by Baillie (1984). This was a very exciting finding at the time, because it resolved the date and provenance of several art-historical chronologies from UK and the Netherlands that had been uncertain for over a decade (Hillam and Tyers, 1995; Eckstein and Wrobel, 2007 and references therein). This find led to the realisation that the trade of oak timber from the south-eastern Baltic towards western Europe had been going on since at least the late Middle Ages (Wazny, 2002). Furthermore, it implied that the provenance of wood from historical and archaeological sites had to be determined before the tree-ring series were used for climatological and ecological studies (Baillie, 1984). Subsequent publications have steadily provided further dendrochronological proof of the scale of the historical timber trade of different species in Northern Europe (Crone and Fawcett, 1998; Zunde, 1998-1999; Klein and Esteves, 2001; Crone and Mills, 2002; Haneca et al., 2005c; Wazny, 2005; Sass-Klaassen et al., 2008; Domínguez-Delmás et al., 2011; Rodríguez-Trobajo and Domínguez-Delmás, 2015) (Fig. 1), with the earliest known long-distance (more than 600 km) transport of oak for construction purposes dating back to the Roman times (Domínguez-Delmás et al., 2014; Bernabei et al., 2019). In North America, dendrochronology has been key to demonstrate the transport of thousands of timbers over more than 75 km to construct the Puebloan houses at Chaco Canyon as early as the 9th century C.E., and to identify a shift in the provenance of the timber occurring during the 11th century (Guiterman et al., 2016; Watson, 2016). In Asia, Baatarbileg et al. (2008) proposed that trees growing at the timberline were transported by waterways to be used in two Mongolian temples located more than 60 km away from the source. All these studies contribute to the notion that (pre)historic timber may have come from elsewhere than where it is found, which is nowadays a standard departing hypothesis.

As happened in past centuries, modern societies also demand timber to be used in furniture, construction and other modern uses (pulp for paper for example), which has caused numerous species and their environments in both temperate and tropical forest to become endangered (see the Convention on International Trade in Endangered Species of Wild Fauna and Flora – CITES – website). In the current globalised world, timber is easily transported over large distances on trucks through land or aboard ships across the oceans. Therefore, authorities fighting illegal logging of endangered species or species growing in protected areas are facing similar questions as dendroarchaeologists: where did the trees grow? what species is being traded in a specific batch of timber? The long-distance timber transport poses therefore an exciting, far-reaching challenge for dendroarchaeologists and forensic scientists alike, and has motivated the improvement of old and development of new methods for wood provenancing.

Fig. 1. Cabinet from the Rijksmuseum (Amsterdam) collection (http://hdl.handle.net/10934/RM0001.collect.55023). The cabinet is made of oak and signed in 1607 (a, b). Dendrochronological research has determined that the top planks are made of Baltic oak (c). Those planks illustrate the high-quality timber products (i.e. radial planks cleft from slow grown trees) that were imported into the Netherlands in the early 17th century (d; second plank from the right on (c)). Source photos: a, b, Rijksmuseum; c, d: Marta Domínguez-Delmás.

3. Approaches to establish the provenance of the timber

Until recent years, the most common procedure for determining the provenance of wood from (pre)historical contexts by dendrochronology was considering the area represented by the reference chronology providing the highest Student's *t*-value (*t*) for a dated sample (see Bridge, 2012 for details). This approach has numerous caveats (Drake, 2018; Gut, 2018), and therefore new methods and multivariant approaches are being explored. The distribution area of the species under investigation has also been used as a rough estimate of the provenance when the samples where not dendrochronologically dated (see e.g. Guibal and Pomey, 2003; Allevato et al., 2010). However, some timbers cannot be identified to species level by wood anatomical features alone, so new efforts in this direction are using wood chemical fingerprints and genetic markers to identify the species (and in cases with limited geographical distributions, also the provenance) of modern and historic timbers from tropical and temperate forests (e.g. Dormontt et al., 2015; NEPcon, 2017). Other studies have explored the potential of isotopic signatures in the wood as geolocators, using stable oxygen, carbon and strontium isotopes (e.g. Kagawa and Leavitt, 2010; Hajj et al., 2017). The fundaments, successes and limitations of these approaches to timber sourcing (tree-ring based dendroprovenancing, with associated multivariant analyses and refined statistical methods, wood species identification, organic chemistry, genetic markers, and isotopic signatures) are presented and discussed here.

3.1. Tree-ring-based chronologies as tools for dendroprovenancing

During the 20th century, the development of reference chronologies in different parts of the world laid the grounds for dendrochronology to be systematically implemented as a dating tool (Nash, 2002). In the 1990s, the EU funded ADVANCE-10 K project (Analysis of Dendrochronological Variability and Associated Natural Climates in Eurasia – the last 10,000 years; Briffa and Matthews, 2002) pooled a large set of existing tree-ring and instrumental climate data from Europe and Fenoscandia with the aim of providing tree-ring based climate reconstructions for the Holocene in Eurasia. Similar efforts were carried out for example in New Zealand (Boswijk et al., 2014, and references therein). As a result, multi-millennia long chronologies of different species that captured regional climatic signals were developed using samples from living trees, historic buildings, archaeological sites and sub-fossil wood remains. Some of these composite master regional chronologies served as excellent tools for dating (pre)historical samples (e.g. Jansma, 1995; Friedrich et al., 2004), but they had very low potential for provenancing because i) they covered relatively large geographical areas, and ii) the exact origin of the underlying historical tree-ring series was uncertain. New tools and approaches to identify the origin of the timber had to be developed. Daly (2007) used part of the historical data included in the ADVANCE-10 K project and proposed three levels of provenancing, from lower to higher geographical resolution. At the third level (lowest resolution) regional master chronologies would be used in the provenance analysis to get a broad idea of the source area; at the second level (mid-resolution), crossdating would be done against site chronologies to fine-tune the provenance; and at the third level (high-resolution), crossdating would be done against series of individual trees (individual timbers) of a given site, to find out whether some timbers may have been obtained from the same tree or from neighbouring trees from the same forest. This method, however, failed to resolve the second caveat mentioned before, as the origin of the wood that made up the historical site chronologies and the underlying individual timbers was still uncertain (Daly, 2007), and it relied on several assumptions that needed to be confirmed (Gut, 2018; see below).

The fundamental principle of tree-ring based dendroprovenancing is that trees growing in the same area will be affected by the same environmental factors and, therefore, will produce similar tree-ring patterns. When prevailing environmental factors change over short distances (i.e. along an elevation gradient, across neighbouring valleys, or in different aspects of the same mountain range), local reference chronologies can be used to determine the origin of the wood with high resolution. Tree-ring based provenance studies take these statements as a departure point and make another assumption: namely, that geographical distance can be expressed by means of statistical tests that measure (dis-)similarity (Gut, 2018). Based on this assumption, the area represented by the chronology providing the best statistical match (typically expressed by Student's *t* value in Europe; Baillie and Pilcher, 1973; Hollstein, 1980; Baillie, 1982), is usually considered as the area of provenance (e.g. Eckstein and Wrobel, 2007; Daly and Nymoen, 2008; Sass-Klaassen et al., 2008; Domínguez-Delmás et al., 2011, 2013a, 2014). Gut (2018) proved these assumptions to hold true for spruces (*Picea abies*) growing along an elevation gradient in Switzerland, a notion already gathered and accounted for by Dittmar et al. (2012) in southern Germany, where elevation-specific chronologies of spruce, and to a lesser extent silver fir (*Abies alba*), retain strong and differentiated environmental signals. However, Bridge (2011) had raised concerns about using this method in the British Isles, and demonstrated that micro-environmental factors (such as soil type) were the cause for higher statistical matches between oak sites located far away than with nearby sites (Bridge, 2012). In the Iberian Peninsula, strong teleconnections have also been found between *Pinus nigra* growing in the centre and in the south of Spain (Richter and Eckstein, 1986; Domínguez-Delmás et al., 2013b). Consequently, it is not surprising that structural timbers from the roof of the nave of Segovia cathedral, in the centre of Spain, date better with a *P. nigra* chronology from the south (at more than 300 km on straight line) than with the nearby *P. nigra* chronology from Guadarrama mountains (Domínguez-Delmás et al., 2017; Sánchez-Salguero et al., 2017) (Fig. 2). If taken strictly, *t*-values would place the provenance of these timbers in the south of Spain, which is very unlikely. These examples clearly demonstrate that the highest *t*-value does not necessarily represent the area of origin, and that sometimes common sense must overrule statistics. The assumptions on which dendroprovenancing studies are based should be tested for each species and area to understand the significance of the results before making inferences about the provenance.

Despite these limitations, this simple (even simplistic) approach is very straight forward and cost-effective to at least establish a general area of provenance (third level according to Daly, 2007). For this reason, recent studies still use it to define the potential area of provenance for historical timbers (e.g. Čufar et al., 2014; Grabner et al., 2004; 2014; Haneca and Van Daalen, 2017; Domínguez-Delmás et al., 2018; Akkemik et al., 2019; Shindo and Claude, 2019). Expanding the network of reference chronologies remains therefore a paramount task for dendroarchaeology. Such chronologies should represent site-specific conditions to allow high-resolution provenance analysis in areas formerly exploited for timber production (Domínguez-Delmás et al., 2015; Wilson et al., 2017). New site chronologies are being developed along elevation and ecological gradients, including also trees that were formerly managed, or that could have been selected in the past for construction purposes (e.g. Thun, 2005; Dittmar et al., 2012; Domínguez-Delmás et al., 2013b; Netsvetov et al., 2017). Reference site chronologies can also be developed from historic timbers with rather local, or known origin (e.g. Ohyama et al., 2007; Kolář et al., 2012; Strachan et al., 2013; Seim et al., 2015; Susperregi and Jansma, 2017; Domínguez-Delmás et al., 2018; Nechita et al., 2018; Boswijk and Fowler, 2019). In Southeast Asia, multi-century long chronologies of several species (e.g. *Tectona grandis*, *Fokiena hodginsii*, *Pinus kesiya* and *P. merkussii*) have been developed (Pumijumnong, 2013), opening the door to dendroarchaeological and timber provenance studies.

Billamboz (2013) advocates implementing a dendro-typological approach to (pre)historical timbers to infer groups of similar provenance based on the age and growth rates observed on the timbers (dendrological and dendrochronological aspects), together with the presence/absence of pith and sapwood (techno-morphological aspects). He illustrated the implementation of this method to timbers from the Roman period in southwestern Germany, inferring subregional sourcing areas for the defined dendro-groups according to their spatial correlations. Domínguez-Delmás et al. (2014) could also differentiate by dendrotypology three clear groups among the oak timbers of a Roman harbour in The Netherlands, which were assigned different provenances based on correlations with master regional chronologies: a first group with fast-grown irregular trees was attributed to the lower course of the Meuse valley; a second group made of slower-grown regular trees was attributed to the south of Germany (Neckar river and tributaries); and a

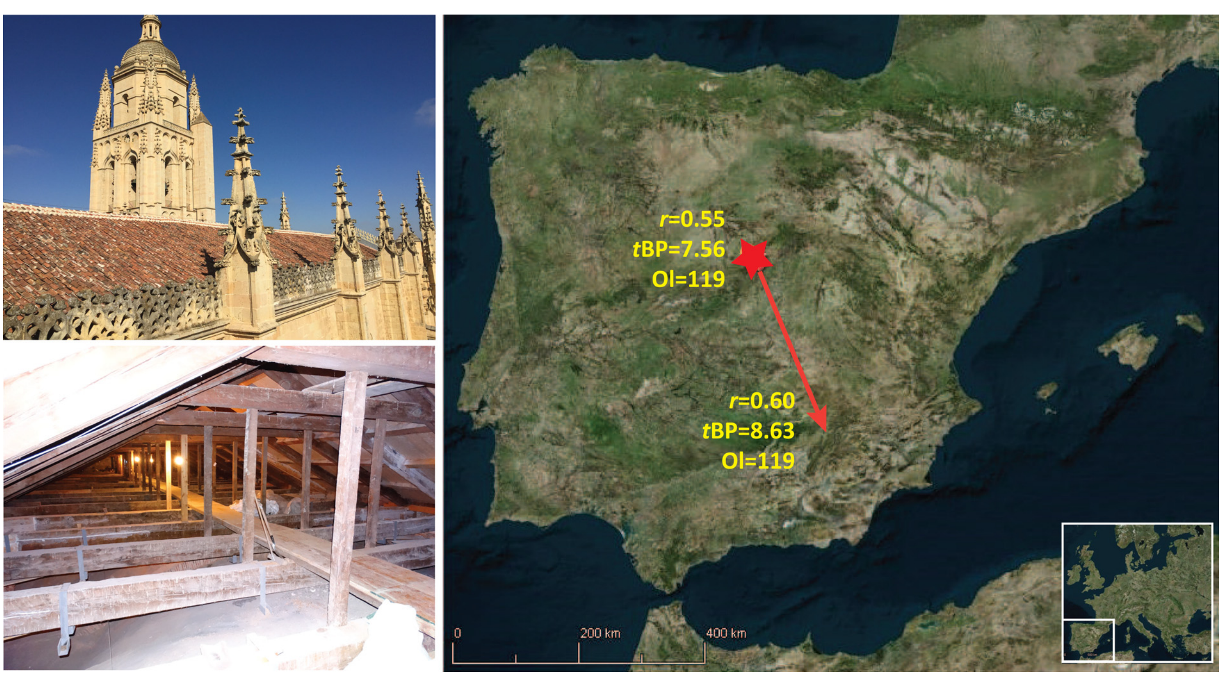

Fig. 2. Statistical crossdating (PAST5 v. 5.0.610) between a window sleeper from the roof of the nave at Segovia cathedral and *Pinus nigra* chronologies from the center (SPAI068, ITRDB, Büntgen and Fernández-Donado, 2010-06-10) and the south of Spain (PBM, Domínguez-Delmás et al., 2013b). In this case, higher statistical values do not represent the area of origin. Photos left: outside (top) and inside (bottom) of the roof of the nave (Marta Domínguez-Delmás).

third group made of older and yet slower-grown regular trees was attributed to the central part of Germany. This result had previously been achieved empirically using a hierarchical cluster analysis, which can be represented graphically in a dendrogram (see Fig. 5 in Domínguez-Delmás et al., 2014). Hierarchical cluster analyses are powerful tools to empirically separate groups of similar provenance, although the suitability of different distance measures and grouping methods should be tested for different species and locations (García-González, 2008).

Prehistoric timber structures such as Neolithic water wells in Central Europe and pile-dwellings were typically made with locally sourced wood (e.g. Billamboz, 2014; Čufar et al., 2015; Tegel et al., 2012; Rybníček et al., 2018, 2020). They are usually dated with regional chronologies from sub-fossil wood-remains, becoming afterwards excellent links to local forests of the past. Dendrotypology can then be used to infer cycles of woodland exploitation and development. In contrast, archaeological wood and timbers from historic buildings in areas of Central Asia that are nowadays depleted of trees have been dated with regional chronologies developed for climatological purposes (Sheppard et al., 2004; Wazny, 2016 for an overview). The lack of woodlands in the vicinities of those archaeological and historical sites hampers assessing the exact provenance of the wood by tree-rings, precluding their use as reference datasets for provenancing purposes. Dendrotypology and/or hierarchical cluster analysis can help in this case define groups of timbers with the same origin. Furthermore, dendrotypology is also an excellent method to identify timbers derived from the same tree (Billamboz, 2013), and it is advisable to use it when dealing with (pre)historic timbers to avoid overrepresentation of single trees in the dataset.

New chronologies based on anatomical features other than ring-width (e.g. earlywood vessel size in oaks, latewood density/blue intensity in conifers) are also being developed and tested for dating and provenancing purposes (Wilson et al., 2017; Akhmetzyanov et al., 2019, 2020, this issue). In the north of Spain, Akhmetzyanov et al. (2019) developed chronologies of 14 different tree-ring and anatomical variables for living trees of four oak species (*Q. robur*, *Q. petraea*, *Q. pyrenaica* and *Q. faginea*), and concluded that combining latewood width and earlywood vessel size represents an optimal approach to pinpoint oak provenance in that area. While the former variable (mostly influenced by summer temperature) discriminates sites by longitude, the latter (influenced by winter/spring temperatures) does it by latitude and altitude, increasing the accuracy of the provenance analysis. The results of studies testing the suitability of latewood density of conifers (measured as blue intensity, BI) for provenancing are ambiguous (see Campbell et al., 2007 and Wilson et al., 2014 for specifics about this method). Wilson et al. (2017) demonstrated that BI is potentially a better variable than ring width to date *Pinus sylvestris* from high elevations, as it retains a stronger, less site-dependent climate signal than ring width, but for that same reason its potential for provenancing could be limited. Akhmetzyanov et al. (2020, this issue) found that a two-step approach using BI and ring-width series could improve provenance accuracy of *P. sylvestris* and *P. nigra* in the Mediterranean, because BI can effectively discriminate elevation, while ring width can assign the location within the elevation groups defined by BI.

Some of the caveats and limitations of the tree-ring based methods for timber provenance described so far are related to the assumptions outlined by Gut (2018) and the statistical tests used in the spatial analysis of tree-ring series (Drake, 2018). Therefore, some recent studies have been dedicated to adapt and refine the statistical methods. Fowler and Bridge (2017) determined empirically the significance to Student's *t*-values calculated with the method proposed by Baillie and Pilcher (1973), which is implemented in the most common dendro-software packages, for different series lengths. They illustrated how *t*-values effectively reduce sensitivity to series length (Baillie, 1982; García-González, 2008), and concluded that although these results present an illustrative guidance, the dendrochronologist's experience and common sense should prevail over the statistics (e.g. a 99.9 % confidence is achieved at $t = 4$ for series of 30 rings, which does not mean that such a result represents a true match). Fowler et al. (2017) tested the effect of different high-pass filters on crossdating results for British oak (*Quercus* sp.) and New Zealand kauri (*Agathis australis*) datasets. They empirically demonstrated that optimal results are obtained for both species with the filter proposed by Baillie and Pilcher (1973) but stressed that some filters performed better on one species than on the other, proposing that species-specific filters should be tested for refined crossdating results. Drake (2018) and Bridge and Fowler (2019) address the pitfalls of using the highest *t*-values as indicators for provenancing and propose new methods. The former conceived novel methodology using Bayesian inference, based on the hypotheses that unlikely sites could be determined and rejected even when showing high correlations (Drake, 2018). He tested the method with the dataset of Chaco Canyon and concluded that only one third of the data matched the sourced previously indicated by other studies (English et al., 2001; Reynolds et al., 2005; Guiterman et al., 2016), whereas two thirds were not allocated by his method to the sources previously proposed. In a similar conceptual line, the later presented the use of field inter-site correlations (considering both positive and negative values) to assist on provenance studies of British oak, and proposed a three-step approach (Bridge and Fowler, 2019): first, inter-sites correlations of indexed chronologies would be calculated, and if the results spread throughout a large area, correlations of residuals (in which the common signal is removed) would be calculated on a second step, and field correlations as last, to refine the area of provenance. Interesting about this method is that it proposes areas that are unlikely to be the source. Boswijk and Fowler (2019) applied the same methodology, calculating spatial patterns of correlations of index and residual chronologies of kauri in New Zealand. They warn about the impact that natural and anthropic disturbances may have in the correlation results, but conclude that it is a good method to establish the provenance of the wood (and certainly to point at unlikely areas) within a small region.

3.2. Identification of wood species to trace the geographic origin of wood

Provenancing based on tree-ring chronologies can only be applied to dated samples; therefore, other methods are needed to ascertain the origin of historical samples that remain undated through dendrochronology. The identification of the wood species can provide an estimate of the area of origin when the geographical distribution of the species under investigation is limited to a well-defined or a small territory. Identification of species and provenance of modern timber is also relevant to detect wood from illegal logging (i.e. wood from protected areas or endangered species). The pressing need to develop forensic tools has promoted a bulk of studies testing different techniques based on wood chemical fingerprinting (i.e. analysis and quantification of organic compounds in wood) and genetic markers (DNA-barcoding, -fingerprinting, and phylogeographic approaches; Lowe and Cross, 2011) for which Dormontt et al. (2015) present a thorough and comprehensive overview. The principles and potential of these approaches are briefly presented and discussed here.

- Visual identification of wood species represents the most straightforward and traditional way to identify wood species. It consists on observing the macro- and micro-anatomical features of the wood in the transverse, radial and tangential sections (e.g. Schweingruber and Baas, 1990; Carlquist, 2001; Crivellaro et al., 2013). To aid in this task, several wood identification keys have been made available online (see for example Delta-Intkey.com, Dallwitz et al., 2000 onwards; WoodAnatomy.ch, Schoch et al., 2004; the InsideWood database, Wheeler, 2011), and the International Association of Wood Anatomist (IAWA) has published two manuals listing microscopic features for hardwood and softwood identification that facilitate the use of the keys (Wheeler et al., 1989; Baas et al., 2004 respectively; Ruffinatto et al., 2015). This visual method requires training and experience, and technological advances in computational imaging have opened the door to the implementation of machine-learning algorithms to automatise the identification of wood species (see Hermanson and Wiedenhoeft, 2011 for a review). Promising results have been reported by Ravindran et al (2018), who used convolutional neural networks to identify species of the *Meliaceae* family from photographs of the transverse section of the wood. Verly Lopes et al. (2020) have also demonstrated the feasibility to use a convolutional neural network to identify on the spot North American hardwoods with 92.60 % accuracy from macro photos of the transverse section taken with a smartphone. He et al. (2020) tested the efficacy to discriminate between three *Swietenia* species combining quantitative wood anatomy data with different machine learning models. Their detection accuracy ranged from 66.7 %–95.0 % depending on the species, being explained by the narrow to wide geographical spread of the trees selected of each species. The question still remains whether such automated methods that are based on wood anatomical features alone can be used to identify timbers (both in temperate and tropical forests) of species with high resemblance. For example, in the north of the Iberian Peninsula there are four main deciduous oak species (*Quercus robur, Q. petraea, Q. faginea,* and *Q. pyrenaica)* that hybridise in transition areas where they are in close proximity. These species cannot be discriminated based on wood anatomical features, and historical oak timbers in this region are typically referred to as deciduous oaks (*Quercus* subg. *Quercus*) (Domínguez-Delmás et al., 2015). The ability to differentiate these species, in particular *Q. faginea* and *Q. pyreniaca* from the other two, acquires paramount relevance in the research of shipwrecks. Whereas *Q. robur* and *Q. petraea* have an extensive geographical distribution in Europe, the distribution of *Q. faginea* and *Q. pyrenaica* is almost exclusively restricted to the Iberian Peninsula. They are also present in areas that were intensively exploited during the Early Modern Period (c. 1450–1800) to supply timber for shipbuilding activities. Therefore, when a (suspected) Atlantic-Iberian shipwreck is found, the identification of most timbers as *Q. faginea* and/or *Q. pyrenaica* would indicate that the wreck corresponds to a ship built in an Atlantic-Iberian shipyard, allowing further inferences about procurement and construction processes in the region. To account for such a high similarity in the wood anatomy of some species, He et al. (2020) recommend using a large number of individuals when developing algorithms for automatic recognition, so that models can be trained incorporating the highest possible variability of each wood anatomical feature.

- Chemical fingerprinting considers that the composition and relative amounts of phytochemicals synthesised by (woody) plants vary per species and location, as they are mainly determined by genetic and environmental factors (Kranitz et al., 2016, and references). Therefore, the spectra obtained through different techniques (e.g. Direct Analysis in Real Time Time-Of-Flight Mass Spectrometry; Fourier transform infrared spectroscopy; Pyrolysis-Gas Chromatography-Mass Spectrometry) can be analysed with multivariate methods (principal component analysis, discriminant analysis, partial least squares, etc.) to potentially identify the chemical fingerprint of specific species growing on different sites. However, studies on different species around the globe show contrasting results. Whereas some have been able to discriminate between species (Cody et al., 2012; McClure et al., 2015; Zhang et al., 2019), between locations of one species (Sandak et al., 2011; Finch et al., 2017) or even between species and provenance (Traoré et al., 2018a), others succeeded in discriminating only one out of six studied species and could not identify the provenance (Paredes-Villanueva et al., 2018), or showed constraints in the discrimination of species, but were able to distinguish provenances (Deklerck et al., 2020). Such disparity of results suggests that the success of chemical fingerprinting strongly depends on the species, the geographical scale of the provenance tested, and the sample size; therefore, future efforts should be directed at further expanding the reference dataset of chemical fingerprints to cover a wide range of species and territories, and exploring the accuracy of the different techniques.
- Genetic markers can provide information at different levels (Lowe and Cross, 2011): DNA barcoding is used to distinguish between species; DNA fingerprinting allows differentiation of individuals from the same species within a population; and population genetics and phylogeography allow identification of individuals from different populations within and between regions respectively. DNA barcoding consists of obtaining short nucleotide sequences from target DNA regions, i.e., genetic loci that characterise each species (Degen and Fladung, 2008). Several studies have demonstrated the potential of this method to accurately identify timbers at the species level (e.g. Muellner et al., 2011; Nithaniyal et al., 2014), and they indicate that DNA target regions are better preserved in the sapwood than in the heartwood, as DNA degradation (rupture of DNA chains into small fragments) starts already in the heartwood of living trees (Jiao et al., 2014). DNA barcodes from vouchered specimens are available for comparison in the Barcode of Life Database (BOLD), which is linked to the GenBank (Benson et al., 2014). GenBank is an open access database containing almost 6000 million genetic sequences from plants in 2013 (release 197, 8/2013), and currently holding genetic information from more than 87 million plant species (GenBank last accessed on 8 April 2020, https://www.ncbi.nlm.nih.gov/nuccore). DNA fingerprinting uses microsatellite markers to track individual logs from the forest (concession) until their final destination, as illegal timber usually enters the supply chain before the batch reaches the sawmill (Lowe and Cross, 2011). Therefore, current studies are dedicated to the development of reference genetic markers at logging concessions for different species of commercial interest that are prone to be substituted by illegal timber (e.g. Nuroniah et al., 2016; Hung et al., 2017; Ng et al., 2017; Paredes-Villanueva et al., 2019; Vanden Abeele et al., 2019). Population genetics and phylogeography also use microsatellites to identify genetic differences within a species and thus delimit geographic areas with similar genes. This method requires an *a priori* identification of the microsatellites representative for each geographic unit. When such genetic reference data is lacking, a so-called assignment test can be used to establish whether the researched timber belongs to a specific population for which genetic data has already been developed. However, the geographical resolution of this method will be determined by the genetic diversity of a given species (Petit et al., 2002).

The advantage of these methods that are being employed with modern timbers is that they require a small amount of material. Therefore they are well suited for investigation of objects identified as cultural heritage assets. However, they all come across the same hindrance when being applied to (pre)historic timber: wood aging and decay. The degradation of the wood structure and DNA starts before the tree dies (heartwood), but the speed at which it progresses and the agents involved depend on the environment in which the tree lives and where the processed timber remains afterwards (Łucejko et al., 2015; Kranitz et al., 2016), and on the conservation treatment applied, if any. Therefore, some studies have been directed at worse-case scenarios, trying to identify wood species and provenance of archaeological (sometimes waterlogged) wood using chemical fingerprinting (e.g. Traoré et al., 2016, 2017, 2018b) and DNA profiling (Deguilloux et al., 2006; Liepelt et al., 2006; Speirs et al., 2009; Guichoux et al., 2011; Jiao et al., 2015; Wagner et al., 2018). Results thus far show limited potential of chemical fingerprinting to identify and provenance archaeological timber. The way in which wood degradation affects the results of these analyses is not yet fully understood (e.g. Traoré et al., 2018b), and further research is needed in this direction to enable the systematic implementation of chemical fingerprinting methods (Colombini et al., 2007; Łucejko et al., 2015). Genetic studies however have shown promising results. In China, Jiao et al. (2015) tested DNA barcoding to discriminate aged (ca. 30 to ca. 90 years old) and ancient (ca. 3000 years old) *Populus euphratica* samples. Whereas they could retrieve and amplify DNA chains from the aged samples, their results were unfruitful with the ancient wood. They attributed the unsuccessful result to the high level of inhibitors in the solution, and/or the lack of DNA material on it. Recently, Wagner et al. (2018) achieved DNA extraction from ancient oak timbers, obtaining valuable insights into the degradation paths of DNA in wood. Their findings open the door to improving extraction and amplification protocols in these type of material.

3.3. Isotopic signatures

Trees absorb different elements through their leaves, bark and roots, incorporating them into their phytochemicals and biomass. Key bioelements in wood are Carbon (C), which is present in the air and is absorbed by trees through the foliage; Oxygen (O) and Hydrogen (H), which originate from rainfall and are absorbed through the roots (McCarroll and Loader, 2014); and to a lesser extent, Nitrogen (N) and Sulphur (S). These two are both present in the air and the bedrock (Thode, 1991; Förstel et al., 2011; Houlton et al., 2018), but while N enters the trees with the soil solution through the roots, different forms of S compounds can enter the tree system through the foliage or the roots (Wynn et al., 2014).

C, O and H are commonly used in environmental sciences because they have stable isotopes (i.e. not subject to radioactive decay) whose ratios reflect climate conditions of the sites where the trees grow. Ratios of stable isotopes of C ($^{13}C/^{12}C$), O ($^{18}O/^{16}O$) and H ($^{2}H/^{1}H$, or D/H), which are expressed conventionally as $\delta^{13}C$, $\delta^{18}O$, and δD (or sometimes $\delta^{2}H$), undergo fractionation; i.e., there is a variation in their relative abundance from the source to the tree, which is driven mainly by the response of the trees to their environment (McCarroll and Loader, 2014; Boner et al., 2007; Loader et al., 2007). The mechanisms ruling fractionation are well understood, and thus stable isotopes can be used to infer climate conditions at the sites where trees grow. For example, isotope ratios of O and H in rainfall are influenced by mean yearly temperature, weather patterns, elevation, and also by the "continental effect", whereby an isotopic enrichment is found the further we move from the coast towards inland (Förstel et al., 2011).

In addition to their potential as timber-origin geographical markers, stable C, O and H isotope ratios are known to have lower inter-tree variability, stronger correlation, and much weaker autocorrelation than ring-widths (Dorado Liñán et al., 2011; McCarroll and Loader, 2014; Loader et al., 2019). Therefore, they are potentially better suited for tree-ring dating (see point 4). This has been demonstrated in Japan by Yamada et al. (2018), who succeeded in dating trees buried after an earthquake in lacustrine sediments by crossdating their tree-ring cellulose $\delta^{18}O$ series with a previously developed $\delta^{18}O$ chronology. They concluded that the trees died in the second half of the 9th century C.E., and attributed the event to one of the two mega earthquakes that stroke Japan in the late 9th century. Furthermore, stable isotopic signatures can aid identifying the tree-rings in tropical species. Ohashi et al. (2016) showed that variations in O isotopes can be used to distinguish tree rings in a tropical species with no distinct annual rings, opening the door to crossdating tropical species that would otherwise be deemed unsuitable by conventional ring-width based dendrochronology. Improvements in methods to extract α-cellulose from tree-rings for stable O and C isotope analyses facilitate the production this type of data (Kagawa et al., 2015), potentially providing the means to develop these proxies at a large scale.

Isotope ratios of N ($^{15}N/^{14}N$) and S ($^{34}S/^{32}S$) absorbed by plants undergo little to no fractionation (Thode, 1991; Förstel et al., 2011), therefore they could be regarded as geochemical markers of the site where trees grow. Similarly, Strontium (Sr) present in rocks is released into the ground and enters the trees also as part of the soil solution. Strontium stable isotopes $^{87}Sr/^{86}Sr$ do not fractionate either, and provide a climate-independent geochemical signature that can be used to determine wood provenance (Hajj et al., 2017; Rich et al., 2016). Unlike Sr, N and S isotopic signals can easily be altered by anthropogenic activities that generate pollution or waste (Förstel et al., 2011; Wynn et al., 2014), leaving Sr isotope ratios as the most optimal geochemical marker for timber origin.

Nevertheless, tests on different stable isotopes show varying results in different areas. For example, Kagawa et al. (2007) conducted a study on *Shorea* species from Southeast Asia with the aim to determine their provenance using O, C, and N stable isotope ratios ($\delta^{18}O$, $\delta^{13}C$, $\delta^{15}N$), and nine inorganic elements (Al, Ba, Ca, Fe, Mg, Mn, Sr, V, Zn). The correlations with the inorganic elements yield no significant results, but $\delta^{18}O$ and $\delta^{13}C$ showed strong correlations with latitude/longitude and served to discriminate between Philippines and Borneo sites. In southwestern USA, Kagawa and Leavitt (2010) obtained promising results establishing the provenance of pinyon pines using $\delta^{13}C$ signatures, but recommended to combine $\delta^{13}C$ with δD and $\delta^{18}O$ and develop annually resolved isotopic chronologies to narrow down the geographical range of the results. In contrast, Horacek et al. (2009) found a clear discrimination between Siberian and Austrian larch trees based on $\delta^{18}O$, whereas $\delta^{13}C$ isotopic signal failed to discriminate between the sites. The development of a geospatial model based on $\delta^{18}O$ and δD isoscapes in the north of Italy succedded to predict the origin of timber in that area within a 95 % confidence interval, and as Kagawa and Leavitt (2010), stressed that a multiproxy approach would yield the most accurate results (Gori et al., 2018).

Strontium isotope ratios ($^{87}Sr/^{86}Sr$) proved key to ascertain the provenance of construction timbers from Chaco Canyon, suggesting that the timber had been sourced in distant mountaintops at 75 − 100 km away (English et al., 2001; Reynolds et al., 2005). However, in the Eastern Mediterranean, Rich et al. (2012) found that the signature of $^{87}Sr/^{86}Sr$ ratios in cedar trees of Cyprus was closer related to the seawater isotopic signature than to that of the bedrock, but highlighted the possibility to discriminate between three provenances of cedar in the eastern Mediterranean (Turkey, Lebanon and Cyprus). Furthermore, they found that differences in signature between heartwood and sapwood are negligible (Rich et al., 2012, 2015), which eases the task of sampling archaeological timbers for Sr isotopic research. Having established Sr reference ratios for cedar in the Eastern Mediterranean, Rich et al. (2016) conducted a study to provenance cedar timbers from three shipwrecks. The results were inconclusive for the two shipwrecks that had sunk and remained underwater for centuries (the 14th century BCE Uluburun shipwreck, sunk in the south of Turkey; and the Athlit Ram shipwreck, sunk off the coast of Lebanon and dated to the early 3rd or late 2nd century BCE). However, the third shipwreck (Senwosret III's Carnegie boat, a funerary ship from the 19th century BCE excavated in Dashur, Egypt), which had never been in the water, could be clearly ascribed to a forest in northern Lebanon (Fig. 2 in Rich et al., 2016). Hajj et al. (2017) provide a much more comprehensive review about the use of Sr isotopic signatures as provenance markers and their potential to trace the origin of wood from archaeological waterlogged shipwreck timbers that have been resting in marine environments for centuries. They stress the need to establish protocols to retrieve the original Sr signature in those samples, and to understand "the respective contributions of rocks and atmospheric deposition in various geological, climatic and pedogenetic contexts" in order to develop high resolution (local) Sr maps.

4. Short tree-ring series and the potential of oxygen isotope chronologies

Most of the dendroarchaeological datasets are biased towards samples with enough tree-ring series to provide dates (more than 100; Baillie, 1982; Kuniholm, 2001), as samples with fewer rings (particularly those with less than 60) have been traditionally discarded due to the difficulty of dating them. In doing so, crucial information about the

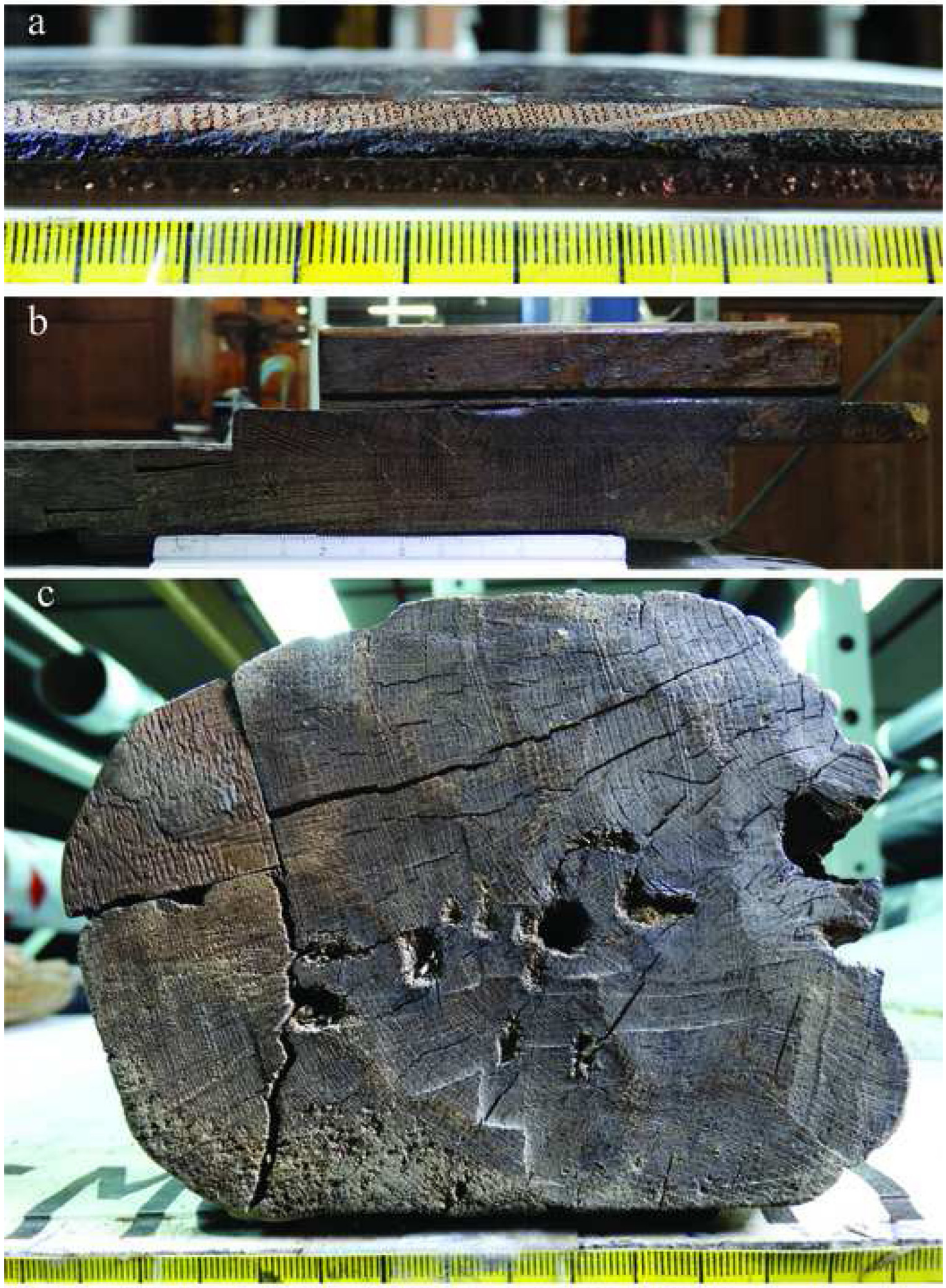

Fig. 3. Dendrochronological research on art historical objects. a) transverse edge of a panel painting (Rijksmuseum, http://hdl.handle.net/10934/RM0001.COLLECT.6492) cleaned with scalpel knives (the panel is lying on its front); b) wooden elements at the bottom of a cabinet door (Rijksmuseum, http://hdl.handle.net/10934/RM0001.COLLECT.426799) where no preparation is needed to visualise the tree rings; c) base of a sculpture (Rijksmuseum, http://hdl.handle.net/10934/RM0001.COLLECT.25706) where just a small portion of the outer rings has been slightly cleaned. Photos: Marta Domínguez-Delmás.

selection of young or fast-grown trees for specific uses, or the availability of young trees in the surroundings of ancient settlements is often disregarded and lost. However, research on Neolithic pile-dwelling settlements in southwest Germany, Switzerland, and northeast Spain has demonstrated how timbers with few tree rings can be used to infer timber availability, periods of high construction activity, use of woodlands and landscape changes (e.g. Bleicher, 2007; Billamboz, 2008; Tarrús, 2008; Čufar et al., 2015). These results have been possible thanks to the large amount of samples with sapwood and/or bark edge collected at each of those archaeological sites, regardless of the number of tree rings (Billamboz, 2013). Furthermore, implementing a dendrotypological approach has proven successful to relatively date samples with less than 60 rings and create floating chronologies at a prehistoric site in Lithuania (Bleicher, 2014b). Sometimes, such short series can be crossdated with longer ones of different species of the same site (Billamboz, 2008; Bleicher, 2014b), facilitating the establishment of a relative (floating), near-absolute (dated by radiocarbon wiggle matching; Bronk Ramsey et al., 2001) or absolute (anchored in time) chronology for the archaeological site.

Successful dendrochronological dating of short tree-ring series has also been demonstrated with archaeological structures and buildings from the Early Modern Period when numerous spruce (*Picea abies*) and pine (*Pinus sylvestris/nigra*) timbers from the same construction phase contained the bark edge and were cut in the same year (Domínguez-Delmás et al., 2017), or within two years (Domínguez-Delmás et al., 2011). It must be stressed that these are exceptional cases, and the condition of having numerous samples of the same structure that come from trees cut in the same year or shortly apart is a requirement for attempting crossdating of short series (Hillam et al., 1987). This requirement however is seldom met, and the need remains to establish the date and provenance of timbers with few tree rings. This is particularly imperative in areas such as Flanders (northern Belgium), where local timbers from fast grown oaks yielding series of 40–60 tree rings are often found in archaeological sites and historical buildings (Haneca et al., 2005b, 2006); and also when researching shipwrecks, as fast grown (probably coastal) oaks were specifically selected in Euro-Atlantic shipyards for timber frames (Loewen, 2001; Ballu, 2008). Such a conscious choice demonstrates the knowledge of master(ship)builders about the raw material they were employing, so excluding those timbers from the research collection would bias invariably our observations and restrict our knowledge gain.

Recently, the construction of an annually resolved chronology of oxygen isotopes ratios ($\delta^{18}O$) extracted from the latewood cellulose of oak samples in central England has provided very promising results to date timbers with short series (Loader et al., 2019). Oxygen isotope ratios in this part of UK strongly reflect the signature of summer rainfall and relative humidity and thus contain a strong high-frequency variability (i.e. strong climate-sensitive signal) in an area where the same climatic factors induce complacent tree-ring patterns that pose a challenge for conventional crossdating. The advantages of this method are that i) a robust chronology can be attained with relatively small sample depth ($n = 10$), ii) it can be used with timbers showing complacent growth, iii) highly significant statistical values can be achieved for the right date with series as short as 50 years, and iv) series do not need to be detrended (Duffy et al., 2019; Loader et al., 2019). A disadvantage of this method is the costly price of the equipment and the set up required for the analysis of samples. Budgetary questions aside, the use of $\delta^{18}O$ for dating short series is very promising and should be further explored. Although this method has only been attested for central England, it has the potential to be effective in other areas with similar sensitivity of the $\delta^{18}O$ signal (e.g. the western Euro-Atlantic façade). Consequently, the development of $\delta^{18}O$ chronologies for dating purposes may become a paramount research line in the coming years.

5. Non-invasive dendrochronology

Having access to tree-ring patterns in the wood is the first step to carry out dendrochronological research, but this can be challenging when the research object is a work of art, an instrument, a cabinet or an archaeological artefact that cannot be sampled. In these cases, the research must be carried out directly on the object. For example, the research of panel paintings is done at the transverse edges of the planks that make up the panel. These edges are often bevelled and very thin, and are sometimes covered by paint, varnish, wax or other layers that hamper the visualization of tree rings. In such cases, the surface must be cleaned, for which sharp scalpel knives are typically used (Fig. 3a). This represents a highly invasive method that can only be justified by the associated knowledge gain. Another less invasive method to prepare the wood is by micro abrasive-blasting with aluminium oxide particles (Heginbotham and Pousset, 2006), which requires a special room and the object to be fully covered except for the surface that is going to be cleaned. Fraiture (2009) describes the use of a laser to clean the end grain of panel paintings, which removed the superficial dirt and other layers without damaging the surface of the wood. It required a room without windows, and the surface of the object had to be protected with tape except for the line to be cleaned. This heavy portable device was a tailor-made prototype and has not been commercialised (Fraiture, email comm. on 16/10/2019). In furniture, the different wooden elements that make up the door of a cabinet, its back and top, or the drawers for example, are scrutinised for sufficient rings and remnants of sapwood, so that the dating will be as close as possible to the felling year of the tree. In those elements, the transverse section is sometimes smooth enough to visualise the tree rings directly (Fig. 3b), but often it is not, and it must also be prepared for the research as it is done on the planks from paintings. Dendrochronological research on sculptures is typically done at the bottom, where the flat surface generally represents the widest transverse section of the piece of wood (Haneca et al., 2005a; Fraiture, 2014). This surface is usually smooth, therefore cleaning it with a brush can sometimes suffice to visualise the tree rings, although it might also be necessary to clean some parts of the surface with some abrasive tool mentioned before (Fig. 3c).

The methods to register the tree rings have improved in the 21st century. In the onset of the study of works of art by dendrochronology, a magnifying lens with a scale was used to measure the ring widths, achieving a resolution of 0.1 mm at best, and ring widths were written down on a paper sheet (e.g. Bauch and Eckstein, 1970; Fletcher, 1977). Another less accurate but also effective method was assigning relative values to each ring (Jansma et al., 2004). In both cases, the measurements served to effectively register and crossdate tree-ring series, but the lack of precision in the measurements implies that the data cannot be used to make inferences about past woodlands and tree selection. To overcome this issue, an alternative is to measure the tree rings of art historical objects directly on the object, but using a measuring device and a microscope, which delivers a resolution of at least 0.01 mm (Tyers, pers comm.). However, a limitation common to these three measuring methods is that the sole record of those interventions are the paper sheets where the ring widths were registered, or the digital measurements obtained through the measuring device. Consequently, re-examination of the tree-ring patterns becomes a hurdle, as it can only happen if access to the art object is granted again (Baillie, 2002). Archiving researched samples has become a paramount question in dendrochronology (Creasman, 2011), and by extension also in the research of art historical objects that are not physically sampled. Advances in digital photography now permit registering tree rings in the objects with photographs while they are simultaneously measured *in situ* with a portable measuring device (e.g. Bernabei et al., 2010, 2017). Tree-ring series can also be captured on digital macro pictures in an overlapping sequence, to be measured subsequently with high precision using image analysis software (e.g. Fraiture, 2014; Rodríguez-Trobajo and Domínguez-Delmás, 2015). In this way, images of the researched surfaces can always be retrieved to recheck possible errors, and to inspect other features if needed. Furthermore, the absolute measurements generated can be used to make inferences about the selection of specific trees, the forests where the wood was sourced, or events that may have affected tree growth (e.g. Haneca et al., 2005a; Fraiture, 2009, 2014; Bleicher, 2014a).

The convenience to preserve some sort of digital "sample" of the researched surface, together with the increasing demand from conservators and curators to develop non-invasive methods has promoted collaboration between computer scientists and dendrochronologists towards the development of non-invasive methods to research art-historical objects (Grabner et al., 2009). In this regard, the field of computational imaging has provided a major contribution to the study of cultural heritage objects by allowing non-invasive research using X-ray computed tomography (XrayCT). XrayCT consists on taking X-ray images of an object while the object is rotated at known degrees. The images are subsequently merged using algorithms that recognise the object features on each X-ray and produce a 3D image that can be "cut" (digitally) at the desired level to visualise the inner structure of the object. Several methods can be used to scan the object (see a description of the most common ones in Van den Bulcke et al., 2017: 580). This technique has been successfully used to retrieve tree-ring sequences from archaeological objects of the Viking era and medieval art in Norway (Bill et al., 2012; Daly and Streeton, 2017), polychrome sculptures in Japan (Okochi, 2016), and musical instruments (Van den Bulcke et al., 2017). In addition to the non-invasive nature of XrayCT scanning, an advantage is that the tree rings can be measured in different parts of the object. This proved crucial to date a Renaissance

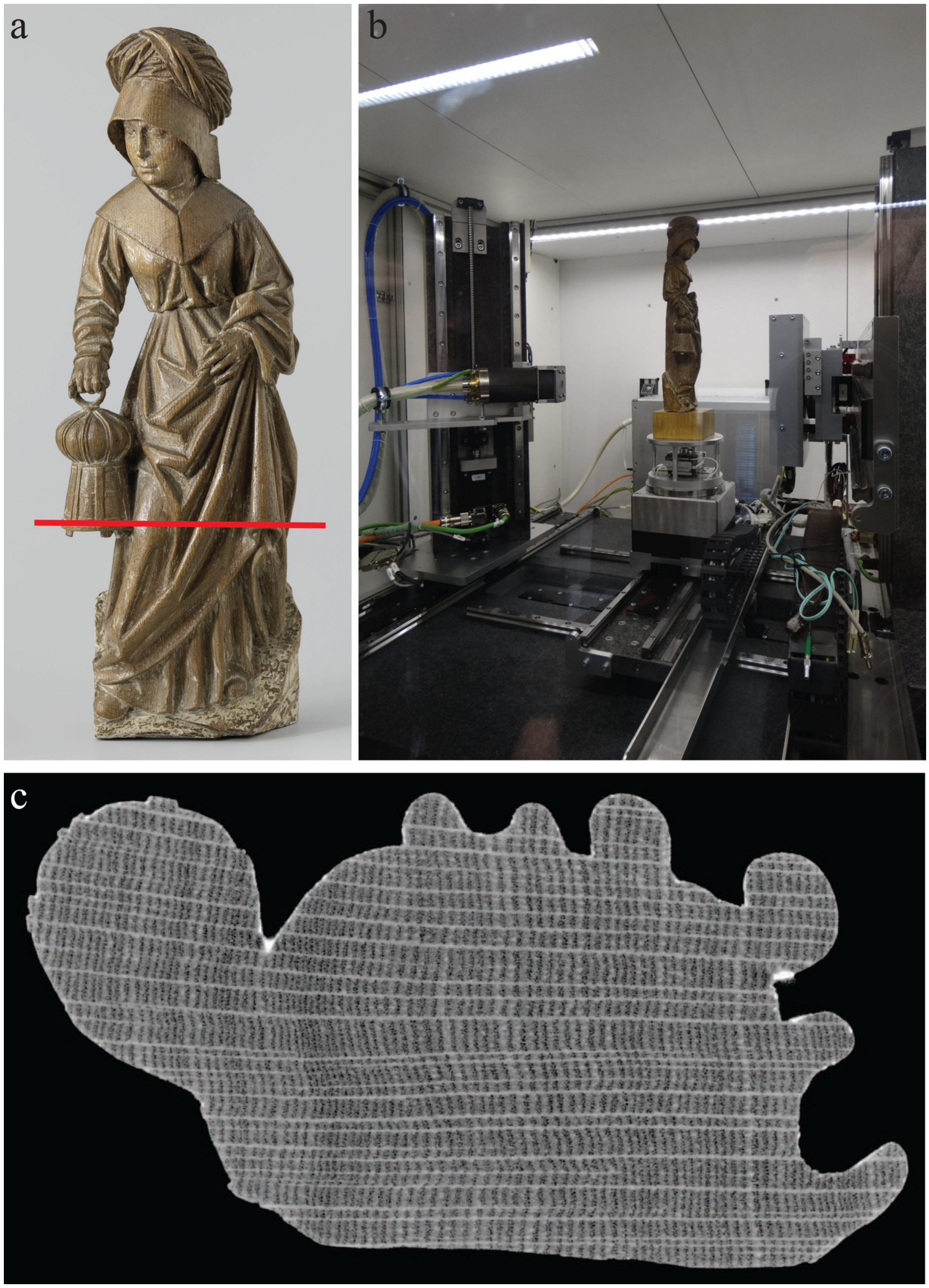

Fig. 4. a) Sculpture of the *Holy woman with lantern* (Rijksmuseum, http://hdl.handle.net/10934/RM0001.COLLECT.24420) (source photo: Rijksmuseum); b) Setup inside the X-ray machine at the CWI in Amsterdam (photo: Marta Domínguez Delmás); c) CT image of the cross-section at the height of the base of the lantern (where the red line cuts the sculpture in (a)) (credit CT image: dr. Alexander Kostenko, CWI). The CT image contained more tree rings than the base and was crucial to date the sculpture.

sculpture from the Rijksmuseum collection (Amsterdam, The Netherlands), in which the widest section was not found at the base, but higher up in the sculpture (Fig. 4) (Domínguez-Delmás et al., in prep). Another study has compared the use of clinical 3D magnetic resonance imaging (MRI) and XrayCT (Mori et al., 2019) to measure tree rings in archaeological (dry and waterlogged) wood. They found that the former method is better suited for waterlogged samples, whereas XrayCT works better with dry samples.

A major limitation of these facilities for non-invasive research used nowadays is however the size of the objects that can be scanned in relation to the resolution that can be obtained. Since the resolution that can be achieved is mainly dependent on the size of both, the source and the detector, the type of detector, and the distance of the object to the detector, the size of the object that can be scanned is also restricted by those factors. At the Dutch National Research Institute for Mathematics and Computer Science (CWI) in Amsterdam, objects up to 40 cm high can be XrayCT-scanned, but the British Museum in London claims to have a CT facility that allows scanning of objects up to several meters tall and 2000 kg of weight (https://www.britishmuseum.org, last accessed on 15/07/2019). Seeing the quick advances this technique has undergone in the past few years, one can only imagine that these limitations will soon be overcome in the near future.

6. Concluding thoughts

Dendrochronology applied to the study of cultural heritage has taken on new challenges in the 21st century. Different techniques for wood provenancing and identification are being tested in new areas, with new species, and on timbers with few tree rings originating from young trees (Pearl et al., 2020). Most of these techniques concur in that their limitations could be overcome by integrating different methods and increasing the geographical spread and resolution of the reference datasets (Dormontt et al., 2015). The efficiency of those efforts would be maximised by the exchange of data and collaboration between laboratories working with modern and (pre)historic timber, as the results would benefit both fields (forensic research on modern timber and dendroarchaeology) alike.

The current network of tree ring chronologies from living trees covers large parts of the temperate forests around the world, and is still expanding into underrepresented areas such as the tropics (Worbes, 2010; Rozendaal and Zuidema, 2011 and references), where dendrochronology had long been considered unfeasible. Similarly, the first multi-century long chronologies based on intra-annual tree-ring characteristics and isotopic signatures have provided interesting results for dating and provenancing timbers, so their potential to be used in dendroarchaeological studies should be further explored. The measurement of earlywood vessel size in oaks is done simultaneously to ring width, earlywood and latewood, thus developing vessel chronologies should become a standard procedure in the near future. The retrospective extension of those chronologies remains a challenge for dendroarchaeology in the 21st century, particularly in areas where climate conditions, fire, war, or disrespectful renovation practices caused historical timbers to be degraded, replaced or lost, disrupting the chronological continuity of the historical/archaeological record of the wood archive. However, sources of historical wood are very diverse worldwide (e.g. shipwrecks, buildings, artefacts, furniture, sculptures, musical instruments, coffins, book covers, etc.), and floating chronologies should continue to be develop until we can fill in the gaps. Again, collaboration between laboratories and data exchange is a pillar to build upon. Only by making data available (openly, by request or through collaboration) can science advance.

Provenancing techniques that achieved successful results on modern timbers (chemical fingerprinting, genetic markers, isotopic signatures) encounter additional challenges when applied to (pre)historical wood. Therefore, future studies should focus on understanding how wood degradation and other interferences (such as seawater signal) camouflage the original signatures in the wood, as this is a paramount step to fully exploit the potential of those techniques applied on (pre)historical timbers from different contexts.

Close collaboration with scientists and practitioners from other disciplines (mathematicians, engineers, historians, carpenters, architects, building historians, foresters, conservators, nautical archaeologists, etc.) has proven key in recent years to the success of large projects (see for example the multidisciplinary Marie Skłodowska-Curie ITN ForSEAdiscovery project, dedicated to research the timber supply for navies of Iberian Empires in the Early Modern Period; Crespo-Solana and Nayling, 2016). In such collaborations, dendrochronology is the bridge between all disciplines, contributing to place new layers of information in an exact time scale, providing evidence and filling in gaps where historical or archaeological methods fall short.

The increasing demand for dendrochronological studies on cultural heritage runs in parallel to the increasing awareness about the potential of this science to provide a wealth of information beyond the date of a timber. We owe such awareness to the work of our predecessors, and in our hands falls the task to continue engaging professionals and the general public, demonstrating with case studies the relevance of wood as an invaluable component of our material culture. Each timber or wooden object is like a time capsule that transports us to past woodlands, brings us closer to past peoples, their technology and their culture. No timber should be lost without having been researched. Likewise, no researched timber should be lost. Samples from living trees and historic buildings are easily stored and preserved, but timbers from archaeological contexts can degrade easily and may require tailor-made preservation treatments depending on the size, type of sample, and type of environment before excavation. Just as digital repositories have been developed to ensure the long-term preservation and sharing of dendrochronological (meta)data (e.g. International Tree-Ring Data Bank, Grissino-Mayer and Fritts, 1997; Digital Collaboratory for Cultural Dendrochronology, Jansma et al., 2012), efforts should be directed in the coming years towards setting up local (e.g. institutional), national, or (why not) international depots for dendrochronological samples.

Finally, the references provided in this review demonstrate that dendrochronology applied to the study of wooden cultural heritage is very alive (as already advocated by Čufar, 2007), and illustrate the research lines taken by this discipline in recent years. The methods and novel approaches presented will surely lead to exciting finds in the years to come, so current challenges are to be viewed (metaphorically) like the single trees in the forest. Every study contributes to draw a picture of the whole. There is so much to be found and waiting to be discovered.

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The author declares that she has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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