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Review

Oaks, tree-rings and wooden cultural heritage: a review of the main characteristics and applications of oak dendrochronology in Europe

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ABSTRACT

We overview the recent development of oak dendrochronology in Europe related to archaeology and art-history. Tree-ring series of European oaks (*Quercus robur* and *Q. petraea*) have provided a reliable framework for chronometric dating and reconstruction of past climate and environment. To date, long oak chronologies cover almost the entire Holocene, up to 8480 BC and the network over the entire area in which the two oaks grow is being improved. We present the main characteristics of oak ring series and discuss the latest methodological advances in defining the calendar year in which the tree-rings were formed and in interpreting such dating in terms of the age of a wooden object. Dendrochronology has established itself as a standard dating tool and has been applied in a wide variety of (pre-)historical studies. Archaeological wood, historical buildings, works of art (such as panel paintings and sculptures) have been successfully investigated. Recent advances in dendro-provenancing have helped to obtain more information on the timber trade in the past. Information on past forest structures, silviculture and timber use have become available through scrutinizing historical and contemporary ring-width patterns.

1. Introduction

Wood has been a basic raw material to men from prehistory to the present. It was used as fuel for heating, to produce tools and was valued as constructional timber. Many objects of art and musical instruments have also been made of wood. To date, those wooden (pre-)historical objects have become part of our cultural heritage and wood has gained importance in (pre-)historical surveys, especially through dendrochronology.

The age of wooden objects can be determined by means of dendrochronology, which is basically a scientific discipline that studies tree-rings in wood. It determines the calendar years of tree-ring formation and the felling dates of trees, which helps to determine the age of wooden objects with a precision that has not been matched by any other method. Dendrochronology has therefore become well established in the field of archaeology, art-history and cultural heritage. In addition, it has helped to improve the calibration of the radiocarbon curve, which assists in dating wood that cannot be dated by means of dendrochronology.

Not all tree species are suitable for dendrochronological dating. Obviously, the species must have (i) anatomically distinct growth rings. Furthermore, the trees (ii) should grow under a wide ecological and geographical range. This implies that the tree species can be found over an extensive area, in different types of woodland or forest. The trees should be able to (iii) adopt a (co-)dominant position in different types of woodland. Dominant trees are more likely to respond to climatological pulses that often prevail over larger areas, whereas suppressed or shaded trees are more influenced by the local forest dynamics. (iv) The heartwood should be sufficiently durable to ensure preservation of the wood. Finally, (v) the wood of the tree species should have been extensively used over a long period of time. European oak corresponds well with these requirements, and is mainly represented by pedunculate (*Quercus robur* L.) and sessile oak (*Quercus petraea* (Matt.) Liebl.). Oak wood is valued for its mechanical properties and its durable heartwood. It has been widely used since prehistoric times, and is also therefore the leading species in (pre-)historic tree-ring research in Europe.

Oak dendrochronology is a dynamic and constantly evolving discipline. After the construction of long, mainly western European oak chronologies in the 1990s, the research efforts of numerous laboratories scattered all over Europe have brought about great progress within this discipline. This paper aims to review recent advances in tree-ring research of European oak and to overview the

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most important applications in archaeological and (art-)historical research. Recent advances in dendro-provenancing and the application of dendrochronology to the elucidation of past silviculture and timber selection will additionally be presented. In conclusion, some possible outlines for the future are formulated.

2. Analysing ring-width series of European oak

2.1. An excellent species for dendrochronological research

Twenty-two native species of the genus *Quercus* can be found in Europe (Tutin et al., 2001). Deciduous oak trees achieved their current geographical extension and started to take in a dominant position in European forests approximately 6000 years ago (Brewer et al., 2002; Petit et al., 2002). The most widely dispersed, *Q. robur* and *Q. petraea*, grow under a broad variety of ecological conditions (Fig. 1). *Q. robur* is more typical of the valleys of large European rivers and damp lowlands, while *Q. petraea* is more likely to be found on drier and hilly terrain (Ducousso and Bordacs, 2003; Mayer, 1980). Oak trees of both species can live for several hundreds of years. The oldest recorded oak was a pedunculate oak growing close to Lake Biel (Switzerland) with 930 years (Schädelin, 1905, reported in Jones, 1959), determined by simple ring count.

The two oak species can be differentiated by their leaves and fruits, but it is difficult to identify the species solely based on their wood anatomy, although subtle differences in growth ring architecture can be noted (Feuillat et al., 1997). However, wood anatomical observations are in most cases the only way to discriminate between the two species when oak timbers from constructions or archaeological sites are examined. Fortunately, despite differences in ecology and wood anatomy, ring-width series of the two oak species can be successfully crossdated and they are therefore often treated as one species in dendrochronological studies.

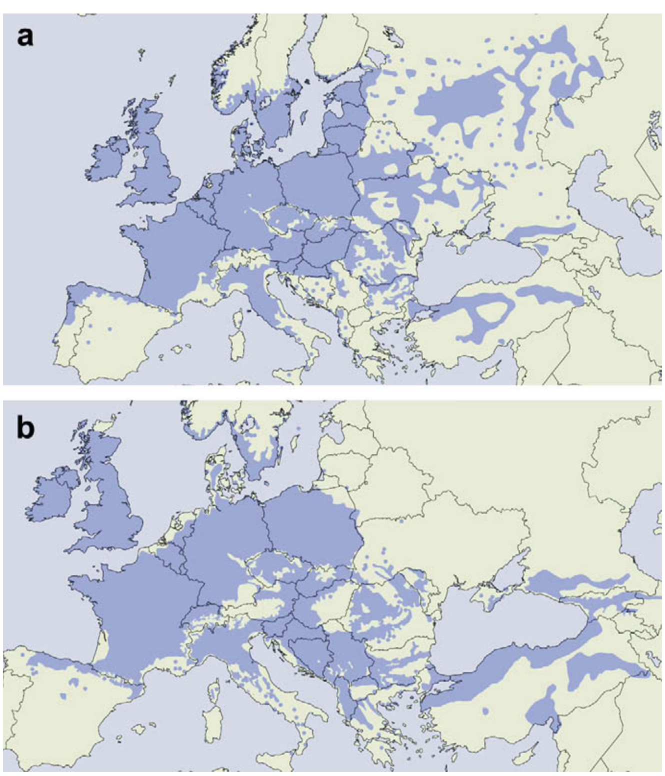

Fig. 1. Geographical distribution of (**a**) *Quercus robur* L. and (**b**) *Quercus petraea* (Matt.)Liebl. (Ducousso and Bordacs, 2003).

2.2. Crossdating

Crossdating is the procedure of matching variations in ring-width or other ring characteristics among several tree-ring series, allowing identification of the exact year in which each tree-ring was formed (Kaennel and Schweingruber, 1995). Since tree-ring series are never identical, crossdating involves statistics and the calculation of correlation values to assess the common variability of two tree-ring series. In crossdating, two ring-width series are shifted along each other at 1-year intervals. A correlation value is calculated at each position. The correct position for undated series on a dated master chronology is usually characterized by high and statistically significant values. Other diagnostic features for crossdating are the synchronous occurrence and spacing of pointer years (i.e. years with conspicuous features, such as an extremely small ring-width) in the tree-ring series.

The length of the tree-ring series is of the utmost importance in a crossdating procedure. When comparing two long crossdated tree-ring series, the correlation values are generally higher and more significant than those for short tree-ring series. Especially for those shorter than 50 years, the statistical parameters are generally low and statistically insignificant, or they may be high but the dating is erroneous. At many archaeological sites in Europe, a large proportion of the wood samples excavated contain fewer than 50–60 rings, and excluding them from dendrochronological analysis could lead to a loss of fine detail (Billamboz, 1996b, 2003; Čufar and Velušček, 2004; Haneca et al., 2006; Hillam, 1987; Hillam and Groves, 1996; Hurni and Orcel, 1996; Hurni and Wolf, 2001). The problem of their dating can be solved by comparing a large number of short series from the same site. When several short series match each other and the reference chronology, their dating can become trustworthy, even with relatively low but consistent correlation values.

2.3. Growth anomalies

Growth ring anomalies, such as missing, false and wedging rings, can impede crossdating. Although false rings are more frequently observed in coniferous species than in broadleaved species from temperate regions, Leuschner and Schweingruber (1996) were able to present a list of unusual intra-annual anatomical features in oaks such as false rings and suggested their classification. Missing or discontinuous rings have not to our knowledge been indisputably reported for *Q. robur* or *Q. petraea*. However, a discontinuous ring for *Q. robur* can be observed in Fig. 2a. This phenomenon is easily recognized on a larger cross-section, but not so easily identified when only a core or narrow strip of a transverse section is available for analysis.

Among the features that can assist in crossdating are particularities in the anatomical structure of the wood, such as exceptionally small earlywood vessels. Fletcher (1975) reported the occurrence of abnormally small earlywood vessels recorded on painted wooden panels, which were usually made of Baltic timber. This feature is, for instance, apparent in growth rings that were formed during the second half of the 15th century. Growth rings from 2 years in particular, 1437 and 1454, are well-known to show this feature. In between, 1443 AD is also a year in which such characteristic tree-rings were formed. Although the size of the earlywood vessels was considerably reduced in these anomalous years, the latewood width was not altered. A remarkable phenomenon because the width of the earlywood of ringporous species is fairly constant compared to the latewood. The vessels often have a diameter of 0.06 mm or less (Baillie, 1991), which is approximately 2.5–5 times smaller than normal. Although this feature tends to be very rare, it has diagnostic properties that can help to support dating results (Fig. 2b).

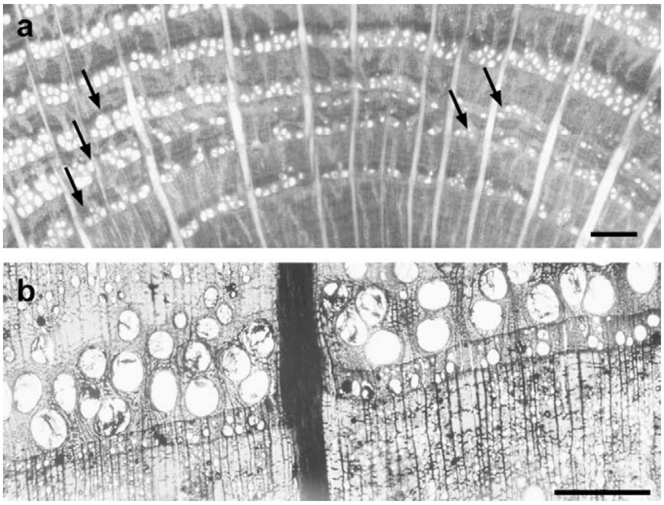

Fig. 2. Conspicuous wood anatomical features observed on two different oak specimens (*Quercus* spp.). (**a**) A discontinuous growth ring. (**b**) Growth ring with extremely small earlywood vessels. Scale bar represents 1 mm.

2.4. Long European oak chronologies

Long and absolutely dated ring-width chronologies are the basic reference frame for dendrochronological dating of (pre-)historic wood. Chronologies are time series which provide an average ring-width value for each growth season for a specific region (Kaennel and Schweingruber, 1995). Worldwide, the longest chronologies have been established on the European continent and are composed of tree-ring sequences of living oak trees, prolonged by those of subfossil and archaeological wood. They span hundreds or thousands of years.

The first long oak chronologies were constructed at universities in Germany (Stuttgart, Köln, Göttingen) and Ireland (Belfast) (e.g. Baillie, 1995; Becker and Delorme, 1978; Pilcher et al., 1984). The longest tree-ring chronology in the world is the South German Hohenheim oak chronology, reaching back to 8480 BC (Friedrich et al., 2004), covering the Holocene after the last ice age. The Belfast oak chronology spans approximately 7272 years (Brown et al., 1986; Pilcher et al., 1984). These chronologies include ring-width sequences from the earliest oak trees, which re-established themselves throughout Europe from glacial refugia when climatic conditions again became favorable for deciduous trees approximately 10,000 years BP (Brewer et al., 2002). They have been successfully used to date wood from the distant past and to reconstruct or interpret diverse past events (e.g. Baillie and Brown, 2002; Becker and Schmidt, 1990; Billamboz, 2003; Eckstein and Wrobel, 1982; Lavier, 2000; Leuschner et al., 2002; Wazny and Eckstein, 1991).

The highest density of oak chronologies can be found in western and northern Europe, according to the International Tree-Ring Database, (ITRDB; http://www.ncdc.noaa.gov/paleo/treering.html), and corresponds to the natural distribution of the two oak species (Fig. 1). The longest oak chronologies have also been constructed in this part of Europe. The European network of oak chronologies has recently been extended to the east and southeast (e.g. Čufar et al., 2008b; Grynaeus, 2000; Wimmer and Grabner, 1998). It has also been refined to cover smaller and more restricted areas, in order to optimize dendrochronological dating procedures for wood from archaeological contexts (e.g. Haneca et al., 2006). Since oak chronologies are composed of tree-ring series of wood originating from diverse sites and contexts, their quality and replication is not uniform over their entire time span. Chronologies are therefore treated as dynamic entities that need to be constantly improved.

2.5. Climate response

Climate steers tree growth on a supra-regional scale. It therefore simultaneously affects the width of growth rings of trees that grow on distant sites. This is certainly the case for European oaks and means that year-to-year variations in ring-width often display a high visual and statistical correlation, not only for oaks from the same forest stand but also among oaks from remote regions.

Monthly average temperature and precipitation values can explain 5–72% of the variation in annual tree-ring-widths of living oak trees (Eckstein and Schmidt, 1974; Krause, 1992; Lebourgeois et al., 2004; Pilcher and Gray, 1982; Rozas, 2001; Ufnalski, 1996). Tree-ring-widths are usually positively correlated with the amount of summer precipitation, especially during June and July (Čufar et al., 2008a,b; Lebourgeois et al., 2004; Pilcher and Gray, 1982; Rozas, 2001). This indicates that wider growth rings usually occur in years with a considerable amount of precipitation during the summer months. In central and northern Europe, warm summers with higher May, June and July temperatures positively affect growth ring-widths (Beeckman and De Pauw, 1998; Eckstein and Schmidt, 1974; Pilcher and Gray, 1982). However, south of the Alps and in the Mediterranean, above average May, June and July temperatures have a negative effect on ring-widths (Čufar et al., 2008a,b; Santini et al., 1994).

Tree-ring series of oak typically correlate as well with monthly climate data describing the preceding growing season. For instance, wide rings tend to coincide with years in which the amount of precipitation during the previous October and November was high (Lebourgeois et al., 2004; Pilcher and Gray, 1982), whereas narrow rings often follow winter months with extremely low temperatures (Pilcher and Gray, 1982; Wazny and Eckstein, 1991). This suggests that European oaks prefer mild and wet winter months.

Modelingthe climate response of oak trees permits the reconstruction of climate, into the pre-instrumental period, using long ring-width chronologies. Such reconstructions allow the identification of climatic anomalies and extraordinary weather events that have a potentially strong influence, for instance, on agriculture or in inducing a strong societal response. As recently presented, a climate reconstruction for SE Slovenia based on a 584-year oak chronology revealed and dated exceptionally dry and wet June conditions for the time span of the chronology (Čufar et al., 2008a). Thirty-four percent of the years identified as having an extremely dry summer were also mentioned in historical written sources as having crop failures, droughts or related events. In Ireland, based on an absolutely dated tree-ring chronology of bog grown oaks, it was noticed that increased numbers of oak populations, derived from the amount of dated oak ring series, synchronized with dry periods throughout the Holocene. In contrast, an increase in the construction of crannogs and forts was observed during the Bronze and Iron Age across Ireland, coincident with wetter periods with a reduced number of oak populations Such increased building activities might be indicative of the protection of limited food resources due to repeated crop failures (Turney et al., 2006).

In addition to ring-width, some other features of oak wood also have the potential to serve as a proxy for reconstructing past climate. More specifically, latewood width (e.g. Weigl et al., 2008), cell dimensions of water conducting tissue (e.g. Fonti et al., 2007; García-González and Eckstein, 2003) and concentrations of stable carbon, oxygen and hydrogen isotopes (e.g. Weigl et al., 2008) have been shown to contain specific climate signals. Further fine-tuning of these potential applications is currently ongoing.

2.6. Exact dating and sapwood estimates

On a dendrochronologically dated piece of wood, it is known precisely in which calendar year each growth ring was formed. For wood samples where the bark is still attached, and where the last ring below the bark is preserved (Fig. 3), it is possible to determine the exact year in which the tree was felled. In the case of ring-porous oaks, even the season in which the tree was felled can be specified (Eckstein, 2007). European oak trees, growing under temperate climatic conditions, form new wood, more particular large earlywood vessels, prior to bud break, which happens around the end of April/beginning of May. The earlywood/latewood transition occurs around the end of June/beginning of July, and radial growth is completed between late August and mid-September. The lignification of the cell walls follows with some delay and can continue into late autumn or early winter (Eckstein, 2007).

When the last ring is not preserved, the year of tree felling can only be approximated. In such cases, the completeness of the sapwood and its state of preservation is of importance. The sapwood is situated in the outer part of the stem and is the 'living' (i.e. physiologically active) part of the wood at the time of felling. For oak, it can be relatively easily distinguished from the darker heartwood, which builds the innermost part of the stem. If only part of the sapwood is preserved (Fig. 3), the initial number of sapwood rings that have been removed or have decayed can be estimated, and the felling date calculated. In cases in which no sapwood is preserved, it is only possible to provide a *terminus post quem*, i.e. the date after which a tree must have been felled or the 'earliest possible felling date'. The latter can be calculated by taking the date of the final ring of the examined tree-ring series and adding the lower limit of the 95% confidence interval from regional sapwood estimates.

The number of sapwood rings varies greatly among oak trees from different sites and regions. Nevertheless, the examination of large tree-ring datasets has made it possible to establish probability distributions for the number of sapwood rings that can be expected in oak trees (Hillam et al., 1987; Hollstein, 1965; Hughes et al., 1981; Kelly et al., 1989; Wazny, 1990). The age and average growth-rate of a tree are often considered to be important variables determining the observed number of sapwood rings. In general, old trees tend to have more sapwood rings compared to younger individuals. However, models that attempt to describe the relationship between the age of the tree or average ring-width and number of sapwood rings usually have a low predictive value (ca. 10%) (Hillam et al., 1987; Hughes et al., 1981).

Table 1 provides an overview of sapwood statistics for different regions in Europe. A geographical trend can be distinguished from these data. The average number of sapwood rings tends to decrease

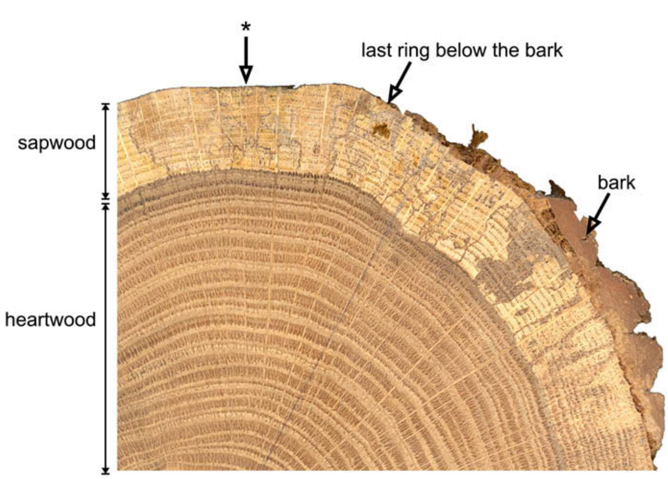

Fig. 3. Cross-section of an oak beam that contains heartwood, sapwood and bark. The tree-ring immediately below the bark coincides with the last year of wood formation, before the tree was felled. At the location marked with a * the last ring below the bark is missing. In such cases we can only estimate the date of tree felling by adding a presumed number of missing rings (in this example this is two rings).

from west to east, i.e., from the British Isles (23.70–32.40) towards the Baltic States (12.76–18.20). The possible physiological basis of this trend is not yet clear. Notwithstanding these sapwood statistics, it should be noted that inter-tree variability is also considerably high. Oak trees tend to have more sapwood rings in the upper part of their stem. It has been demonstrated that oaks from Northern Wales can have up to 13 sapwood rings more in the upper part of the stem than in a cross-section from the lower bole at 0.5 m (Hughes et al., 1981).

3. Examples of tree-ring studies on wooden cultural heritage

3.1. Archaeological wood

The application of dendrochronology as a dating tool in archaeological studies has evolved simultaneously with the advances in tree-ring research. Douglass (1914) was the first to explore the possibilities of tree-ring analysis in archaeological studies. This resulted in the construction of a ca. 1.200 year long pine chronology and the dating of nearly 40 prehistoric settlements in the southwest USA (Douglass, 1935). In Europe, the Viking settlement of Haithabu (Hedeby, Germany) provided one of the first opportunities to study and date a massive amount of well-preserved historical oak timbers, used for the construction of houses and a harbor with several landing stages, based on dendrochronological procedures (Eckstein, 1969). Since then, many archaeological surveys have benefited from dendrochronological dating (e.g. Baillie, 1995, 2002; Čufar, 2007).

Among the oldest, dendrochronologically well investigated archaeological sites are the prehistoric lake shore settlements (pile dwellings) from the circum Alpine region in Europe. They were inhabited in the Late Neolithic, Copper and Bronze Ages from 6000 to 800 BC and have been archaeologically investigated for more than a century. Most of the preserved wood on these sites originates from the wooden piles on which the buildings stood. Oak predominates among the identified wood species. Many wood samples from these sites in Switzerland, Germany and France have been dendrochronologically dated (e.g. Billamboz, 1990, 1996a, 2006b; Hurni and Orcel, 1996; Pétrequin, 1996; Pétrequin et al., 1998; Tercier et al., 1996; Viellet, 2002). These locations are situated in an area with long, well replicated chronologies for oak and good teleconnections between sites. On prehistoric sites south and southeast of the Alps, in Italy, Slovenia and Austria, dendrochronological dating of oak timbers is difficult. Reference chronologies for this region do not reach back to prehistoric times, and attempts to teleconnect the floating chronologies of prehistoric sites with references from more northward locations have not usually been successful. Chronometric dating is then only possible with the help of radiocarbon and wiggle-matching. Despite this, dendrochronology helps to obtain and better interpret information about human colonization of the area, as well the palaeo-environment (e.g. Čufar and Martinelli, 2004; Čufar and Velušček, 2004; Čufar, 2007; Grabner et al., 2007).

Well-known archaeological sites in the United Kingdom, with prehistoric bog settlements, horizontal mills, crannogs and subfossil wood from wet bog environments, have been dendrochronologically dated and this has helped to identify phases in building activities (Baillie, 1995; Baillie and Brown, 2002; Boswijk and Whitehouse, 2002; Crone and Mills, 2002; Hillam and Groves, 2003). One of the most famous examples is the oldest wooden causeway, the 'Sweet Track', on the Somerset Levels (England), precisely dated to 3807–3806 BC (Hillam et al., 1990).

3.2. Buildings and constructions

Due to its excellent mechanical properties and high durability, oak is one of the preferred timbers for construction purposes. Oak beams

Table 1
Sapwood statistics for different regions in Europe

	Tree age-class	Average no. of sapwood rings	Standard deviation	Median	Range (min-max)	95% conf. interval	Sample depth
Germany (Hollstein, 1965, 1980)							
	<100	16.00	4.50	–	–	–	–
	100–200	20.40	6.20	–	–	–	–
	>200	25.90	7.50	–	–	–	–
	n.s.	19.00	7.54	–	7–66	8.22–37.95	446
Northern Germany (Wrobel and Eckstein, 1993)							
	n.s.	16	–	–	10–30	–	–
NW England and Wales (Hughes et al., 1981)							
	<100	23.70	5.90	–	–	–	64
	100–200	26.70	8.60	–	–	–	104
	>200	32.40	8.90	–	–	–	7
	n.s.	25.80	8.00	–	10–55	13.7–44.6	175
British Isles (Hillam et al., 1987)							
	<100	22.35	9.11	–	9–46	9.16–46.33	106
	≥100	31.74	10.23	–	14–66	15.59–58.15	91
England and Wales (Miles, 1997)							
North	n.s.	–	–	–	10–60	12–45	295
South	n.s.	–	–	–	4–57	9–41	406
Wales*	n.s.	–	–	–	8–50	11–41	219
Ireland (Baillie, 1982)							
	n.s.	31.32	8.99	–	14–62	16.74–53.93	65
Northern France (Pilcher, 1987)							
	n.s.	26.58	7.04	–	12–49	15.25–43.26	118
Western Sweden (Bräthen, 1982)							
	150–200	16.00	–	–	13–21	–	7
	>200	21.00	–	–	15–23	–	5
	n.s.	15.84	4.65	–	9–32	8.73–26.55	69
Poland (Wazny, 1990)							
	<100	12.76	3.25	–	6–22	–	51
	100–200	17.30	4.30	–	9–31	–	114
	>200	18.20	4.64	–	9–30	–	41
	n.s.	16.00	4.60	15	6–31	9–24**	206
Southern Finland (Briffa, unpublished)							
	n.s.	13.85	3.19	–	7–24	8.32–21.80	60
Belgium (Haneca, unpublished)							
	<100	17.36	5.50	18	5–31	6.58–28.14	225
	≥100	24.48	6.60	24	13–39	11.54–37.42	68
Czech Republic (Rybnicek et al., 2006)							
		12.75	–	–	5–21	–	–
Italy (Martinelli, pers. comm.)							
	n.s.	13.23	6.06	15	5–38	5.66–30.93	95

n.s. = not specified.
*Wales and border counties.
**90% interval instead of 95% confidence interval.

have been used for the construction of both vernacular and ecclesiastical architecture, from castles and cathedrals to more modest buildings throughout Europe. An exhaustive overview of dendrochronologically dated buildings would fill many pages, so only a few are presented here.

Dating beams, posts and rafters from roof framings makes it possible to put stylistic and constructional evolution in strict chronological order. This has been repeatedly demonstrated by Hoffsummer, who investigated roof framings in Belgium and Northern France (Hoffsummer, 1995, 1996, 2002). For instance, a clear progression in the slope of church roofs was observed during the 13th century, corresponding to the introduction of Gothic architecture. Furthermore, different construction phases can often be distinguished within a single building. A dendrochronological examination at the Windsor Castle (Berkshire, England), for example, revealed a so far unknown construction or repair phase in the roof (Hillam and Groves, 1996). The medieval roof timbers did not date to the 14th century as expected, but to the late 15th and early 16th century.

Even the question of where building timber was acquired can in some cases be answered in detail by dendrochronological analysis. From a merchant's house in Lübeck, for instance, 15 timbers from the roof could be dated. The felling dates are apparently spread over a period of more than 33 months. These mixed felling dates, randomly distributed throughout the same roof construction, clearly support the assumption that the building timber was purchased from a local timber market, where wood was stored and sold (Eckstein, 2007). Comparable evidence of stockpiling was found when analysing 1760 dated oak timbers from 389 buildings from mainland Britain (Miles, 2006). It was noticed that stockpiled oak timbers were used especially for the construction of high-status churches and cathedrals. This contrasts with low-status rural agricultural buildings, of which only one-third had timbers stockpiled for more than 1 year.

Based on dendrochronological reports from vernacular buildings, the oak timber of wooden houses, barns and hay racks was often cut in winter, pre-processed in spring, and hewn or sawn to final shape and dimensions in late summer/early autumn, when the building was erected (Miles, 2006). The timber generally originated from local forests. This procedure was frequently used until the beginning of the 20th century. When large amounts of timber were needed, e.g. for the construction of churches and castles, the timber was often brought form distant sites or was collected over a period of time. More time therefore elapsed between felling and erection of the building (Eckstein, 2007).

3.3. Art-historical objects

Wood has been one of the preferred raw materials for many artists for centuries. This material was not only used to create objects of art, it was also used as a functional support. The two most obvious examples are wooden sculptures and panel paintings, respectively. Such objects have been the subject of many wood anatomical and dendrochronological surveys (e.g. Bauch, 1968, 1978a,b; Bauch et al., 1978; Bauch and Eckstein, 1981; Eckstein et al., 1975a; Fletcher, 1986; Fraiture, 2002; Haneca et al., 2005a; Hillam and Tyers, 1995; Klein, 1986; Klein and Wazny, 1991; Klein, 1993; Läänelaid and Nurske, 2006; Lavier and Lambert, 1996).

Panel paintings were chiefly produced during the 15th–17th centuries, since from the 16th century onwards, wooden panels were increasingly replaced by canvas. Oak was the preferred raw material for panels, especially in the Low Countries, England and Germany. The successful application of tree-ring dating to panel paintings benefits from the fact that quarter sawn boards were often used in order to achieve optimal dimensional stability. Long tree-ring series can therefore be measured, increasing the chance of successful dating. In Greece, too, many icons were painted on oak panels. In Italy, on the other hand, poplar was more commonly used by panel makers, which hampers current tree-ring dating of Italian panel paintings (e.g. Čufar, 2007).

Wooden sculptures are another example of fine arts that have high potential for tree-ring dating (e.g. Fraiture, 2000; Haneca et al., 2005a). The wood species used for carving greatly depends on where the craftsman was working. Oak, and to a lesser extent walnut (*Juglans regia* L.), is typical of Flanders, the Netherlands and England, whereas in Germany and Central Europe lime (*Tilia* spp.) and in the Mediterranean poplar (*Populus* spp.) were more frequently used.

It is clear that there is a big difference between dendrochronological analysis of an isolated work of art created from a single piece of wood and, for instance, an altarpiece made of numerous wooden blocks (Lavier and Lambert, 1996). In the former case, numerous sculptures can be used for the analysis, in order to capture the most recent growth ring (De Boodt et al., 2005). However, even dendrochronological analysis of a limited number of sculptures can in some cases provide a great deal of information, as was demonstrated by the dating of the Triumphal Cross and Screen in Lübeck Cathedral (Eckstein, 2007).

Other objects that have been the subject of tree-ring analysis include, for example, wooden book covers (Lavier and Lambert, 1996). It was observed from a collection of medieval books in France that oak was the preferred wood species from the 8th to the 15th century, and began to be replaced by beech and elm (*Ulmus* spp.) from the early 15th century. Musical instruments are also often the subject of dendrochronological analysis, although oak was seldom used to make instruments. In some cases it was used for parts of organs (even for organ pipes) and harpsichords (calvecimbalo), but never for resonation elements of stringed instruments (e.g. Beuting, 2000; Burckle and Grissino-Mayer, 2003; Klein et al., 1986).

In some cases, seasoning and pre-processing wood can be time-consuming (Eckstein, 2007). With panel paintings, for example, Bauch and Eckstein (1981) suggested that the interval between tree felling and creation of the panel painting was on average 5 ± 3 years. Longer storage times, of 10–15 years, were revealed by dendrochronological research of signed and dated panel paintings of the Cologne School and Flemish Masters from the 14th to 15th century (Bauch, 1978b; Klein, 1986). Tree-ring dating can become more complicated with 18th century panel paintings. There was a shortage of high quality oak at that time and some artists started to reuse older oak panels, which can now lead to conflicting dating reports. It has been observed that the time between felling of the oak tree and making the sculpture is rather short for the creation of wooden sculptures, approximately 1–4 years (Eckstein, 2005; Haneca et al., 2005a).

4. Dendro-provenancing

4.1. The general principle

Trees experiencing similar growth conditions are expected to develop a comparable ring-width pattern. This is one of the basic principles of dendrochronology. Trees from distant geographical locations will develop growth ring patterns with different characteristics, driven by discrepancies in the local climate and site conditions. This supports the assumption that a tree-ring pattern contains information related to the location at which the tree grew. Comparison of individual tree-ring series with chronologies that reflect the average growth conditions for specific regions allows the sourcing of the origin of the timber, i.e., dendro-provenancing. It is assumed that the highest similarity will be observed when a tree-ring series is compared to the reference chronology that covers or approaches the region in which the tree was cut. The similarity is usually expressed by one of the commonly used correlation measures in crossdating. An extensive network of reference chronologies is a prerequisite for taking full advantage of dendro-provenancing.

Some successful results of dendro-provenancing were already reported in the 1960's and 1970's, although at that time only a limited number of reference chronologies were available for European oak. Dendro-provenancing was first applied on tree-ring series from a Hanseatic Cog ship, excavated in Bremen harbor and dated by dendrochronology to 1378–1379 AD (Liese and Bauch, 1965). The highest correlation with the available master chronologies was found with a chronology from the *Weserbergland*. This chronology covers a region ca. 300 km further south, and correlation analysis strongly suggests that this region can be considered to be the original timber source. Similar observations were made during the examination of wine barrels from an archaeological excavation in Dorestad (The Netherlands), in which a high and robust correlation was observed with a reference chronology that was established with tree-ring series from ca. 400 km further up the River Rhine (Eckstein et al., 1975b). This demonstrated the impact of historical timber trade on dendrochronological dating.

4.2. Dendro-provenancing and the 'Baltic' timber trade

High-quality oak timber was a scarce commodity during the Middle Ages in Western Europe due to intensive exploitation and conversion of local woodlands (Beeckman, 2005). Large quantities of high-grade oak timbers were therefore imported from remote areas. One of the best examples, supported by physical evidence through oak dendro-provenancing, is the 'Baltic' timber trade.

When tree-ring dating was first applied to art-historical objects, such as sculptures and panel paintings made of oak, dendrochronologists were confronted with oak timber characterized by uniform growth and narrow growth rings. The atypical growth ring patterns could not at first be absolutely dated, since no significant correlation was found with the master chronologies available at that time. Nevertheless, they correlated very well with each other, which resulted in the construction of floating chronologies made of tree-ring series from art-historical objects, one in England (Fletcher et al., 1974) and one in The Netherlands (Eckstein et al., 1975a). The two chronologies displayed high similarities and could be easily crossdated. It was suggested that wood with this specific growth pattern originated from forests on the coastal plains along the North Sea (Eckstein et al., 1975a), or from oak trees that grew under stressful conditions in England (Fletcher, 1977). Such stressful conditions were assumed because the tree-rings were narrow, especially when compared to the ring-width of oaks from local wood resources in England. The *missing link* was found when a chronology was constructed for Gdansk-Pomerania, in Northern

Poland (Eckstein et al., 1986). It clearly demonstrated that the timber used for the construction of panels from the 14th up to the middle of the 17th century, was often of Baltic origin. This was further confirmed by documents from historical archives (Wazny and Eckstein, 1987).

Dendro-provenancing has become the focus of renewed interest and has been used to determine the original timber source of non-static objects such as ships (Bonde, 1997), barrels (Houbrechts and Pieters, 1999), furniture, panel paintings and altarpieces (Haneca et al., 2005c). Such studies demonstrate how dendro-provenancing can help to document the historical timber trade (Eckstein, 2007; Eckstein and Wrobel, 2007; Wazny and Eckstein, 1987; Wazny, 2005) and even make it possible to specify when certain forested areas were exploited (Haneca et al., 2005c). For instance, examining tree-ring series of Brabantine wooden altarpieces (15th–16th century) showed that the wood used to carve late 15th century sculptures originated from forests in the vicinity of Gdansk, where early 16th century sculptures were made of wood originating from more inland regions (De Boodt et al., 2005).

4.3. Dendro-provenancing and shipwrecks

Shipwrecks often yield suitable timbers for dendrochronological dating (Bonde, 1997; Bridge and Dobbs, 1996; Liese and Bauch, 1965). The place where a shipwreck was excavated is not usually related to the place of construction or the original timber source. Dendro-provenancing offers the possibility of determining the origin of the wood, which can be brought down to a very local level in some cases (Daly, 2006, 2007). However, care should be taken, since recent studies have shown that in some cases wood from different locations was used in the construction of a single hull (van Daalen and van der Beek, 2004). A large dataset that includes timbers from all constructional parts of a ship is required.

Dendrochronological research on shipwrecks in the Mediterranean, on the other hand, is more complicated. Apart form oak, multiple timber species were involved in the construction of ships, and not only oak. Moreover, the lack of an extensive network of local chronologies often hampers dendrochronological dating. It is therefore also hard to determine the origin of the timber used to construct the ships. Nevertheless, there is a considerable list of 'Mediterranean' shipwrecks that have been analysed by dendrochronologists, yielding a collection of floating chronologies (Guibal, 1996). Remains of ships from the Venetian Republic, which for centuries ruled all over the Mediterranean, have in particular been often studied (Martinelli, pers. comm.). The Venetians were known to use vast amounts of timber, particularly oak, for maintaining and expanding their fleet. It is known that this led to a shortage of wood, which lead to protective measures for the remaining local forest (punishment for unlawful cutting, prohibition on the use of oak wood for other purposes (e.g. furniture) than shipbuilding) and to the development of a sophisticated system of acquiring wood from a wide area (e.g., Istria and the eastern Adriatic coast).

5. Forest history and management

5.1. Short rotation systems

Since wood was an important commodity, local forests have always been exploited and altered by men. Changes in population often coincided with a changed attitude to surrounding woodlands and guided the choice of forest products. Rising demographic pressures, in particular, caused common selective cutting and harvesting to be replaced by more drastic activity, such as clear felling for conversion to arable land.

At the Neolithic settlements around the lakes of Chalain and Clairvaux (France), changes in population already triggered changes in woodland use (Pétrequin, 1996; Pétrequin et al., 1998). When settlements were small and had few inhabitants, young ash (*Fraxinus excelsior* L.) and oak trees from secondary forests were used for house building. They probably re-sprouted from stumps, as suggested by the conspicuous wide growth rings. When the number of inhabitants increased, together with the number of villages around the lakes, almost exclusively larger oak poles were used, which indicates that the need for agricultural products dramatically increased and induced rapid conversion of the secondary forest to arable land. Pétrequin (1996) and Pétrequin et al. (1998) suggested that construction timber was then collected in primary forests or old-grown secondary forests, which is also reflected in the increased size of the oak poles.

Other examples in which timbers from different types of woodland were used are crannogs and wooden trackways in England (Crone, 1987, 2000). Here, not only changes in species composition but also different growth patterns were observed in consecutive construction phases. In southwestern Germany, a massive amount of tree-ring series from pile-dwellings along the lakeshores of Lake Constance were able to provide an image of past woodland development in relation to human occupation (Billamboz, 1992, 1996a, 2006a,b) The investigated tree-ring patterns clearly reveal cycles of forest exploitation (thinning, coppice, …) and regeneration, both related to demographic evolutions during the Bronze Age (Billamboz, 2002).

Such interventions in the original vegetation led in the long term to shortages in available timber. This led to regulations dealing with proper forest use and implied protective measures by the state (e.g. England, Venice). One particular silvicultural technique, in a certain sense already used in prehistoric times (e.g., Crone, 1987; Pétrequin et al., 1998), that became more popular during the Roman era and especially during the Middle Ages, was coppicing (Bechmann, 1990; Rackham, 2003; Vera, 2000). Re-sprouting from a stool is considerably faster than regeneration from seed. In the short term, this yields considerable amounts of small diameter timber. Since coppicing became a widespread technique in forest management, wood from coppiced trees is often found in archaeological sites throughout western Europe. Timber from such short rotation systems only contains a limited number of tree-rings. This hampers dendrochronological crossdating. However, it has been demonstrated that tree-ring series from coppiced woodland differ significantly from ring-width series recorded on cross-sections from trees of dense (primary) forest (Haneca et al., 2005b, 2006).

5.2. Pollarding and trimming

Past management interventions are sometimes reflected in the wood anatomy of the trees (e.g. Haas and Schweingruber, 1993). Pollarding or trimming (i.e. cutting the branches) of oak trees has been common practice in Europe for millennia (e.g., Ellenberg, 1988; Goodburn, 1994; Rackham, 2003). Pollarding provided leaves and young shoots that were used as fodder for domestic animals, especially during the winter months. This procedure stimulates abundant regeneration of branch wood and causes changes in the anatomy of the stem wood. In oak trees, abrupt and sustained growth depressions in the ring-width pattern reflect a pollarding or trimming event (Bernard, 1998; Rozas, 2005). More specifically, the earlywood width is not altered in the first year after pollarding, but the latewood is reduced considerably. Earlywood width and total ring-width decrease in the 2 following years, after which ring-width gradually increases over the next 3–4 years (Bernard et al., 2006). This altered growth after pollarding thus leaves behind a specific signature in the wood. The total effect of such practices can be observed in the anatomy of up to seven successive growth rings (Fig. 4). This particular pattern has also been observed in archaeological oak samples (Bernard, 1998; Bernard et al., 2006).

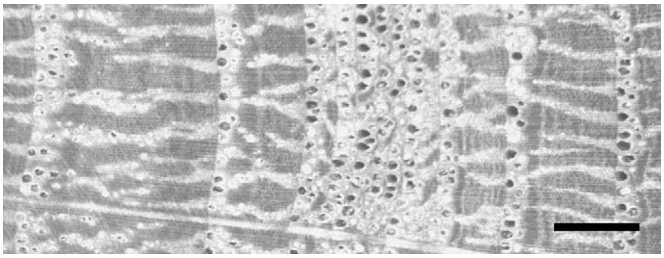

Fig. 4. An abrupt growth reduction, observed on a cross-section of a roof construction of a medieval storehouse (ca. 1365–1370 AD, Lissewege, Belgium). The particular anatomical structure might be induced by pollarding. Scale bar represents 2 mm.

6. Concluding remarks and outlines for the future

To date, dendrochronology is the most precise dating method applicable in (pre-)historical studies, and will certainly retain that position in the future. The specificity of annual growth rings, combined with the fact that many cultural objects, historical buildings and archaeological remains are made of wood (in Europe especially of oak), means that dendrochronology has a substantial advantage over other dating techniques. In addition, standard dating precision, up to the calendar year, can even be improved by the use of state of the art knowledge of wood formation and wood anatomy. In particular cases, this can help to determine the season or even the month of tree felling (Eckstein, 2007).

Building new reference chronologies, improving existing ones and extending the global chronology network should continue. Besides the exact dating of (pre-)historical objects, long tree-ring chronologies are valuable sources of information for a wide range of environmental studies, such as those involving reconstruction of past climate, environment, forest management and forest structure (e.g. Billamboz, 1992, 1996a, 2006a,b; Crone, 1987; Eckstein, 2004, 2007; Haneca et al., 2006; Lebourgeois et al., 2004; Leuschner et al., 2002; Leuschner et al., 2007; Rackham, 2003), or can help to fine-tune radiocarbon calibration (e.g. Friedrich et al., 2004; Reimer et al., 2005). Investigation of the past is, of course, important for the assessment of current and prediction of future changes in climate and environment.

Dendrochronological dating is hampered when only short ring-width series are available (e.g. Billamboz, 2003), or if the examined wood specimen contains various growth anomalies. In such cases, dendrochronology sometimes fails to provide an accurate felling date for the examined oak specimen. It is therefore important to enhance the current statistical methodology and gain more expertise in working with short series. Recent advances in multivariate crossdating procedures based on tree-ring specific wood density features are encouraging in this field. These analyses do not solely rely on ring-width measurements, but incorporate density related descriptors of each growth ring into multivariate time series (König, 2005). Dating of historical timbers with less than 50 tree-rings, based on multivariate crossdating techniques has only so far been successfully implemented for spruce (*Picea abies*) (König, 2008). However, this methodology could in future be applied to oak timbers. Furthermore, additional wood anatomical particularities (including growth anomalies) could be used as dendrochronological markers useful for crossdating. This has not been fully explored yet, partly due to the intensive and time-consuming procedures involved in quantifying wood anatomical features of broadleaved tree species.

Recent methodological advances in (semi-)automated image analysis therefore open new perspectives for quantitative wood anatomical studies (García-González and Fonti, 2008; Vansteenkiste, 2002). For instance, currently ongoing studies demonstrate that the size and distribution of some cell types, such as large earlywood vessels, contain different climatic and environmental signals than ring-width measurements (Fonti et al., 2007; García-González and Eckstein, 2003; García-González and Fonti, 2006). This heralds new possibilities for the development of time series that accurately quantify the year-to-year variability in wood anatomy, which can contribute to palaeoclimate reconstructions (Eckstein, 2004) and tree-ring dating.

In order to obtain precise dating of man-made wooden objects and constructions, it should be clear that dendrochronology only dates the tree-rings; it does not tell when an object was fashioned. The attitude of a community towards woodlands and wood as a basic raw material can create temporal disjunctions between the date of a ring-width series and the fashioning of timber elements (Dean, 1996). In particular, the time that elapsed between tree felling and the actual creation of the object is of the utmost importance for the interpretation of dendrochronological dates. This still requires better knowledge of the origin of the wood, the duration of timber transport, seasoning and (pre-)processing of wood. In order to document all these elements, more interdisciplinary and international cooperation is required in the future. Intensive collaboration between dendrochronologists, (art-)historians and archivists in particular has the potential to provide relevant information on these issues.

Furthermore, the continuously expanding reference frame of absolutely dated site chronologies will probably increase the number of successful applications of tree-ring dating. As a consequence, dendro-provenancing will enable more detailed information to be gained on the historical timber trade and the exploitation of (primary) forests during all periods of (pre-)history.

It is clear that dendrochronology is currently applied in a wide range of environmental and historical studies. In addition to exact dating of historical timbers, tree-ring analysis succeeds in providing relevant information for climate reconstructions, the study of past forest management and structure, etc. In other words, dendrochronology concerning the wooden cultural heritage has clearly evolved beyond dating.

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