

Tree-ring analyses of European oak:  
implementation and relevance in (pre-)historical  
research in Flanders

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# **Tree-ring analyses of European oak: implementation and relevance in (pre-)historical research in Flanders**

by

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Gent, 14 november 2005.



**Jaarringanalyses van Europees eiken:  
toepassingsmogelijkheden en relevantie in (pre-)historisch onderzoek in  
Vlaanderen**

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**Samenvatting**

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Reeds tijdens de Romeinse overheersing en de Middeleeuwen werden bossen in Vlaanderen intensief geëxploiteerd voor de voorziening in brandhout en timmerhout. Daarnaast werden uitgestrekte bosgebieden omgevormd naar landbouwgronden om te voldoen aan de stijgende voedselbehoefte, met een sterke inkrimping van het bosareaal tot gevolg. In Vlaanderen werd naar schatting al op het einde van de 13<sup>de</sup> eeuw een lagere bebossingsindex genoteerd in vergelijking met deze van de 19<sup>de</sup> eeuw. Hout afkomstig uit de middeleeuwse bossen is ondertussen deel geworden van Vlaanderens cultureel erfgoed. Archeologische vondsten, historische gebouwen, schilderijen op houten panelen en religieuze sculpturen zijn maar enkele voorbeelden van constructies en objecten die werden gecreëerd door het verwerken van hout. Voornamelijk inlands eiken (*Quercus robur* L. en *Q. petraea* (Matt.) Liebl.) werd veelvuldig gebruikt voor constructie doeleinden en geprefereerd door schrijnwerkers en ambachtslui voor zijn intrinsieke mechanische eigenschappen.

Groeiringreeksen van eik hebben de karakteristieke eigenschap dat ze synchroniseren. Met andere woorden, de afwisseling van bredere en smallere groeiringen die te zien zijn op een stamdoorsnede bevatten een uniek patroon dat terug te vinden is bij de verschillende individuen van een populatie. Meer nog, het gemiddelde groeiringpatroon van een bestand of een bepaalde streek zal dikwijls een sterke overeenkomst vertonen met eiken uit andere, zelfs veraf gelegen regio's. Dit fenomeen laat zich enkel verklaren door de sturende invloed van klimaatsvariabelen op de groei van eiken. Hierdoor kan dendrochronologie gebruikt worden als dateringstechniek. Door steeds oudere groeiringreeksen, die een zekere overlapping vertonen met meer recente groeiringreeksen, op te meten en te verwerken kunnen lange, absoluut gedateerde tijdreeksen van gemiddelde ringbreedtes bekomen worden. De vergelijking van een ongedateerde groeiringreeks met een dergelijke referentie laat dan toe om de exacte plaatsing in de tijd te achterhalen.

Niet zelden leidt dendrochronologisch onderzoek in Vlaanderen tot teleurstellende resultaten bij de datering van houten objecten. Het hout dat wordt gevonden tijdens archeologische opgravingen en bouwhistorisch onderzoek is meestal gekarakteriseerd door brede ringen met abrupte veranderingen in radiale aanwas. Bovendien overspannen de opgemeten groeiringreeksen dikwijls minder dan honderd jaar. Daardoor blijven correlatiewaarden met de geraadpleegde referentiechronologieën laag en bieden ze weinig zekerheid over de gevonden datering. Ook het niet voorhanden zijn van een Vlaamse referentiechronologie bemoeilijkt het daterend onderzoek. Aangezien de meerderheid van de groeiringreeksen die beschikbaar zijn voor daterend onderzoek in Vlaanderen meestal vrij kort zijn, is het van groot belang om de toepassingsmogelijkheden van dergelijke reeksen in dendrochronologisch onderzoek te exploreren. Daartoe werden de houten artefacten van middeleeuwse archeologische sites, in en nabij leper

(West-Vlaanderen), grondig geanalyseerd en hun relevantie voor daterend onderzoek en de opbouw van chronologieën geëvalueerd. Daaruit blijkt dat de korte reeksen evenzeer gebruikt kunnen worden voor de opbouw van chronologieën. De datering van dergelijke reeksen blijft echter problematisch. Enkel de vergelijking met verschillende referentiechronologieën van omliggende gebieden (Maasvallei, zuid Nederland, Duitsland, etc.), en daarbij nagaan of éénzelfde positie herhaaldelijk terugkomt in de correlatieanalyses, biedt een uitkomst.

Daarnaast blijkt ook duidelijk dat de opgemeten groeiringspatronen meer informatie bevatten over de opbouw en beheer van het bos waarin het hout werd geoogst. Na vergelijking met groeiringspatronen van hedendaagse bomen, uit bestanden met een gekende structuur en beheer, blijkt dat gelijkaardige patronen worden teruggevonden. Zo zijn de korte groeiringsreeksen van archeologisch en bouwhistorisch hout dikwijls gelijkaardig aan de groeiringspatronen van hakhout. De langere reeksen, dus de bomen die op latere leeftijd werden gekapt, hebben meestal ook smallere groeiringspatronen en vertonen meer gelijkenis met hooghout bestanden of de overstaanders bij hakhoutbeheer. Zodoende kan er meer informatie gewonnen worden over het beheer en structuur van het Vlaamse bosbestand doorheen de eeuwen heen. Een gedetailleerd onderzoek van de anatomische structuur van het hout kan tevens een beeld opleveren van de lokale groeiomstandigheden. Zo blijkt dat de diameter van de vroeghoutvaten duidelijke aanwijzingen geeft over variaties in de plaatselijke hydrologie.

Het hout dat gebruikt werd voor de creatie van 14<sup>de</sup>-16<sup>de</sup> eeuwse kunstvoorwerpen daarentegen, die nu deel uitmaken van museum- en privécollecties, is gekarakteriseerd door een totaal verschillend groeiringspatroon. Smalle groeiringspatronen en een weinig uitgesproken leeftijdstrend kenmerken het eikenhout dat werd gebruikt bij het vervaardigen van panelen, o.a. voor de schilderijen van de Vlaamse primitieven, en beeldsnijwerk. Ondertussen is duidelijk geworden dat er vanaf de 9<sup>de</sup>-10<sup>de</sup> eeuw duchtig handel werd gedreven in hout. De lokale voorziening in hout van hoge kwaliteit kwam door de continue inkrimping van het bosareaal en de invoering van beheersvormen met korte rotatietijden (b.v. hakhout) in het gedrang. Daarom werden grote hoeveelheden hout ingevoerd vanuit bosrijke gebieden. Bestaande handelsconnecties met de Hanse steden, die voornamelijk de handel controleerden rond de Baltische zee, leidden ertoe dat voornamelijk Baltisch eikenhout werd ingevoerd. Een gedetailleerde studie van gesneden Brabantse retabels en retabelsculpturen uit de 15<sup>de</sup>-16<sup>de</sup> eeuw toont aan dat middeleeuwse schrijnwerkers en beeldsnijders de ingevoerde assortimenten eikenhout prefereerden boven het hout dat beschikbaar was op de lokale markt. Ook de gildereglementen uit de 15<sup>de</sup> eeuw omvatten richtlijnen voor de beeldsnijders met betrekking tot de vereiste kwaliteit van het hout, die hen bijna verplichtte om zich tot de ingevoerde assortimenten te wenden. Daarenboven wordt aangetoond dat de analyse van het hout en de groeiringspatronen van retabelsculpturen, stylistische en iconografische toewijzingen in kunst-historisch onderzoek kunnen ondersteunen of helpen weerleggen, en zelfs kan bijdragen tot de reconstructie van ontmantelde of beschadigde retabels.

Naast een exacte datering van de sculpturen, meer informatie over de voorkeur van middeleeuwse beeldsnijders ten aanzien van hun grondstof en de organisatie van het werkproces levert de analyse van de groeiringspatronen ook een beeld van het

exploitatiegebied waar de bomen werden geveld. Daartoe moeten de groeiringreeksen van de sculpturen vergeleken worden met een uitgebreide databank van chronologieën, berekend met groeiringdata van lokaal hout. Zo een databank, met een hoge ruimtelijke resolutie, is na jarenlang dendrochronologisch onderzoek op lokaal archeologisch hout beschikbaar voor Polen. Een dergelijke analyse met groeiringdata van paneelschilderijen en sculpturen, gecreëerd uit Baltisch eikenhout toont aan dat er een duidelijke verschuiving is in exploitatiegebieden. Hoewel steeds in de nabijheid van rivieren, om zo de geveld boomstammen gemakkelijk te kunnen transporteren, gingen de houthakkers en handelaars steeds verder van de exporthaven weg om geschikte eiken te vellen.

Ondanks het beschikbaar komen van steeds meer lokale referentiechronologieën en verdere methodologische ontwikkelingen blijven sommige stukken hout ondateerbaar via jaarringanalyse. Hun groeiringpatroon blijkt te kort of bevat geen gemeenschappelijk signaal met de beschikbare referentiechronologieën. Als alternatieve dateringsmethode kan dan het gehalte aan de radioactieve koolstofisotoop  $^{14}\text{C}$  worden bepaald. Dit levert een theoretische radiokoolstofouderdom op van het geanalyseerde stuk hout. Deze moet echter nog gekalibreerd worden omwille van de variabiliteit in de jaarlijkse atmosferische radiokoolstofproductie. Uiteindelijk levert dit een interval op van mogelijke kalenderjaren waarbinnen het hout werd gevormd. De precisie van deze dateringstechniek is echter veel lager in vergelijking met een dendrochronologische datering, en is bovendien sterk variabel in de tijd. Combinatie van verschillende radiokoolstofdateringen en groeiringdata laten echter toe om de precisie te verhogen. Als bijvoorbeeld een reeks van acht opeenvolgende radiokoolstofdateringen wordt uitgevoerd, op stukjes hout waarvan de onderlinge chronometrische afstand gekend is (i.e. het aantal groeiringen tussen de bemonsteringspunten), kan er een datering tot op 25 jaar precies bekomen worden.

Uit deze studie van inlands en geïmporteerd eikenhout in Vlaanderen blijkt duidelijk dat dendrochronologie niet alleen als een dateringstechniek moet aanzien worden. Relevante informatie voor kunsthistorisch, bouwhistorisch, archeologisch en paleobotanisch onderzoek kan afgeleid worden uit de analyse van groeiringpatronen van (pre-)historisch eikenhout. Daardoor blijkt het extreem nuttig om houtbiologen en dendrochronologen nauw te betrekken bij het bestuderen van Vlaanderens cultureel erfgoed gemaakt uit hout. Een multi-disciplinaire aanpak van dergelijke studies zal ontegensprekelijk een duidelijke meerwaarde geven aan (pre-)historisch onderzoek in Vlaanderen.



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## Summary

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Throughout human history, forests and woodlands in Western Europe experienced a high anthropogenic influence. In densely populated areas forests were cleared and converted to arable land or were exploited for the supply of firewood and construction timber. In Flanders, it is estimated that the forest cover by the end of the 13<sup>th</sup> century was even lower than in the 19<sup>th</sup> century. To date, several assortments of timber, available on the local wood market during the Roman era and the Middle Ages, have become part of our cultural heritage. Archaeological remains, historical buildings, panel paintings and religious sculptures are only a few examples of constructions and objects that were created by processing wood. Especially European oak (*Quercus robur* L. and *Q. petraea* (Matt.) Liebl.) was highly appreciated by craftsmen.

Tree-ring series of oak have the characteristic that they tend to crossdate. In other words, ring-width series display a certain element of synchronicity between remote sites. This feature allows to use dendrochronology, i.e. the scientific study of tree-ring patterns, as a dating tool. However, in Flanders tree-ring dating has seldom been applied and has often led to inconclusive results. Especially archaeological oak timbers or wood from historical buildings is often characterized by short (less than 50 years) and variable growth patterns. Therefore, it was assessed and demonstrated that such series have a potential for dating purposes and chronology building.

It is believed that the high anthropogenic pressure on the original forest cover has stimulated the implementation of short rotation systems. Past forest management interventions and forest stand structure development are recorded in the growth patterns and the wood anatomical structure of archaeological and subfossil wood. By comparing them with growth patterns of contemporary trees from stands with well-known stand structure and management history it was noticed that the same patterns are encountered. Consequently, it is now possible to distinguish wood specimens that originate from, for instance, a coppice stand or a high forest by scrutinizing their growth patterns. Moreover, close observation of the wood anatomy, for instance, the size and distribution of earlywood vessels, provides an image of the variability in past hydrological conditions.

Tree-ring series from wooden sculptures and panel paintings from 15<sup>th</sup>-16<sup>th</sup> century display a completely different nature. Since local timber sources mostly provided small sized and fast grown timber, craftsmen started to look for sizeable oaks with a fine grain. Such assortments became available due to the establishment of an important timber trade. Especially oak timber from the Baltic region was imported. By studying the growth patterns on art-historical objects it becomes clear that medieval woodworkers were well aware of the intrinsic variability and technological properties of the imported oak timber. Moreover, analysis of extensive datasets of tree-ring series from art-historical objects provides more insights and information on the original timber source, wood processing activities and the creative process.

It is obvious that dendrochronology has become more than a dating tool in (pre-) historical studies. This work demonstrates that it is highly valid to approach Flanders' precious cultural heritage, created out of wood, from a multidisciplinary point-of-view, in which dendrochronology, wood technology and biology should play an important role.





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## Introduction and outline

# 1

Chapter

To date, in an industrial world with a wide spectrum of polymers and composites available, men still relies on wood as a basic material for simple tools, furniture and decoration. Moreover, wood has been appreciated by men, throughout history, for construction and creative purposes. If not preferred for its specific mechanical or technological properties, wood is visually appreciated for its inherent variation in structure and texture. The main reason for this variability is due to the presence of growth layers. For many trees in Western Europe, these growth layers, or growth rings, are known to have an annual resolution. It was soon recognized that these growth rings provide the means, not only to measure tree age, but to go back in time and provide a *fingerprint* of past environmental conditions.

Tree-ring analysis already has a long history in Europe. Ever since the development of dendrochronology as an independent scientific discipline in the 1950s, long chronologies have been compiled and used as a reference for the dating of historical wood specimens. Dendrochronology, as an archaeometric tool, has provided precise calendar dates for many archaeological sites, art-historical objects, architectural buildings and many more. The precision obtained by tree-ring dating is unmatched by any other dating method. However, it should be clear that dendrochronology has

evolved beyond dating and is able to provide proxies for the reconstruction of environmental variables.

By the end of the last glacial period, when climatic conditions became more favourable, oak spread rapidly through Europe. Especially **pedunculate oak (*Quercus robur* L.)** and **sessile oak (*Q. petraea* (Matt.) Liebl.)** soon took in a (co-) dominant position in European deciduous forests (Brewer *et al.* 2002; Petit *et al.* 2002). European oaks often display a high similarity in their year-to-year variation in ring-width, even when confronting trees from remote forest sites. This clearly demonstrates that oak trees have an analogous response to large-scale climatological conditions. Nevertheless, it is well understood that trees from a specific region not solely record one common, climatic-driven signal in their growth-ring pattern. Local growing conditions modulate the growth-ring pattern and anatomical structure as well. Among these local, endogenous pulses are gap-phase stand dynamics and forest management practices. The latter is expected to become more dominant when forests and woodlands are intensively exploited.

In Europe, man, at some point in time, has influenced nearly all forests and woodlands (Buis 1985; Rackham 2003). Already in prehistoric times, the original vegetation in Western Europe was affected on a large scale. Forests were cleared and converted to arable land and pastures, or were cut for the supply of firewood and construction timber. During the Middle Ages, Flanders was one of the most densely populated areas in Western Europe. Moreover, it became one of the major trade centres and was a meeting point for merchants from northern and southern Europe. As a consequence, the local vegetation, and forests and woodlands in particular, were exploited to cope with the rising need for forest products. It was estimated that the forest coverage in Flanders reached one of its lowest values as early as by the end of the 13<sup>th</sup> century (Tack *et al.* 1993). This continuous, high anthropogenic pressure on the original forest vegetation is still reflected in the current, fragmented forest cover in Flanders.

It is clear that this intensive exploitation of the timber resources must have had a dramatic impact on the forest cover, species composition, woodland architecture, etc. Such dynamics are partly archived in the growth-ring patterns and anatomical

features of preserved wood specimens. Ring-width patterns of wood from archaeological sites in Flanders are predominantly short and often display sudden changes in growth rate. This hampers the implementation of dendrochronology as a standard chronometric dating tool in archaeological research. An objective of this work is **to assess the potential of tree-ring analysis in a region with a high anthropogenic impact on the original vegetation.**

Due to the high human impact on local forests and the devastating reduction in forest cover, sizeable timber with a uniform growth-pattern became a valuable commodity during the Middle Ages. As a consequence, merchants started to explore more remote forested areas and imported large amounts of excellent timber into Flanders. This is of great importance for tree-ring analysis and tree-ring dating in Flanders. The main branch of industry that required such high-quality timber was shipbuilding. Due to the well-established trade connections between the powerful medieval towns in Flanders and the Hanseatic League, massive amounts of oak timber were imported from the Baltic area. These assortments were soon noticed by craftsmen, sculptors and painters who highly appreciated the imported timber as basic material above the timber available on the local market. This implies that tree-ring analysis in Flanders can not only focus on wood from local forests and woodlands when studying our cultural heritage.

In this dissertation it will be assessed **how tree-ring analysis can provide relevant information in the field of archaeology, art-history, palaeoecology, forest history and (pre-)historical research in general.**

In **Chapter 2**, a literature review of tree-ring analysis in archaeological and art-historical research is presented. It attempts to provide an overview of the development of dendrochronological research in Europe, the methodological advances and discusses the potential of tree-rings series as proxies for environmental variables. Subsequent chapters are organized into three parts, each presenting oak wood from a different background. **Part I** focuses on wood in an art-historical context. Sculptures from carved, Late Gothic altarpieces are presented and examined in **Chapter 3**. They can be considered as one of the most remarkable end products of high-quality oak timber during the 15<sup>th</sup> and 16<sup>th</sup> centuries. This will be

exemplified by studying the growth-ring patterns and wood anatomical structure of the individual sculptures in order to provide more detailed information on medieval workshop practices and relevant information for the art-historical research. **Chapter 4** reflects on the origin of the high-quality timber that was appreciated by the medieval wood carvers and craftsmen. It is known that considerable amounts of oak timber were imported from the Baltic area. In order to document historical trade-routes, an evaluation is made of the possibilities to reconstruct the original timber source by scrutinizing ring-width patterns and regional chronologies.

Growth patterns from wood specimens of Roman and Medieval archaeological sites are the basic material for **Part II**. It is assessed if the short and highly variable ring-width series, that are often characteristic for archaeological sites in Flanders, can be used for dating purposes and chronology building (**Chapter 5**). Moreover, it is evaluated if comparison of those ring-width patterns from archaeological artefacts with ring-width series of contemporary forest stands with a well-known structure can provide images of former stand structure and management practices (**Chapter 6**).

In **Part III** of this dissertation, specimens of subfossil wood are examined. Despite the advances in dendrochronology, some wood specimens will prove to be unsuitable for tree-ring dating, and hence remain undated. Especially in a palaeobotanical context it can be expected that the dendrochronological framework of reference chronologies does not cover the appropriate time frame. Radiocarbon analysis can be a valuable alternative. Nevertheless it should be stressed that the precision obtained by this dating technique is not even close to conventional tree-ring dating. Combination of tree-ring data and radiocarbon measurements, referred to as *wiggle-matching*, is a valuable tool to obtain high-precision dating. In **Chapter 7**, the theoretical background, advantages and limitations of this technique are presented. This dating procedure is implemented on subfossil wood specimens, excavated along the river Scheldt. From the subfossil oaks, tree-ring data and particular wood anatomical features are examined and interpreted with special regard to the growing conditions experienced by subfossil trees at the beginning of the Holocene (**Chapter 8**).

Finally, **Chapter 9** reflects on the utilization potential of dendrochronology in Flanders and future research needs.







# Tree-rings of European oak and their relevance in archaeological and (art-)historical research: a review

## Chapter

# 2

### Summary

Over the past decades, dendrochronology has established itself as a standard dating tool in archaeological and (art-) historical research. Moreover, tree-ring analysis has evolved beyond dating and is now able to offer more detailed information on past environments and environmental trends. Especially tree-ring series of European oak (*Quercus robur* L. and *Q. petraea* (Matt.) Liebl.) have provided a reliable framework for chronometric dating and reconstruction purposes.

To date, long oak chronologies cover almost the entire Holocene, up to 8.480 BC. Exhaustive studies of well-replicated databases of site chronologies have provided an overview of pan-European pointer years which are able to support crossdating. Tree-ring dating has been successfully implemented in a wide variety of (pre-) historical studies. Especially archaeological artefacts, architectural buildings and art-historical objects as panel paintings and sculptures have been most popular subjects. For the latter, new preparation techniques have been developed. Moreover, recent advances in 3D-computertomography and image analysis open new perspectives.

Furthermore, the recorded tree-ring series have provided the means to reconstruct past climate and to identify catastrophic events and climate anomalies. In addition, more information on past forest structure, silviculture and timber trade becomes available through scrutinizing historical and contemporary ring-width patterns.

## 2.1 Introduction

Dendrochronologists have provided a powerful chronometric dating tool to archaeologists and art historians over the last decades. Tree-ring analysis not only enabled the proper calibration of the radiocarbon curve, but has become a standard dating method in a wide variety of historical studies (Kuniholm 2001 and 2002; Nash 2002; Pearson 1997; Sass-Klaassen 2002). Tree-ring analysis allows to allocate ring-width series, recorded on wooden objects, on a time axis with annual resolution. In some cases the felling date of a tree can be determined even up to the season of a calendar year. The precision of dendrochronology as a dating tool has not been matched by any other method. But dendrochronology has evolved beyond dating. Tree-ring analysis is capable in providing additional information on a wide spectrum of environmental variables, evolving through time. Even arguments that found behavioural theories (Dean 1996) or help to identify catastrophic events (Baillie 2002) can be formulated by studying the annual growth pattern of contemporary, archaeological and prehistoric wood samples.

Leonardo da Vinci (1452° - 1519<sup>†</sup>) was the first to report the apparent relation between ring width and the prevailing annual weather conditions\*. The implementation of dendrochronology in Europe, as established by A.E. Douglass (1867° - 1962<sup>†</sup>) on pines from arid regions in the southwest of the USA (Douglass 1909 and 1914), took off during the 1930's. Although some earlier attempts to study and crossdate the growth ring patterns of contemporary trees had been reported (Kaptey 1914; Seckendorff 1881), Bruno Huber was the first academic to test the basic principles of dendrochronology in Central Europe on a large scale (Huber 1939, 1941, 1943 and 1952; Huber and Holdheide 1942; Huber et al. 1949). It was soon noticed that the tree-ring patterns of, for instance, European oaks (*Quercus robur* L. and *Quercus petraea* (Matt.) Liebl.) have substantially different characteristics compared to the trees studied by A.E. Douglass. The growing conditions in Europe's temperate region are usually less limiting compared to the semi-arid environment in

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\* Original text from *Trattato della pittura*: "Li circuli delli rami segati mostrano il numero delli suoi anni e quali furono più umidi o più secchi secondo la maggiore o minore loro grossezza".

Authors' interpretation: *The rings in cut branches (stems) show their number of years, as well as those years that were moister or dryer, according to their larger or smaller width.*

the southwest of the United States of America. Moreover, tree-ring series from European trees not solely include information about a single, limiting factor but enclose data on a wide variety of environmental factors. Therefore the overall correlation of tree-ring series from one particular forest site are generally much lower compared to the American pines from the southwest. In addition, the average life-span of European trees from temperate forests is considerably shorter. This required some basic adaptations in the methodology, what resulted in testing and implementation of new statistical crossdating algorithms.

Not all tree species are suited for dendrochronological analysis applied in (pre-) historical studies. In order to assess the potential of a tree species in (pre-)historical research some prerequisites can be formulated. (i) Tree species with a wide ecological and geographical range are preferred. This implies that such trees can be found over an extensive area, in different types of woodland or forest. (ii) The species should be able to take in a (co-) dominant position in different types of woodland. Dominant trees are more likely to respond to climatological pulses compared to suppressed or shaded trees that are more influenced by the internal forest dynamics. Besides this, (iii) the heartwood should be sufficiently durable in order to assure preservation in a waterlogged environment and adequate resistance to insect attacks. Under these conditions, the wood species will most probably also be highly appreciated for construction purposes. Therefore European oak has become one of the major species in historical tree-ring research. Approximately 6.000 years ago, deciduous oak trees reached their current geographical extension and started to take in a dominant position in Central European forests (Brewer et al. 2002; Petit et al. 2002a). They can become up to several hundreds of years old. Although the tree-ring series are more complacent and significantly shorter compared to the American pines from the southwest it has been demonstrated repeatedly that it is possible to construct long chronologies that contain a strong common signal, from contemporary and historical oak specimens. The heartwood of oak is durable to moderately durable (according to the current EN 350 standards) and was thanks to its excellent mechanical properties highly appreciated as construction timber on various archaeological sites and historical buildings, and was used by many craftsmen, sculptors and famous painters for their panels. All these characteristics have given oak a leading position in dendrochronological research in Europe, with on average 60

publications each year over the last two decades, according to the online Bibliography of Dendrochronology (<http://www01.wsl.ch/dendrobiblio>).

For dating purposes additional requirements need to be fulfilled. The wood has to be adequately preserved so that the anatomical features in general, and the tree-ring boundaries more specific, are still easy to discern. Also, the preserved wood specimens need to display a sufficient number of growth rings. Longer series allow a correlation analysis, with a reference chronology or contemporary series from the same location, with a more reliable statistical inference compared to a similar analysis with short ring-width series. And last, a reference chronology should be available that covers the appropriate time period and adequately represents the average annual radial growth of the original timber source (Eckstein et al. 1984).

The application of dendrochronology as a dating tool in archaeological studies has evolved simultaneously with the advances in tree-ring research. Douglass was the first to explore the possibilities of tree-ring analysis in archaeological studies (Douglass 1914). This resulted in the construction of a ca. 1.200 year long reference chronology and the dating of nearly 40 prehistoric settlements in the southwest of the USA (Douglass 1935). In Europe, the Viking settlement of Haithabu (Hedeby, Germany) provided the opportunity to study a massive amount of oak timber used for the construction of houses and a harbour with several landing stages (Eckstein 1969). It can be considered as one of the first opportunities to study and date historical wooden constructions in Europe by recording the growth ring patterns of the preserved wood specimens on a large scale. Since then many archaeological studies have been carried out with the help of dendrochronologists.

The use of dendrochronology as a dating tool in historical research on art objects was introduced by Josef Bauch, a scholar of Huber, from the Ordinariat für Holzbiologie in Hamburg (Bauch 1968). He was the first to investigate the oak panels from paintings of Dutch, Flemish and German painters. The very first analyses were executed on panel paintings from a Dutch artist, Philips Wouwerman (1619° - 1668<sup>+</sup>), which could be dated against reference chronologies from southern Germany. These analyses triggered the interest in this particular research area and made dendrochronology become a widely applied and accepted dating technique by art

historians. Most popular objects were, from the beginning on and still are, panel paintings (e.g. Bauch et al 1978, Bauch and Eckstein 1981, Hillam and Tyers 1995). To a lesser extent sculptures (e.g. Fraiture 2000), furniture (e.g. Lavier and Lambert 1996, Jansma *et al.* 2004), musical instruments (e.g. Burckle and Grissino-Mayer 2003, Klein *et al.* 1986) and wooden book covers (Lavier and Lambert 1996) have also become the subject of dendrochronological analysis.

This paper aims to review the specific characteristics of tree-ring analysis on oak specimens in Europe, with special interest in applications for (pre-)historical studies in general, and more specific, in archaeology and the study of art-historical objects. This document intends to summarize the main characteristics of tree-ring series from oak, the consequences for the methodology and suggests possible outlines for the future.

## 2.2 The genus *Quercus* in Europe

In Europe, 22 native species of the genus *Quercus* can be found (Tutin *et al.* 2001). Additionally, some other species like *Q. palustris* Muenchh. and *Q. rubra* L. were introduced in manmade forests. A lot of them are ring-porous species. This makes it relatively easy to distinguish the tree-ring boundaries, contrary to the few oak species that have a diffuse porous appearance, e.g. *Q. suber* L. Worldwide many oak species have been used in dendrochronological studies and the construction of long chronologies. According to Grissino-Mayer (1993), tree-ring patterns of 44 oak species have already been examined, of which 27 proved to crossdate significantly. In Europe, tree-ring series from 3 native oak species (*Q. robur*, *Q. petraea* and *Q. pubescens* Willd.) can very often be successfully crossdated. Not only tree-ring series from the same stand, but also site chronologies scattered over a wide region can display a high visual and statistical correlation. This clearly demonstrates that oak trees, especially *Q. robur* and *Q. petraea*, have an analogous response to large-scale climatological signals. Nevertheless this does not guarantee that all specimens from the same forest stand will significantly crossdate. Local differences in stand structure, pedology, social status and microclimate can disrupt the crossdating process. Six other *Quercus* species only crossdate between cores from the same tree, but are usually of no value in the construction of regional chronologies and do

**Table 2.1:** *Quercus* species in Europe (Flora Europaea, Tutin *et al.* 2001). The cross-date index (CDI) is 2 for species that proved to crossdate between specimens from the same site and between site chronologies, 1 for species that only crossdate within one site and 0 for species that have a low potential for crossdating (after Grissino-Mayer 1993).

| Species                                       | Vernacular name                        | CDI | Distribution *  |
|---|--|-----|---|
| <i>Quercus petraea</i> (Matt.) Liebl.         | sessile oak, durmast oak, chestnut oak | 2   | W.C. & S.E. Europe; southwards to C. Spain and S. Albania; northwards to 60° N. in Norway                             |
| <i>Quercus pubescens</i> Willd.               | pubescent oak, downy oak, white oak    | 2   | W., C. and S. Europe; extending eastwards to the Krym   |
| <i>Quercus robur</i> L.                       | pedunculate oak, English oak           | 2   | Most of Europe, except much of the north-east and parts of the Mediterranean region                                   |
| <i>Quercus canariensis</i> Willd.             | Mirbeck's oak, Algerian oak            | 1   | Spain and S. Portugal   |
| <i>Quercus cerris</i> L.                      | Turkey oak, mossy oak                  | 1   | S. & S.C. Europe; westwards to S.E. France; naturalized in N.W. Europe  |
| <i>Quercus faginea</i> Lam.                   | Portuguese oak                         | 1   | Spain and Portugal  |
| <i>Quercus frainetto</i> Ten.                 | Hungarian oak, Italian oak             | 1   | Balkan peninsula; extending northwards to N.W. Romania; S. & C. Italy   |
| <i>Quercus hartwissiana</i> Steven            | -                                      | 1   | S.E. Bulgaria and Turkey  |
| <i>Quercus polycarpa</i> Schur                | -                                      | 1   | S.E. Europe; extending northwards to C. Czech Republic and Slovakia   |
| <i>Quercus rubra</i> L.                       | red oak                                | (1) | Planted for timber and shelter, especially in C. Europe; sometimes naturalized  |
| <i>Quercus ilex</i> L.                        | evergreen oak, holm oak, holly oak     | 0   | Mediterranean region; extending to N. Spain and W. France; planted elsewhere in W. & S. Europe; sometimes naturalized |
| <i>Quercus lusitanica</i> Lam.                | -                                      | 0   | Portugal and S.W. Spain   |
| <i>Quercus macrolepsis</i> Kotschy            | Valonia oak                            | 0   | S. part of Balkan peninsula; Aegean region; S.E. Italy  |
| <i>Quercus pyrenaica</i> Willd.               | Pyrenean oak                           | 0   | W. Europe; northwards to N.W. France  |
| <i>Quercus suber</i> L.                       | cork oak, cork tree                    | 0   | S. Europe; from Portugal to S.E. Italy  |
| <i>Quercus coccifera</i> L.                   | Kermes oak, Israelian oak              | 0   | Mediterranean region (but absent from much of Italy); Portugal  |
| <i>Quercus canariensis</i> x <i>pubescens</i> | -                                      | 0   | N. Spain  |
| <i>Quercus congesta</i> C. Presl              | -                                      | 0   | S.W. Italy and Sicily; Sardinia; endemic  |
| <i>Quercus dalechampii</i> Ten.               | -                                      | 0   | S.E. Europe; extending to S.E. Slovakia and W. Italy  |
| <i>Quercus mas</i> Thore                      | -                                      | 0   | N. Spain; endemic   |
| <i>Quercus pedunculiflora</i> K. Koch         | -                                      | 0   | S.E. Europe   |
| <i>Quercus sicula</i> Borzi                   | -                                      | 0   | Sicily; endemic   |
| <i>Quercus trojana</i> Webb                   | Macedonian oak                         | 0   | Balkan peninsula (mainly in the west); S.E. Italy   |
| <i>Quercus palustris</i> Münchh.              | pin oak                                | (0) | Planted for timber; mainly in E.C. Europe   |

\* N = Northern; E = Eastern; S = Southern; W = Western; C = Central



not guarantee the possibility to construct a site chronology with a high common year-to-year variability (Table 2.1).

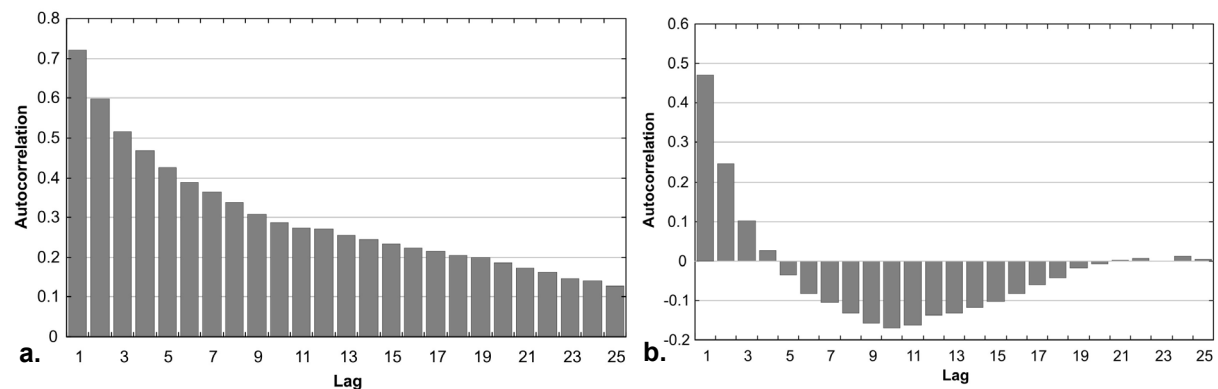
The most widely dispersed oak species, *Q. robur* (pedunculate oak) and *Q. petraea* (sessile oak), are both trees that grow under a broad variety of ecological conditions. Pedunculate oak, which is known to have a wider ecological and geographical range, is more typical for the valleys of the large European rivers and moist lowlands, while sessile oak is more likely to be found on hilly terrain (Mayer 1980). Most European long tree-ring chronologies are built with tree-ring series of *Q. robur* and *Q. petraea*. Often it is not possible to make a clear distinction between both species based on their wood anatomical features. The differences in wood anatomy are subtle, but predominantly rely on the number of earlywood vessel rows (more than 2 for *Q. robur*) and the percentage of latewood (less than 60% for *Q. robur*; more than 70% for *Q. petraea*) in the total ring width, when rings of ca. 2 mm wide and a cambial age of 60-120 years are selected (Feuillat *et al.* 1997). When wood is found on an archaeological site, a wood anatomical examination is in most cases the single possible approach to discriminate between these two species. Fortunately, it has been demonstrated repeatedly that ring-width series from *Q. robur* and *Q. petraea* crossdate well, despite the differences in their phenology. As a consequence ring-width series of both species are often pooled into one chronology and regarded as one single species.

Despite the wide range in ecological conditions experienced by oak trees in Europe, tree-ring profiles have some characteristics in common. Descriptive statistics of tree-ring series from European oak, submitted to the International Tree-Ring Data Bank (ITRDB; Grissino-Mayer and Fritts 1997), are summarized in Table 2.2. Tree-ring data from trees between 100 and 200 years old were selected and grouped according to their provenance. The measured tree-ring widths range from more than 1 cm down to a fraction of a millimetre. The average ring width does not seem to be in relation with geography, and is probably more controlled by specific site conditions. One common feature is the strong first-order autocorrelation (0.61 - 0.77) of the raw ring-width series. All subsequent autocorrelation values are also high (Figure 2.1a), and remain significant ( $p = 0.05$ ) up to lag 20. This indicates the presence of a strong and distinct age trend. When the age trend is removed by passing a moving average

window of 20 years to the raw date, the high-order autocorrelations drop down. The first-order autocorrelation on the other hand remains significant ( $r^2 = 0.47$ ), although lower than for the raw ring-width series (Figure 2.1b). This suggests a strong dependency of the trees annual increment to the growth conditions in the preceding year.

**Table 2.2:** Descriptive statistics from ring-width series of oaks (*Q. robur* and *Q. petraea*), grouped by their county of origin, available in the ITRDB (Grissino-Mayer and Fritts 1997) and unpublished data (Belgium). The data are sorted by increasing mean sensitivity. All trees are between 100 and 200 years old.

| Region                | No. of trees | Average length | Ring width (mm) |      |       | Standard deviation | First-order AC | Mean sensitivity |
|-----------------------|--------------|----------------|-----------------|------|-------|--------------------|----------------|------------------|
|                       |              |                | Min             | Mean | Max   |                    |                |                  |
| Sweden                | 28           | 160            | 0.16            | 1.79 | 7.82  | 0.70               | 0.72           | 0.191            |
| Lithuania             | 14           | 109            | 0.30            | 2.43 | 7.92  | 0.90               | 0.70           | 0.200            |
| Italy (north)         | 33           | 136            | 0.09            | 2.03 | 10.44 | 0.91               | 0.77           | 0.202            |
| Poland (south)        | 110          | 162            | 0.27            | 1.85 | 11.19 | 0.79               | 0.74           | 0.204            |
| Poland (north)        | 78           | 147            | 0.29            | 1.90 | 8.10  | 0.75               | 0.71           | 0.211            |
| Norway                | 160          | 136            | 0.04            | 1.70 | 7.40  | 0.68               | 0.72           | 0.216            |
| Northern Ireland      | 71           | 146            | 0.07            | 1.19 | 8.00  | 0.51               | 0.75           | 0.219            |
| Netherlands (central) | 178          | 110            | 0.04            | 1.77 | 11.20 | 0.96               | 0.77           | 0.245            |
| Germany (north)       | 38           | 124            | 0.21            | 1.85 | 7.06  | 0.78               | 0.66           | 0.257            |
| France                | 62           | 144            | 0.08            | 0.85 | 4.47  | 0.40               | 0.68           | 0.259            |
| England (north)       | 43           | 146            | 0.02            | 0.54 | 5.82  | 0.31               | 0.77           | 0.261            |
| England (south)       | 43           | 138            | 0.07            | 0.93 | 4.41  | 0.47               | 0.72           | 0.262            |
| Germany (northwest)   | 83           | 122            | 0.25            | 2.02 | 9.34  | 1.01               | 0.72           | 0.263            |
| Ireland               | 75           | 136            | 0.05            | 0.64 | 3.96  | 0.31               | 0.70           | 0.268            |
| Germany (west)        | 109          | 145            | 0.16            | 1.77 | 9.99  | 0.90               | 0.71           | 0.270            |
| Netherlands (south)   | 24           | 103            | 0.08            | 1.31 | 6.43  | 0.66               | 0.61           | 0.274            |
| Belgium               | 60           | 141            | 0.12            | 2.41 | 9.68  | 1.29               | 0.74           | 0.278            |
| England (west)        | 28           | 150            | 0.16            | 1.65 | 8.74  | 0.80               | 0.70           | 0.298            |



**Figure 2.1:** Average autocorrelation of all ring-width series, presented in Table 2.2, at different lags for the **-a** raw ring-width series, and **-b** detrended series (moving average with a 20 year window).

Mean sensitivity ( $\bar{S}$ ) is a measure of the variation in ring width from year to year and theoretically ranges from 0 (no difference between adjacent years) to 2 (equivalent to

a ring width measurement of zero). A low value represents more constant ring widths.

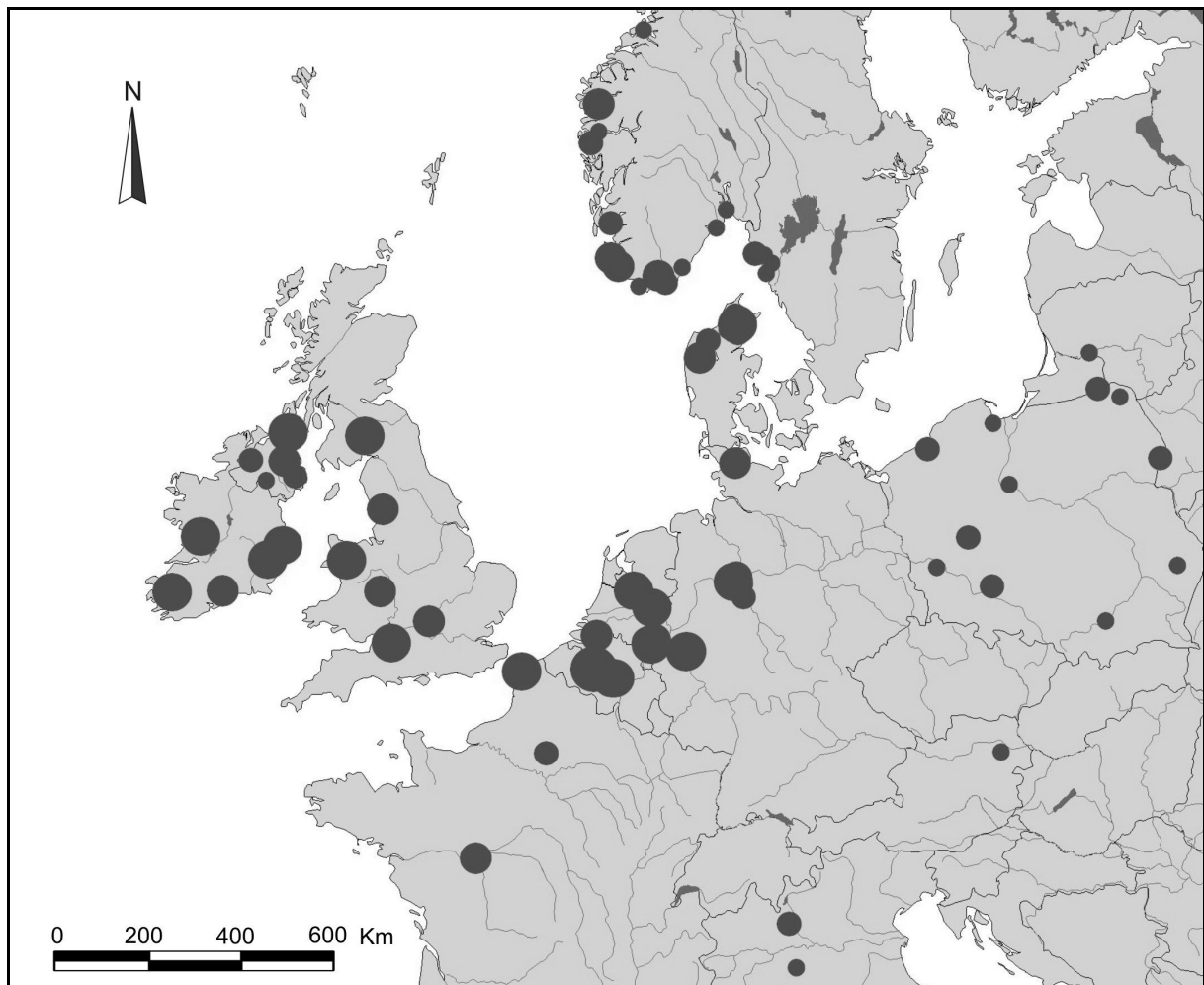
$$\bar{S} = \frac{1}{n-1} \sum_{i=1}^{n-1} \frac{|x_{i+1} - x_i| \times 2}{(x_{i+1} + x_i)} \quad (2.1)$$

This parameter seems to display a certain geographical trend. Tree-ring series from Lithuania and Poland clearly have a lower mean sensitivity than, for example, oak trees in central Belgium and England (Figure 2.2). Oak specimens with a Baltic provenance are thus characterized by a more regular tree-ring pattern compared to oak growing under a more Atlantic climate. This contrasts the generally accepted idea that the cambium exhibits a more sensitive behaviour when trees are growing at the edge of their ecological range. It is striking that the lowest values are encountered for trees from vast forested areas, where the highest values are found in regions with a more fragmented forests cover and a high anthropogenic influence on the forest ecosystems. The latter may provoke exogenous pulses in the growth pattern induced by more intensive forest management. This increases the variability in the ring-width patterns. Strackee and Jansma (1992) also criticized the mean sensitivity as a statistical descriptor of ring-width series and demonstrated its dependency of the variance and first-order autocorrelation (Jansma 1995). A large value of the variance, a low first-order autocorrelation, or a combination of both will increase the mean sensitivity.

The climate-growth relationship, as demonstrated by correlation and regression analyses, is not a simple one for European oaks. The observed correlations are often complex to explain. Simple correlations and response functions between ring-width series and monthly temperature and precipitation records are able to explain 5 to 72% of the total variation in total ring width (Eckstein and Schmidt 1974; Krause 1992; Lebourgeois *et al.* 2004; Pilcher and Gray 1982; Rozas 2001; Ufnalski 1996). In most cases they explain more than 20%. Usually a positive correlation is observed with the amount of precipitation throughout the summer, especially during the months June and July (Lebourgeois *et al.* 2004; Pilcher and Gray 1982; Rozas 2001). Correlations with the average monthly temperature of the current growing season are more variable and sometimes contrasting when comparing areas distant from each other. In the Mediterranean region negative correlations between mean temperatures

in May-June-July and ring-width are frequently observed (Santini *et al.* 1994), where for more northern locations in Europe often a positive correlation is observed (Eckstein and Schmidt 1974; Pilcher and Gray 1982).

Typical for oak ring series are the sometimes significant correlations with climate data from the previous growing season, especially for data describing the average weather conditions in the preceding autumn and winter. The hydric balance in October-November of the previous year often yields positive correlations with the ring width of the following growing season (Lebourgeois *et al.* 2004; Pilcher and Gray 1982). Small ring widths often coincide with low winter temperatures (Pilcher and Gray 1982; Wazny and Eckstein 1991), which suggests that oaks prefer mild winters.



**Figure 2.2:** Spatial distribution of mean sensitivity values of oak ring series (*Quercus* spp.) in Europe. The series selected for this map are submitted to ITRDB, supplemented with some additional data from Flanders (northern Belgium). The diameter of the bullets is proportional to the value of the mean sensitivity.

### 2.3 Building long European oak chronologies

Dendrochronologists have always aimed at creating long chronologies. The first millennium-long chronologies in Europe were established at universities in Germany (Göttingen, Köln and Stuttgart) and Ireland (Belfast) by archiving the growth patterns of subfossil oak trees (e.g. Becker and Delorme 1978; Pilcher *et al.* 1984). The term subfossil indicates that the wood is not, or only slightly, chemically modified over the years, in contrast with fossil wood that has been mineralised or petrified.

The long European ring-width series were built independently from each other, but proved to crossdate significantly after mutual comparison (Baillie 1995; Pilcher *et al.* 1984). In their current state, they span more than 10.000 years, covering the Holocene after the last Ice Age. Consequently they must include ring-width sequences from the earliest oak trees that re-established themselves through Europe from the glacial refugia, when the climatological conditions became more favourable to deciduous trees ca. 10.000 years BP (Brewer *et al.* 2002).

The Göttingen oak chronology runs back from the present to 7197 BC (9.147 BP) (Leuschner 1992) and the Hohenheim oak chronology up to 8480 BC (10.429 BP) (Friedrich *et al.* 2004). For the latter some tentative extensions exist with tree-ring series from Preboreal pines, back to 9922 BC (Kromer and Spurk 1998; Spurk *et al.* 1998). Although there is no acceptable correlation between the ring-width series of the oak and the pines, radiocarbon measurements allow to link both chronologies with an uncertainty of  $\pm 20$  years. The Belfast chronology spans approximately 7.272 years (Brown *et al.* 1986; Pilcher *et al.* 1984). The absolutely dated wood specimens that contribute to these long chronologies have provided the basic material for the high resolution radiocarbon calibration curve.

The long chronologies are usually composed of tree-ring series from different sites that are scattered over a vast and extent region. In order to optimize the success rate in dating wood from archaeological contexts it soon became necessary to construct chronologies that cover well outlined and more restricted areas. The Hohenheim and Belfast chronologies have now more become a reference and verification tool for the

construction of regional reference chronologies. Today, hundreds of regional oak chronologies exist that enable precise and accurate dating. An overview of long oak chronologies is presented in Table 2.3. This list only attempts to provide a brief overview of Europe's widely used oak chronologies suited for dating purposes. A more exhaustive list can be found in the online Euro Catalogue ([www.dendro.bf.uni-lj.si/first.html](http://www.dendro.bf.uni-lj.si/first.html)), a searchable database of European chronologies (Levanič 2001).

**Table 2.3:** List of some long European oak reference chronologies

| Region                     | Period<br>(BC/AD) | Length<br>(years) | Author                       |
|----------------------------|-------------------|-------------------|------------------------------|
| Germany                    |                   |                   |                              |
| Hohenheim                  | 8480 BC – present | 10.429            | Friedrich <i>et al.</i> 2004 |
| Göttingen                  | 7197 BC – present | 9.147             | Leuschner 1992               |
| Germany (south)            | 370 BC – 1950 AD  | 2.320             | Becker 1981                  |
| Germany (west)             | 400 BC – 1975 AD  | 2.375             | Hollstein 1980               |
| Germany<br>(Weserbergland) | 1004 AD – 1970 AD | 967               | Delorme 1973                 |
| Ireland                    | 5289 BC – present | 7.272             | Pilcher <i>et al.</i> 1984   |
| France (north)             |                   |                   |                              |
| Paris Basin                | 348 BC – 1995 AD  | 1.648             | Bernard 1998                 |
| France (west)              | 887 AD – 1995 AD  | 1.109             | Lambert <i>et al.</i> 1996   |
| Aquitaine (southwest)      | 813 AD – 1992 AD  | 1.180             | Lambert <i>et al.</i> 1996   |
| France (east)              | 581 AD – 1991 AD  | 1.411             | Lambert <i>et al.</i> 1996   |
| the Netherlands            |                   |                   |                              |
| South                      | 427 AD – 1752 AD  | 1.326             | Jansma 1995                  |
| Central and north          | 1023 AD – 1666 AD | 644               | Jansma 1995                  |
| Coastal                    | 2258 BC – 1141 BC | 1.118             | Jansma 1995                  |
| Belgium (south)            |                   |                   |                              |
| Ardennes                   | 1146 AD – 1991 AD | 846               | Hoffsummer 1995              |
| Liège                      | 672 AD – 1714 AD  | 1.043             | Hoffsummer 1995              |
| Meuse valley               | 671 AD – 1991 AD  | 1.320             | Hoffsummer 1995              |
| Namur                      | 919 AD – 1638 AD  | 720               | Hoffsummer 1995              |
| England                    |                   |                   |                              |
| East Midlands              | 882 AD – 1981 AD  | 1.100             | Laxton and Litton 1988       |
| Southern England           | 1083 AD – 1589 AD | 507               | Bridge 1988                  |
| East-Anglia                | 944 AD – 1789 AD  | 846               | Bridge <i>unpublished</i>    |
| Poland                     |                   |                   |                              |
| East Pomerania             | 996 AD – 1985 AD  | 990               | Wazny 1990b                  |
| Baltics                    |                   |                   |                              |
| Baltic1                    | 1156 AD – 1597 AD | 442               | Hillam and Tyers 1995        |
| Baltic2                    | 1257 AD – 1615 AD | 359               | Hillam and Tyers 1995        |

## 2.4 Methodological advances

### 2.4.1 Preparation techniques

The first step in a dendrochronological study, even before measuring actual growth-ring characteristics, is the preparation of a wood specimen in order to highlight the wood-anatomical structure. An essential requisite for ring-width measurements is that the growth-ring boundaries are clearly visible. For European oak, growth rings are relatively easy to distinguish. The ring-porous structure of the wood, is characterized by 1 to 5 rows of large earlywood vessels (*Q. robur* and *Q. petraea*: 150 - 300  $\mu\text{m}$ ) followed by a more dense arrangement of smaller latewood vessels, tracheids and parenchyma.

The preparation method depends on the condition of the wood. Waterlogged archaeological or subfossil wood is often of no further value after systematic listing and mapping by the archaeologists in the field. Therefore a robust and destructive sampling strategy can be used by taking cross-sections of ca. 5 to 10 cm thick with a hand- or chainsaw. Such samples should be kept wet or should be frozen until measuring to avoid excessive deformation of the wood during a rapid drying-process (Eckstein *et al.* 1984). For historical buildings, cross-sections of beams and rafters are the preferred samples. If this is not possible dry-wood corers provide an acceptable alternative. Since oak becomes harder to work when dried and aged it is necessary to take caution when sampling with a dry-wood corer. Most drills should be mounted on devices able to rotate with a slow and constant speed in order to increase the lifetime of the drill and avoid excessive heating. Once a cross-section or increment core is collected, further preparation can be done by using scalpel and razorblade for wet specimens. Scalpels, sanding paper and small rotating sanding instruments (e.g. Dremel<sup>®</sup>) are more appropriate for dry specimens. When preparing dry oak samples by sanding it is important to remove all dust at regular time intervals. Accumulation of dust in the earlywood and latewood vessels will reduce the overall visibility of the anatomical features. The detection of the growth-ring boundaries will hence become less accurate. In some cases it can be useful to fill the earlywood vessels with a coloured paste (Sass and Eckstein 1994). Technical advances in surface preparation now allow to surface a wood sample with a diamond flycutter (Spiecker *et al.* 2000). This method yields a polished surface that allows to study the

anatomical features of the wood under high magnification, with reflected light microscopy (Figure 2.3a).

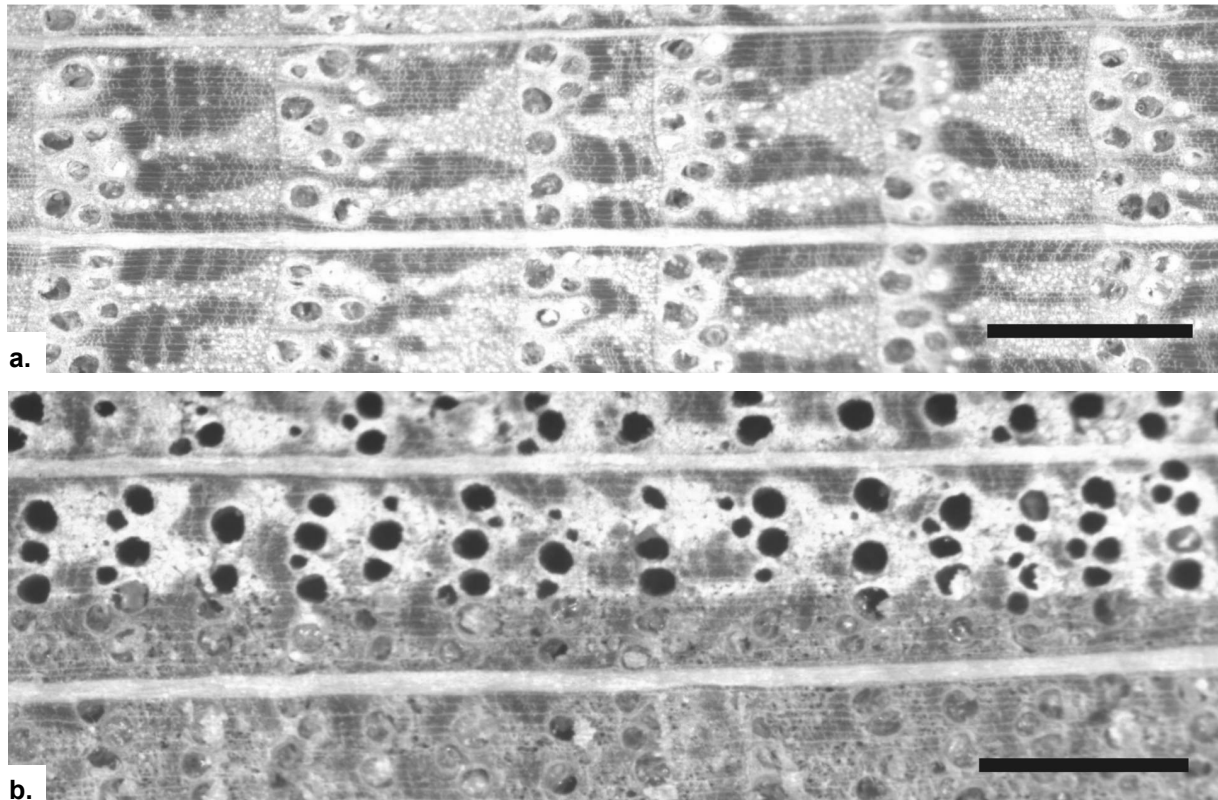
When the dendrochronological study involves precious and/or fragile works of art, more gentle or techniques that do not remove any material should be used. During the 15<sup>th</sup> and 16<sup>th</sup> centuries, quarter sawn oak panels have been most popular among painters. The growth-ring boundaries can be distinguished on the upper and lower side of the panels, but it is often essential to remove accumulated dirt and dust prior to the actual measurements. If such an intervention is insufficient to highlight the growth-ring boundaries, preparation with a scalpel and/or sanding paper can be considered.

Especially for ring-porous species, recently, a more advanced technique is introduced. This procedure, called *micro-abrasion*, can also be applied on sculptures and other wooden objects. Basically, small spherical particles are blown on a delimited transverse section of the wood. When the abrasive particles collide with the wood, accumulated dust is removed. By carefully selecting the appropriate dimensions for the abrasive, e.g. glass particles of 45-90  $\mu\text{m}$ , a specific nozzle ( $\varnothing$  1.2 mm), and pressure (ca. 4 bar), it is possible to remove the accumulated dirt and secretory elements from the earlywood vessels, leaving the growth-ring boundaries clearly visible (Figure 2.3b). A similar method was first introduced by Schultz (1982) and later refined and applied on sculptures by the *Laboratoire de Chrono-écologie* at Besançon (France). In the case of stained art objects it is necessary to protect the polychrome before implementing the micro-abrasion technique in order to avoid any damage through impact of the spherical particles. Usually a radial oriented strip on the transverse section of approximately 0.5 cm, accessible for the abrasive, is sufficient. When the edge grain is too rough or when the cell walls are inclined, the micro-abrasion technique is usually not able to highlight the growth-ring boundaries adequately. In such cases, some further preparation with scalpel and sanding paper can be considered, evidently in close consultation with curators and restorers.

Recent advances in 3D computer tomography (3D-CT) open new perspectives for dendrochronologists. With optimized scanning techniques it now becomes possible to obtain a detailed 3D-image of a complete sculpture. This technique is entirely non-



destructive and does not require any pre-treatment. The main drawback is that the required resolution for the detection of the growth-ring boundaries is sometimes hard to obtain. Especially when large sculptures are involved it becomes nearly impossible to scan such an object at the required resolution. A successful application of 3D-CT for tree-ring analysis was obtained when analysing three Celtic oak sculptures from the *Württembergisches Landesmuseum* in Stuttgart (Germany) (Friedrich 2004). It revealed that a minimal resolution of 100 to 130  $\mu\text{m}$  is required to study oak specimens (De Mol and Heller 2004). Such accurate images are hard to obtain when the X-rays have to penetrate more than 15 cm. This implies that panel paintings, although often very thin, are very complicated objects for such analysis. The X-rays have to penetrate the boards in all cross-sectional directions, so also through the complete width of the panels. It is not unusual for the boards that constitute a panel to be wider than 15 cm. As a consequence, it often becomes hard to achieve a satisfactory resolution. Future developments and innovation could make this scanning technique a widely applied tool for tree-ring analysis of precious wooden objects.



**Figure 2.3:** Detailed image of a transverse section, **-a** polished with a diamond flycutter, **-b** before (lower part) and after (upper part) micro-abrasion. Scale bar represents 2 mm.

### 2.4.2 Measuring procedure

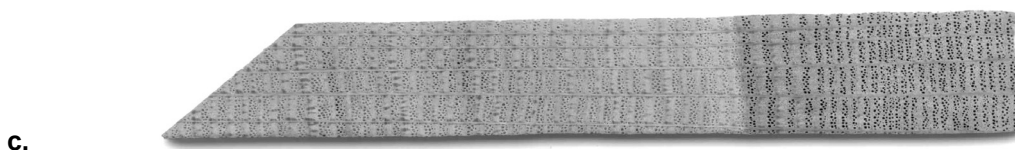
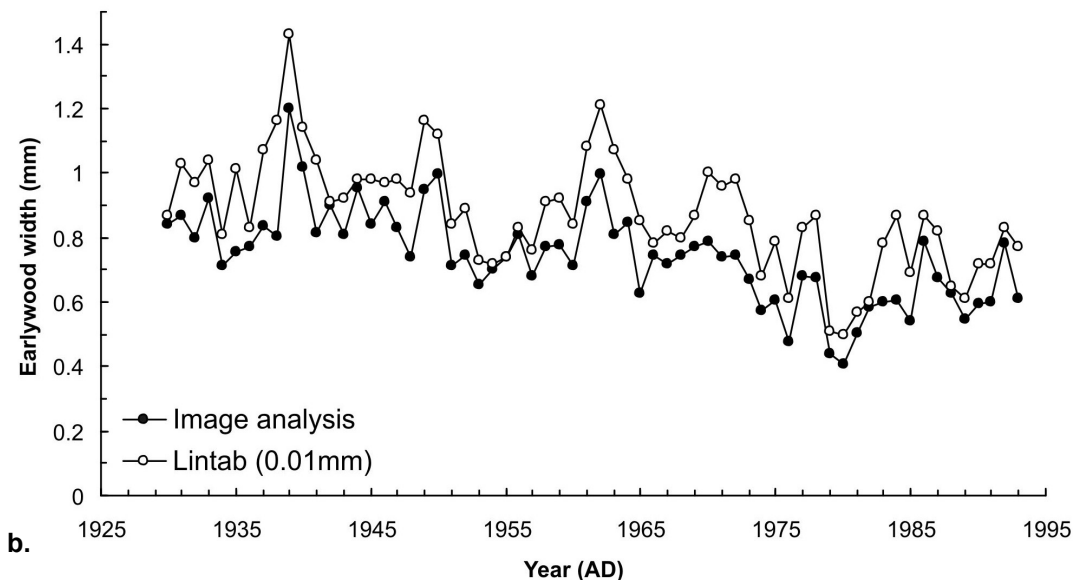
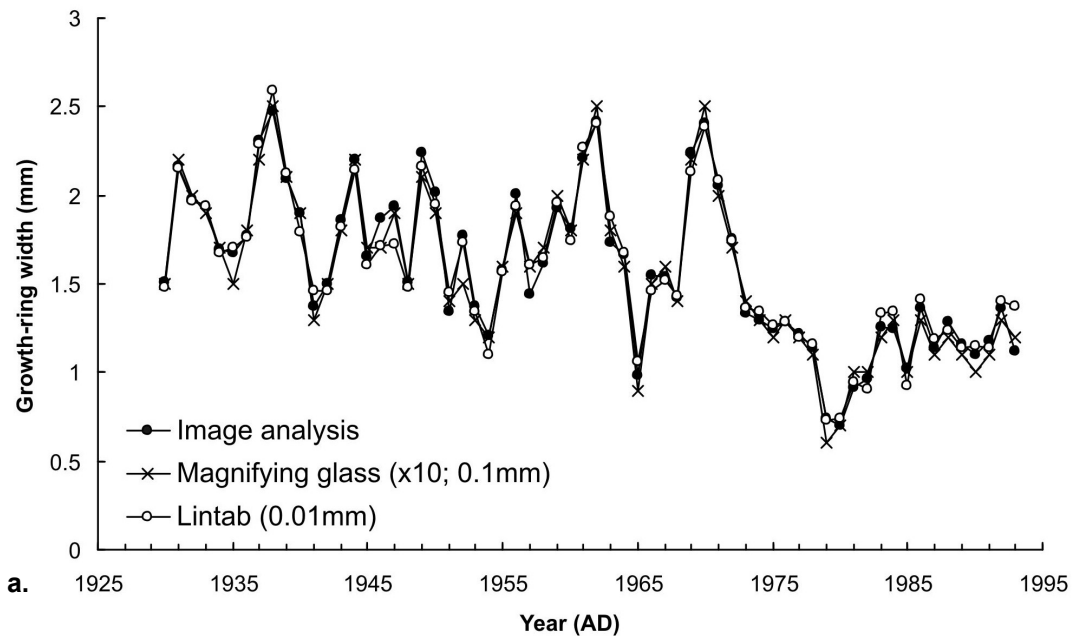
High-quality measurements require a dynamical combination of high and low resolution observations, especially for oak. This means that it is necessary to observe the growth rings under different magnification to verify the exact location of the growth-ring boundaries.

The simplest way to measure growth-rings widths is based on the use of a magnifying glass that encloses a scale bar. This technique is often applied on panel painting and sculptures in museums worldwide. The precision of the measurements depends on the scale bar in the magnifying glass, and is usually restricted to 0.1 mm. Recording the lateral displacement of a measuring stage, by use of a personal computer, is currently the most popular method to measure ring-width series. The growth rings are observed with a stereomicroscope with cross hairs in one of the eyepiece reticules. Currently measuring stages with a precision of 0.01 mm and 0.001 mm are widely available (TA Measuring System/Velmex, Lintab/RinnTech<sup>®</sup>, TimeTable/Scienc, ...).

Over the last decade, software has been developed that allows a fast quantification of wood anatomical features (García González and Eckstein 2003; Vansteenkiste 2002). Analysis of ring widths can now be performed on scans of X-ray film of exposed slices of wood (Guilley *et al.* 2002). With such systems it is possible to measure the actual ring width over a wide tangential range. Contrary, measurements with a binocular and measuring stage only records the ring width over one particular radial line. However, the analysis of 7 cross-sections containing approximately 60 growth rings demonstrates that an excellent average correlation ( $r^2$ ) of 0.990 (min 0.983; max 0.995) is found between the measurements performed with a Lintab stage and the image analyses (Haneca, *unpublished data*). These high correlation values slightly drop down to 0.977 (min 0.956; max 0.988) when comparing the measurements of the image analysis with the measuring glass (Figure 2.4a).

Interpretation of the earlywood/latewood transition in oak specimens is not essential in the measuring process of total ring widths. It becomes a tentative task for the dendrochronologist when separate time series of earlywood width and latewood width are needed. The image analysis system, stated above, identifies this boundary

following the large earlywood vessels. With a measuring stage and stereomicroscope a straight line approximates this boundary, and is often aligned according to the *outermost* earlywood vessels. This explains why the average correlation between the earlywood-width measurements is only 0.820, with a minimum of 0.704, when comparing the image analysis system with the measuring stage (Figure 2.4b).



**Figure 2.4:** Example of **-a** ring-width and **-b** earlywood measurements on an oak specimen (**-c**), executed with a Lintab measuring stage (Rinn 2003) and stereomicroscope (0.01mm), a magnifying glass (x10; 0.1mm) and image analysis (Vansteenkiste 2002) on scanned X-ray film (Haneca, unpublished data).

### 2.4.3 Crossdating

The procedure of matching variations in ring width or other ring characteristics over several tree-ring series, allowing the identification of the exact year in which each tree ring was formed, is called *crossdating*. It is the most essential procedure in dendrochronological research (Douglass 1941). Crossdating is not a black-box system since tree-ring series never are 100% identical. This inherent variability is a common feature for all biological material. Therefore both visual comparisons as statistical correlation analysis should be considered. Within a statistical analysis two series are shifted along each other, with one-year intervals, and a correlation value is calculated at each position. The highest value is supposed to deliver the correct position for undated series along a time axis.

The statistic that comes close to the definition of crossdating is the *Gleichläufigkeitskoeffizient (GLK)*, also referred to as the *percentage of parallel variation* (Eckstein and Bauch 1969). Prior to the calculation of the *GLK* a value of +1/2 is attributed to each year with an increasing ring-width value relative to the former year, -1/2 for a decreasing value and 0 for an invariable value, and this at each position  $i$  for both series  $x$  and  $y$  ( $G_{ix}$  and  $G_{iy}$ ). The *GLK* then reflects the percentage of simultaneous increases or decreases in ring width, relative to the former ring, for all overlapping positions ( $n$ ) between the two series.

$$GLK = \frac{1}{n-1} \sum_{i=1}^{n-1} |G_{ix} + G_{iy}| \quad (2.2)$$

with  $G_{ix}$  and  $G_{iy} = +1/2, -1/2$  or  $0$

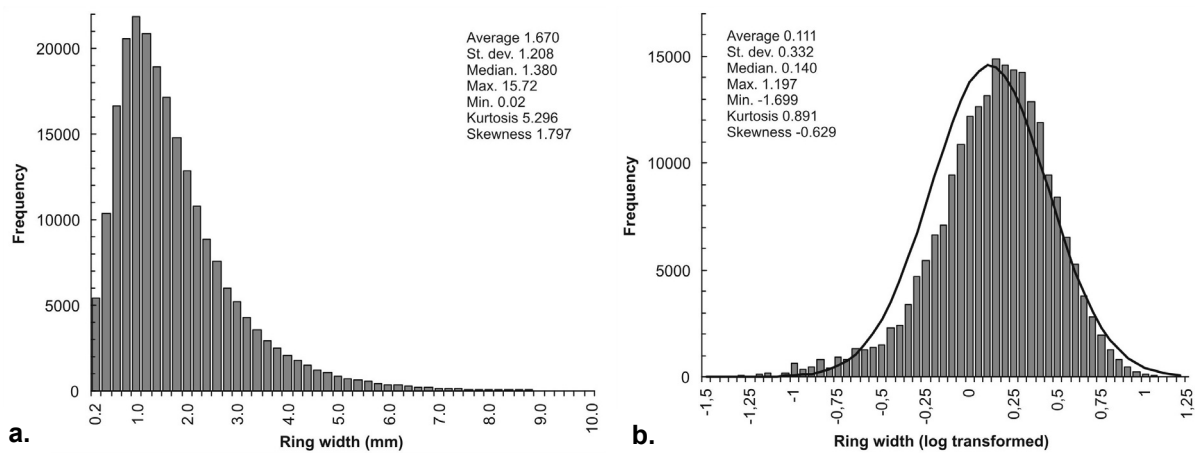
When a random set of growth-ring series are compared a *GLK* of 50 will be observed. Threshold values for the *GLK* can be calculated according to the required level of statistical significance - assuming that the *GLK* values for a comparison of two series follow a normal distribution - with the formula:

$$GLK \geq 50 + \frac{\delta}{\sqrt{n}} \quad (2.3)$$

where  $\delta = 1.645$  for  $p = 0.05$ ;  $\delta = 2.326$  for  $p = 0.01$  and  $\delta = 3.09$  for  $p = 0.001$ .

Another type of statistical comparison was introduced by Baillie and Pilcher (1973) and Hollstein (1980). Both aimed to provide a parametric test statistic based on the

Pearson correlation coefficient  $r$ . Since the correlation coefficient tends to follow a  $t$ -distribution with  $n-2$  degrees of freedom it becomes possible to test the hypothesis  $H_0$ , *there is significant linear correlation*, between two series. In order to test this hypothesis it is necessary that the initial data follow a normal distribution. This requires that any trend is removed. By calculating the distribution and descriptive statistics of ring-width series from European oaks, submitted to the ITRDB, it can be seen that ring-width measurements are significantly skewed to the right (Figure 2.5a). Therefore a logarithmic transformation is essential to obtain a normal distribution (Figure 2.5b) before calculating the test statistic.



**Figure 2.5:** Distribution of ring-width measurements from European oak of tree-ring series submitted to the ITRDB, **-a** before and **-b** after logarithmic transformation (N= 224.628).

For the Baillie and Pilcher (1973) procedure each ring width  $y_i$  is converted to the percentage of the five-year running mean ( $y_{i,BP}$ ), with  $y_i$  as the centre value in order to remove any trend from the data. The natural logarithm is then calculated to obtain normalization.

$$y_{i,BP} = \ln\left(\frac{5 \times y_i}{y_{i-2} + y_{i-1} + y_i + y_{i+1} + y_{i+2}}\right) \quad (2.4)$$

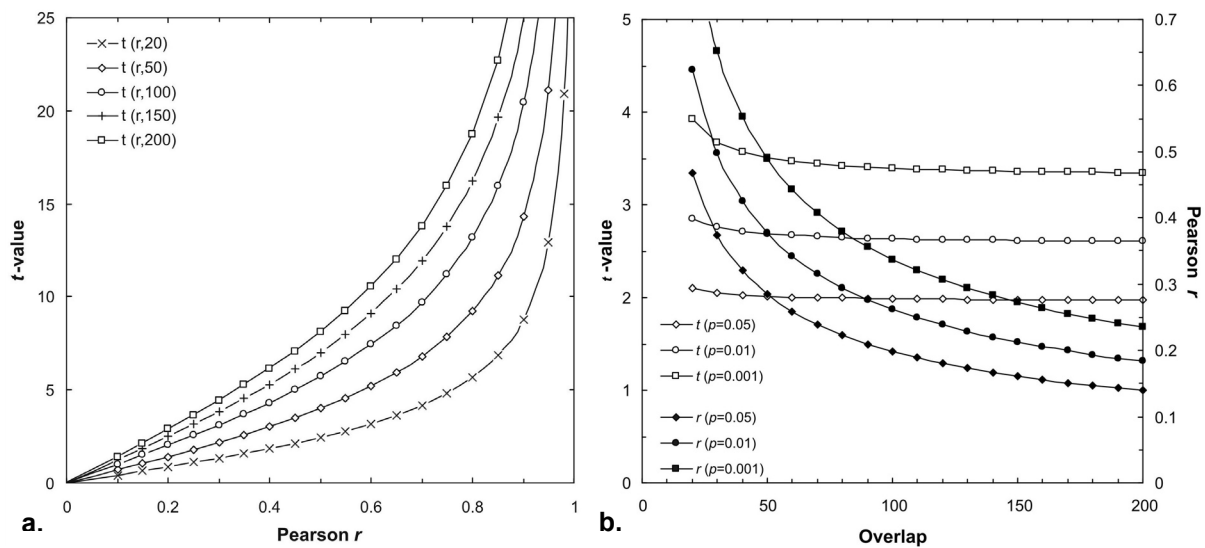
For the Hollstein (1980) procedure, the initial data are normalized by a logarithmic transformation after division of each ring-width value by its following value (= *Wuchswert*).

$$y_{i,H} = \log\left(\frac{y_i}{y_{i+1}}\right) \quad (2.5)$$

After the appropriate transformation, a  $t$ -value is calculated following

$$t_{H/BP} = r \frac{\sqrt{n-2}}{\sqrt{1-r^2}} \quad (2.6)$$

In theory, the probability of obtaining a  $t$ -value of 3.5 by chance (statistical type II error) is approximately less than one in a thousand, depending on the overlap (see Figure 2.6). This value of 3.5 for the  $t$ -statistic has proven, in actual practice, to be too low to guarantee a correct synchronisation. Repeatedly, more than one position along a reference chronology yields a  $t$ -value higher than 3.5 by which this value remains inconclusive. Therefore statistical correlation measures for crossdating tree-ring series always need visual confirmation.



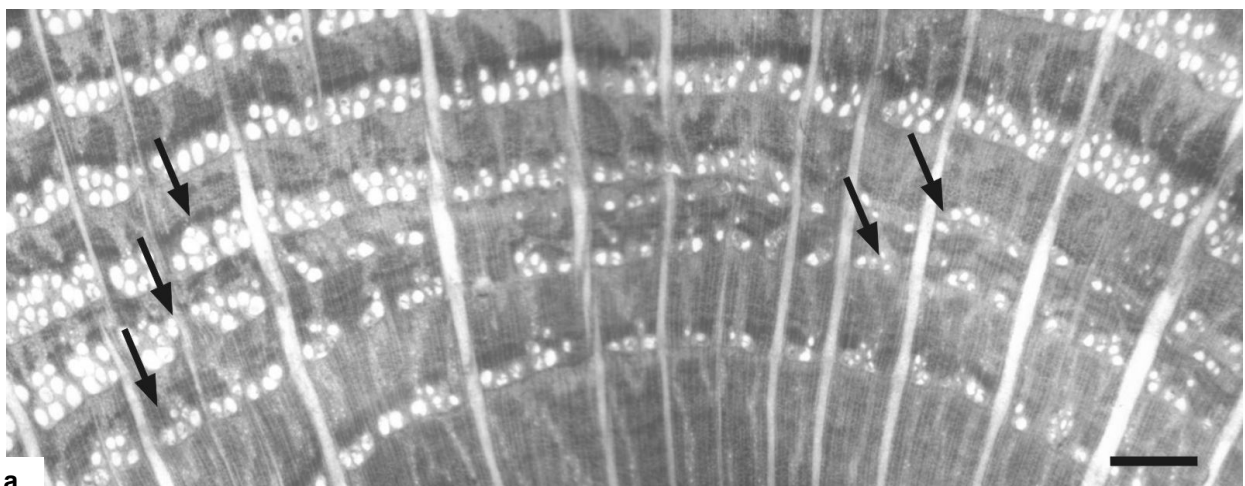
**Figure 2.6:** -a The relation between Pearson  $r$  and  $t$ -values (Baillie and Pilcher 1973) according to the overlap (i.e. number of tree rings) of two series, and -b the critical values of  $r$  and  $t$  at different uncertainty levels.

Visual comparison and verification of undated series with master chronologies has traditionally been done by superimposing printed graphs over a light box. The graphs are then shifted by one-year intervals manually. Over the last few years this procedure has been implemented as an on-screen tool in most dendrochronological software packages (Aniol 1983; Knibbe 2004; Rinn 2003).

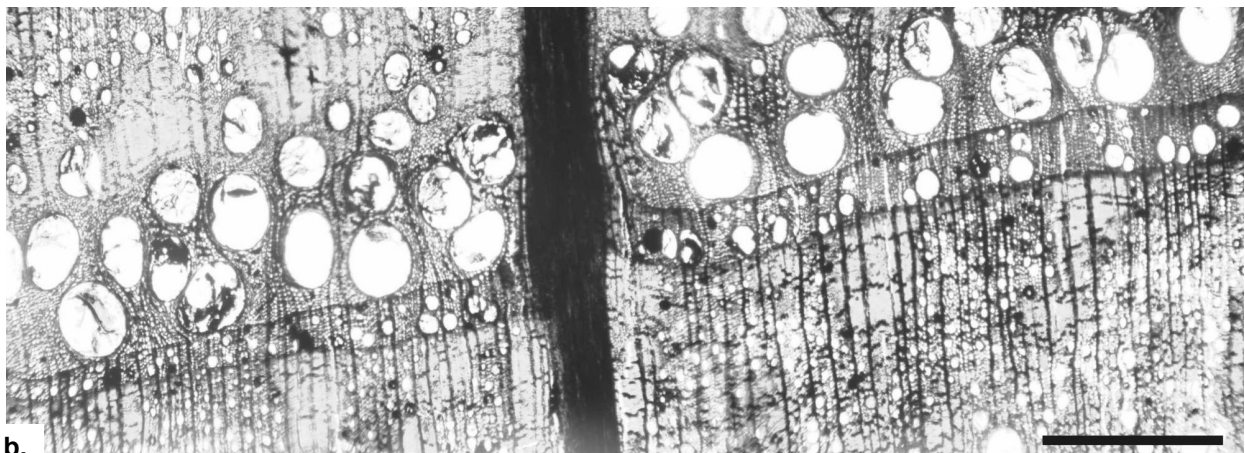
Well-known growth-ring anomalies that are able to disrupt the crossdating process are the presence of missing, wedging or false rings. A missing ring is defined as a tree ring which is absent, due to failure of cambial activity, over the whole circumference of a stem disc. When a tree ring is simply discontinuous over a cross-section, it is described as a wedging or discontinuous ring (e.g. Trouet *et al.* 2001).

An additional, apparently complete growth zone with well-marked boundaries, formed within one growing season is known as a false ring. The described anomalies in the growth pattern can only be identified by crossdating (Kaennel and Schweingruber 1995).

Such features are more frequently observed in coniferous species than in broadleaved deciduous species from temperate regions. False annual rings or intra-annual rings can be found in the Mediterranean region for e.g. *Q. ilex* (Cherubini *et al.* 2003; Zhang and Romane 1991). The occurrence of missing rings or discontinuous rings have not been reported in literature for *Q. robur* or *Q. petraea*, but the possibility has never been excluded. In Figure 2.7a a discontinuous ring for *Q. robur* can be observed. This phenomenon is easily recognized on a cross-section, but as is often the case for decayed archaeological wood, not so easily identified when only a small transverse section is available.



a.



b.

**Figure 2.7:** 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.

#### 2.4.4 Exact dating and sapwood estimates

By shifting an undated ring-width series along an absolutely dated chronology allows to calculate crossdating statistics for each overlapping year. The position at which the crossdating statistics are the highest identifies the best match position. When at that position, the synchronicity between the ring-width series and the chronology is supported by sufficiently high correlation values and confirmed by a visual inspection, then each ring-width measurement can be attributed to the corresponding calendar year of the chronology. This reveals the time span in which the tree had been growing.

However, the accuracy of dating historical wood specimens highly depends on the completeness of the sapwood. When the bark or the last sapwood ring is preserved the growing season in which the tree was felled can be determined. In case of a ring-porous species, like *Q. robur*, *Q. petraea* and *Q. pubescens*, even the season in which the tree was felled can be specified. When only part of the sapwood is preserved it is possible to estimate the initial amount of sapwood rings that were removed or lost. When no sapwood is preserved, it is only possible to provide a *terminus post quem*, i.e. a date after which a tree must have been felled.

When the number of missing sapwood rings are estimated, the distribution on the number of sapwood rings for the specified species needs to be considered. For oak the distribution of the number of sapwood rings is highly variable. Nevertheless, based on large datasets it becomes possible to assess with confidence the approximate number of sapwood rings that can be expected on a piece of oak timber. Considering the number of sapwood rings from a large number of trees, the distribution is usually skewed to the right (Hillam *et al.* 1987; Kelly *et al.* 1989). A logarithmic transformation of the data is then most appropriate to obtain normalization. Starting from these normalised data it is possible to calculate the average number with its confidence limits:

$$\bar{x} \pm t \sqrt{s^2 \left( \frac{1}{n} + 1 \right)} \quad (2.7)$$

with:  $\bar{x}$  the average number of sapwood rings,  $s^2$  the variance,  $n$  the number of measurements and  $t$  the appropriate Student's  $t$  value.



Retransformed this yields an average number of sapwood rings with confidence limits at a well-defined uncertainty level (if  $n > 120$ ;  $t = 1.96$  for  $p = 0.05$ ,  $t = 2.58$  for  $p = 0.01$ , etc.). Applied to dated tree-ring series with incomplete sapwood it becomes possible for the dendrochronologist to provide a range of estimated felling dates (Hughes *et al.* 1981).

Over the last decades, many papers have been published that provide sapwood estimates for certain regions. Hollstein (1965) was one of the first to examine a large dataset of tree-ring data of oak specimens with regard to the number of sapwood rings. He divided his dataset arbitrarily into age classes and calculated the average number of sapwood rings for each age class of 100 years wide. Age and average growth of a tree are often considered as important variables related to the observed number of sapwood rings. Nevertheless, models that attempt to describe the relationship between the age of the tree or the average ring width and number of sapwood rings have usually a low predictive value (ca. 10%) (Hillam *et al.* 1987; Hughes *et al.* 1981).

Table 2.4 provides an overview of published sapwood statistics for different regions in Europe. From these data a geographical trend can be distinguished. The average number of sapwood rings tends to decrease from the British Isles (23.70 – 32.40) towards the Baltic States (12.76 – 18.20). The physiological basis of this trend is not clear yet. Notwithstanding this list of sapwood statistics it should be noted that the 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 compared to a cross section from the lower bole at 0.5 m (Hughes *et al.* 1981). And also around the circumference the number of sapwood rings is not a constant value.

#### **2.4.5 Dendro-provenancing**

Trees experiencing the same growing conditions are expected to develop similar ring-width series. This is one of the basic principles of dendrochronology. Distant geographical locations and different site conditions produce different ring patterns. This supports the assumption that a certain tree-ring profile contains information on the location where the tree was growing. Although mainly driven by differences in

climate, also local hydrology and pedology influence the average growth pattern of a certain region. Comparison of individual tree-ring series with chronologies that reflect the average growing conditions for specific regions allows to source the origin of the

**Table 2.4:** Sapwood estimates for different regions in Europe (n.s. = not specified).

|   | Tree age-<br>class | Average no. of<br>sapwood rings | Standard<br>deviation | Median | Range<br>(min-max) | 95% conf.<br>interval | Sample<br>depth |
|---|--------------------|---------------------------------|-----------------------|--------|--------------------|-----------------------|-----------------|
| <b>Germany</b> (Hollstein 1965 and 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             |
| -----   |                    |                                 |                       |        |                    |                       |                 |
| <b>NW England and Wales</b> (Hughes <i>et al.</i> 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             |
| <b>British Isles</b> (Hillam <i>et al.</i> 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              |
| <b>England and Wales</b> (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             |
| <b>Ireland</b> (Baillie 1982)                           |                    |                                 |                       |        |                    |                       |                 |
|   | n.s.               | 31.32                           | 8.99                  | -      | 14 - 62            | 16.74 - 53.93         | 65              |
| -----   |                    |                                 |                       |        |                    |                       |                 |
| <b>Northern France</b> (Pilcher 1987)                   |                    |                                 |                       |        |                    |                       |                 |
|   | n.s.               | 26.58                           | 7.04                  | -      | 12 - 49            | 15.25 - 43.26         | 118             |
| -----   |                    |                                 |                       |        |                    |                       |                 |
| <b>Western Sweden</b> (Brathen 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              |
| -----   |                    |                                 |                       |        |                    |                       |                 |
| <b>Poland</b> (Wazny 1990b)                             |                    |                                 |                       |        |                    |                       |                 |
|   | <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             |
| -----   |                    |                                 |                       |        |                    |                       |                 |
| <b>Finland</b> (Briffa <i>unpublished</i> )             |                    |                                 |                       |        |                    |                       |                 |
|   | n.s.               | 13.85                           | 3.19                  | -      | 7 - 24             | 8.32 - 21.80          | 60              |
| -----   |                    |                                 |                       |        |                    |                       |                 |
| <b>Belgium</b> (Haneca <i>unpublished</i> )             |                    |                                 |                       |        |                    |                       |                 |
|   | <100               | 17.56                           | 5.98                  | 18     | 5 - 36             | -                     | 181             |
|   | >100               | 25.28                           | 7.73                  | 24     | 12 - 47            | -                     | 72              |

\* 90% interval instead of 95% confidence interval

\*\* Wales and border counties

timber. It is assumed that the highest similarity in tree-ring pattern will be observed when the individual tree-ring series is compared to the reference chronology that covers or approaches the region where the tree was cut. The similarity is usually expressed in one of the commonly used correlation measures used in crossdating ( $t$ -values,  $GLK$ ,  $r^2$ , ...). In order to take full advantage of this technique an extensive network of reference chronologies is a prerequisite.

Notwithstanding the limited number of reference chronologies that were available for European oak in the 1960's and 70's some successful papers on dendroprovenancing were reported. It was first applied on tree-ring series from a Hanseatic Cog ship, excavated in the Bremen harbour and dated by dendrochronology to 1378/79 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 as the original timber source. Similar observations were made during the examination of wine barrels from an archaeological excavation in Dorestad (the Netherlands), where 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.* 1975). This demonstrated the impact of the timber trade on dendrochronological dating, as was discussed later repeatedly, especially with regard to Baltic timber (Bonde 1992; Bonde *et al.* 1997; Haneca *et al.* 2005c; Wazny 1990a and 2002; Wazny and Eckstein 1987).

When tree-ring dating was first applied on art-historical objects, such as sculptures and panel paintings made of oak, dendrochronologists were confronted with oak timber characterized by a uniform growth and small growth-ring widths. At first, the atypical growth-ring patterns could not be absolutely dated since no significant correlation was found with the available master chronologies at that time. Nevertheless they correlated very well with each other what 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.* 1975). Both 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.* 1975) or from selected trees of forest sites within England where the oak trees grew under stressful conditions (Fletcher 1977). Such stressful conditions were expected due to the narrow character of the oak rings, especially 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, Northern Poland (Eckstein *et al.* 1986). It clearly demonstrated the Baltic origin of the timber that was used for the construction of panels for artists working between the fourteenth up to the middle of the seventeenth centuries. This was further confirmed by documents from historical archives (Wazny and Eckstein 1987).

Over the last few years this topic has gained renewed interest. The intensive work and collaboration of various dendrochronologists has resulted in a long list of regional reference chronologies, especially for oak, which constitute a geographical network that allows the identification of the original timber source. This is of particular interest when non-static objects as ships (Bonde 1997), barrels (Houbrechts and Pieters 1996), furniture, panel paintings and altarpieces (Haneca *et al.* 2005a) are the subject of a dendrochronological study. Such examples of dendro-provenancing can help to document the historical timber trade (Wazny 2005; Wazny and Eckstein 1987) and even allow to specify when certain forested areas were exploited (Haneca *et al.* 2005c).

## **2.5 Climatic signals in ring-width series of oak**

In historical studies dendrochronology is predominantly applied as a dating tool for tree-ring series, recorded on wooden artefacts. Nevertheless, tree-ring series are able to provide more information than purely a felling date. Since changes in a tree's environment are recorded in its tree-ring pattern, it becomes possible to use such series as proxies for climatological variables. The main problem for climatological reconstructions is that oak trees growing under temperate conditions in Europe do not respond to one single climatic factor. This contrasts the tree-ring series from southwest USA where trees display a clear response to moisture availability. In Europe on the other hand there is a complex response of oaks from temperate forests to the environmental conditions. Nevertheless simultaneous depressions and

rises in ring width of extensive tree-ring datasets reveal that trees recorded related, large-scale climatic events in their growth pattern and anatomical structure.

### 2.5.1 Climate reconstructions

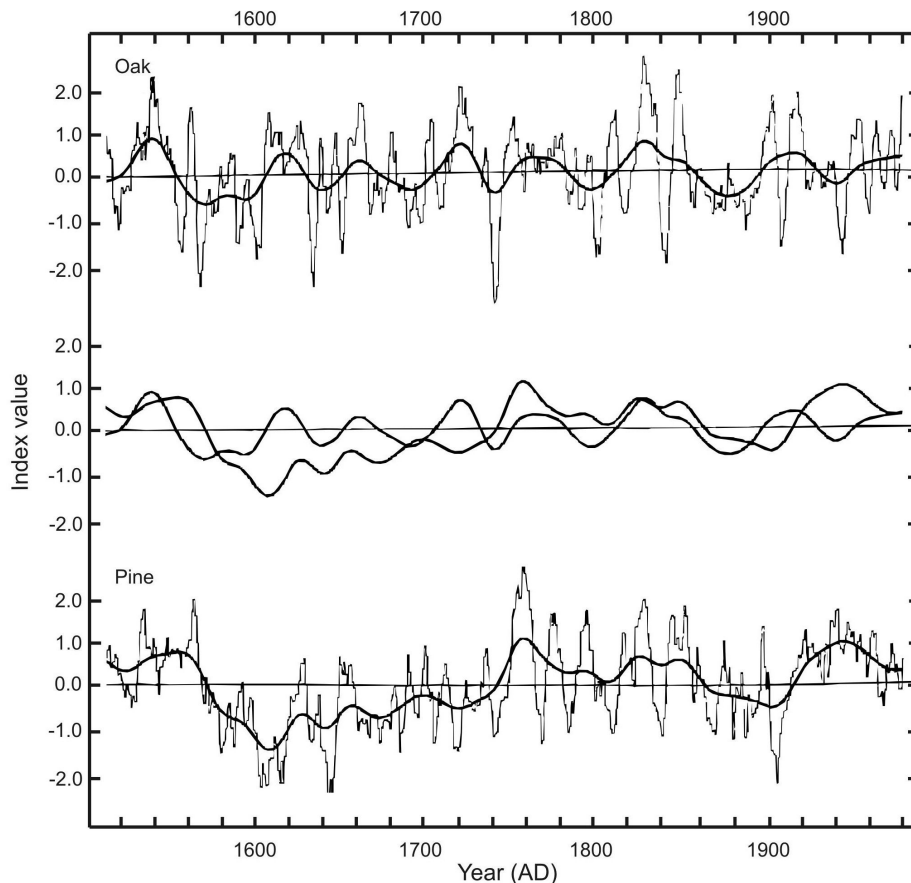
In Europe, the longest instrumental climatological records go back 200 to 250 years. The best known series is the Central England temperature record which starts in 1772 (Parker *et al.* 1992). However, the longest temperature archive was recorded in Uppsala (Sweden) from 1722 on. In order to retrieve more information on past weather conditions beyond the instrumental records, proxy datasets are used to derive, for example, past temperature and precipitation-levels. Tree-ring series have proven to be reliable, long and well-replicated proxies for climate reconstructions. Ring-width or ring-density records from conifers (*Picea* spp., *Pinus* spp., *Larix* spp., *Abies* spp.) have been used repeatedly for temperature reconstructions (see Martinelli (2004) for an overview). European oaks on the other hand do not display a high potential for climate reconstruction. There is no linear and highly significant relation between a climate factor, as precipitation or temperature, and the ring widths.

Comparison of long ring-width series of oak with a summer-temperature reconstruction for Fennoscandinavia from pines (Briffa *et al.* 1992) reveals some degree of parallelism (Figure 2.8). Nevertheless, often opposite trends are observed as well, e.g. in the early 1600s, the early 1700s and around 1900 (Briffa *et al.* 1999).

### 2.5.2 Large-scale climate anomalies

Abrupt changes in environmental conditions on a large-scale are sometimes related to a catastrophic event, e.g. a volcanic eruption. A volcanic eruption blows a huge amount of ash into the atmosphere, blurring the incoming solar radiation. Emission of sulphuric acid (SO<sub>2</sub>-gas) into the stratosphere triggers the formation of sulphuric acid particles which reflect the sun rays and further reduce the amount of radiation reaching the earth's surface. Such a catastrophic event can influence weather conditions worldwide and limit the photosynthetic potential. The eruptions of the Pinatubo (1991) and the Tambora volcano in Indonesia (1815), the latter being the most severe, are two examples of well documented volcanic events. The Pinatubo eruption reduced the temperature in the Northern hemisphere by 0.5 to 0.6°C in the following two years. The year following the massive eruption of the Tambora volcano

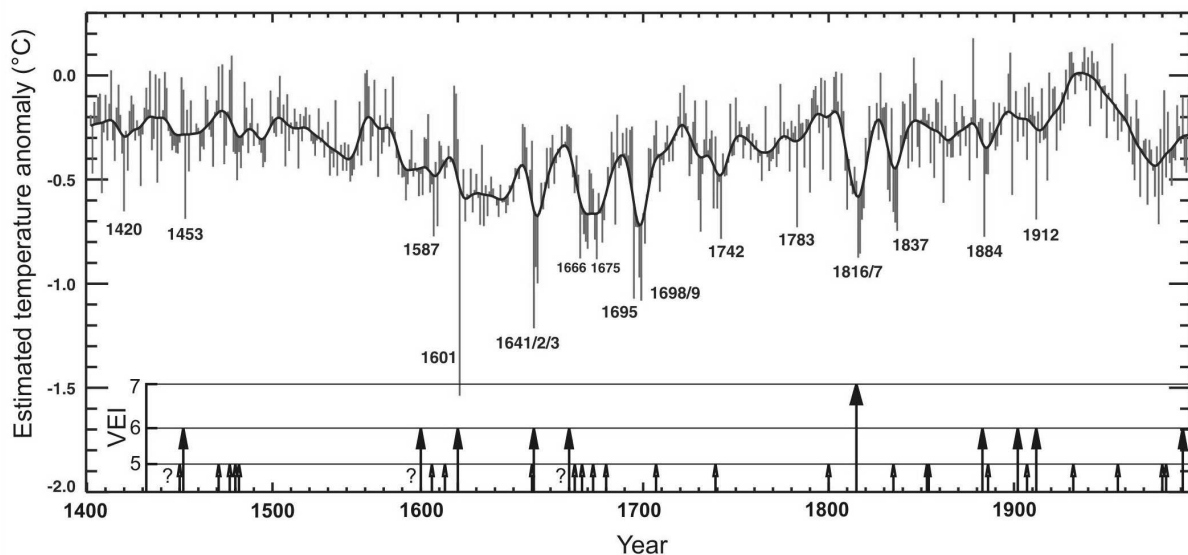
is known as the *year without a summer*. Late frost events and wet summer conditions during 1816 resulted in low crop yields followed by food shortage and famine in Europe. This event can be clearly identified in temperature reconstruction from tree-ring density series (Briffa 2000; Briffa *et al.* 1998 and 2004) (Figure 2.9). However absolutely dated ring series of European oak do not display a dramatic decrease in ring width in the years following the above stated volcanic events.



**Figure 2.8:** Comparison of a temperature reconstruction (deviations from the 1901-1950 mean), based on ring-density series of Fenno-scandinavian conifers (lower curves), with the reconstruction from a ring-width chronology of oak, covering approximately the same region (upper curves).

Nevertheless, Baillie (1995) repeatedly demonstrated a simultaneous, pan-European response of oak to severe volcanic eruptions before the two events mentioned above. These assumptions were confirmed by close comparison with concentrations of sulphuric acid in long ice-cores from Greenland, the occurrence of frost rings in the Bristlecone pines (LaMarche and Hirschboeck 1984) and simultaneous clusters of narrow tree rings in the German and English oak ring records. Such catastrophic events were identified for 1628 BC (eruption of the Santorini volcano, now the

southernmost island of the Cyclades, Greece), 1159 BC (probably the eruption of the Icelandic volcano Hekla) and 207 BC. Tree-ring series of oak also exhibit highly similar characteristics in their ring-width patterns around 540 AD (536 - 545 AD), as well in the Irish bog-oak records as in German chronologies (Hollstein 1980). However, no acidic layer is found in one of the available long ice cores. So here there is no hard proof that a volcanic eruption has caused this obvious and simultaneous depression in the tree-ring records (Baillie 1994). The stable carbon isotope profile of archaeological oak specimens, that grew around 540 AD, display a pronounced decrease in  $\delta^{13}\text{C}$  of ca. 1.5 per mil over three years, down to  $-24.71$   $\delta^{13}\text{C}$  in the 542 AD tree-ring. This pattern corresponds to the  $\delta^{13}\text{C}$  profile of trees that grew during the eruption of the Tambora volcano in 1815 AD. These data strongly suggest that around 540 AD some major environmental change took place, whether or not related to volcanism (Loader *et al.* 1999).



**Figure 2.9:** This figure is reprinted from Briffa *et al.* 2004. It provides estimates of warm-season temperature ( $^{\circ}\text{C}$ ) anomalies from the 1961– 1990 mean for land areas north of  $20^{\circ}\text{N}$ , based on tree-ring density data. The smoothed curve is the 25-year low-pass filtered reconstruction produced using the Age-Band Decomposition approach of Briffa *et al.* (2001). The Volcanic Explosivity Index (VEI) is indicated by the arrows at the bottom; ‘?’ marks those eruptions from which the date is uncertain.

This demonstrates that tree-ring analysis on absolutely dated series is able to date catastrophic events with high impact on human populations and the global environment to the year. Comparison with archaeological evidence and historical records helps to interpret and estimate the impact of such events on a society (Baillie 1995).

### 2.5.3 Event and pointer years

A pointer year is defined as a concentration of crossdated event years within a group of crossdated tree-ring series. An event year is described as a year with a conspicuous feature as a missing ring, presence of reaction wood or a traumatic zone (Kaennel and Schweingruber 1995; Schweingruber *et al.* 1990). Such an event year is supposed to echo extreme ecological events and to reflect the tree's reaction on short or long term influences of various kinds (e.g. drought, frost, insect defoliation, etc.). The first year of an abrupt change in growth rate is also considered to be an event year. Usually this is recognized by the occurrence of extreme small or wide growth rings compared to the radial growth in the preceding years. In practice a pointer year is often identified by an analogous increase or decrease in ring width for a certain threshold percentage in a crossdated group of tree-ring series.

Synchronous event years can be observed at different levels of spatial resolution. Sometimes event years only occur on a regional scale or even stand level (e.g. insect outbreak). On the other hand, large-scale climatological events can induce positive or negative event years in a large number of trees on a pan-European scale. Today an extended list of pointer years covering the complete AD section of the time axis is available. Figure 2.10 lists the pan-European pointer years for the last 2000 years. Here a pointer year is recognised when at least 75% of all tree-ring series display a similar increase or decrease to the previous year (Kelly *et al.* 2002). The dataset used for this analysis consists of tree-ring data from the British Isles, Norway, Sweden, Estonia, Denmark, Poland, Germany and the Netherlands (Kelly *et al.* 2002).

Wood anatomical particularities, such as extreme small earlywood vessels in oak specimens, have proved to be valuable features for crossdating as well. Fletcher (1975) reported the occurrence of abnormally small earlywood vessels recorded on panel paintings with a Baltic origin. This feature is for instance apparent in growth rings that were formed during the second half of the 15<sup>th</sup> century. Especially two years, seventeen years apart are well known to show this feature; 1437 and 1454 AD. In between, 1443 AD, is also a year in which this feature is often recognized. Although the size of the earlywood vessels is considerably reduced, the latewood width was not altered. The historical objects on which these features are observed



are usually made of Baltic timber. The vessels are often 0.06 mm in diameter or less (Baillie 1991), which is approximately 2.5 to 5 times smaller than normal. Although this feature tends to be very rare it has diagnostic properties that can help to support dating results (Figure 2.7b).

The actual cause to the formation of such exceptionally small earlywood vessels is not always clear. Several authors linked this feature with severe winters and cold conditions in spring (Fletcher 1975; Tapper *et al.* 1978). Others rather suggest that a single event, e.g. an extremely cold night or wind chill, could trigger the formation of small vessels (Baillie 1991; Leuschner and Schweingruber 1996). The same type of earlywood vessels have been observed for roadside trees that experienced high concentrations of de-icing salt (Eckstein *et al.* 1976). This probably provoked serious drought stress during the differentiation of the earlywood vessels in March-April. Asshof *et al.* (1999) have observed this phenomenon in the wood formed after a year with heavy defoliation by insects on horsechestnut trees. This also increased the risk on cavitations during the ontogeny of the earlywood vessels, resulting in the formation of smaller vessels.

Drought stress in winter and spring was also associated with the development of small earlywood vessels on a maritime site in the northwest of the Iberian Peninsula (García González and Eckstein 2003). Furthermore, a disturbance in the tree's hormonal fluxes can also lead to reduced earlywood vessels. A high concentration of auxin (Indole Acetic Acid, IAA), which allows a rapid differentiation of the secondary cell wall and thus little time for cell expansion, will lead to vessels with reduced diameters. When young leaves are developing, increasing amounts of free auxin are produced and distributed throughout the plant. This plant hormone influences the axial vascular differentiation by inhibiting the vessel elongation, what results in vessels with small diameters (Aloni 2001 and 2004).

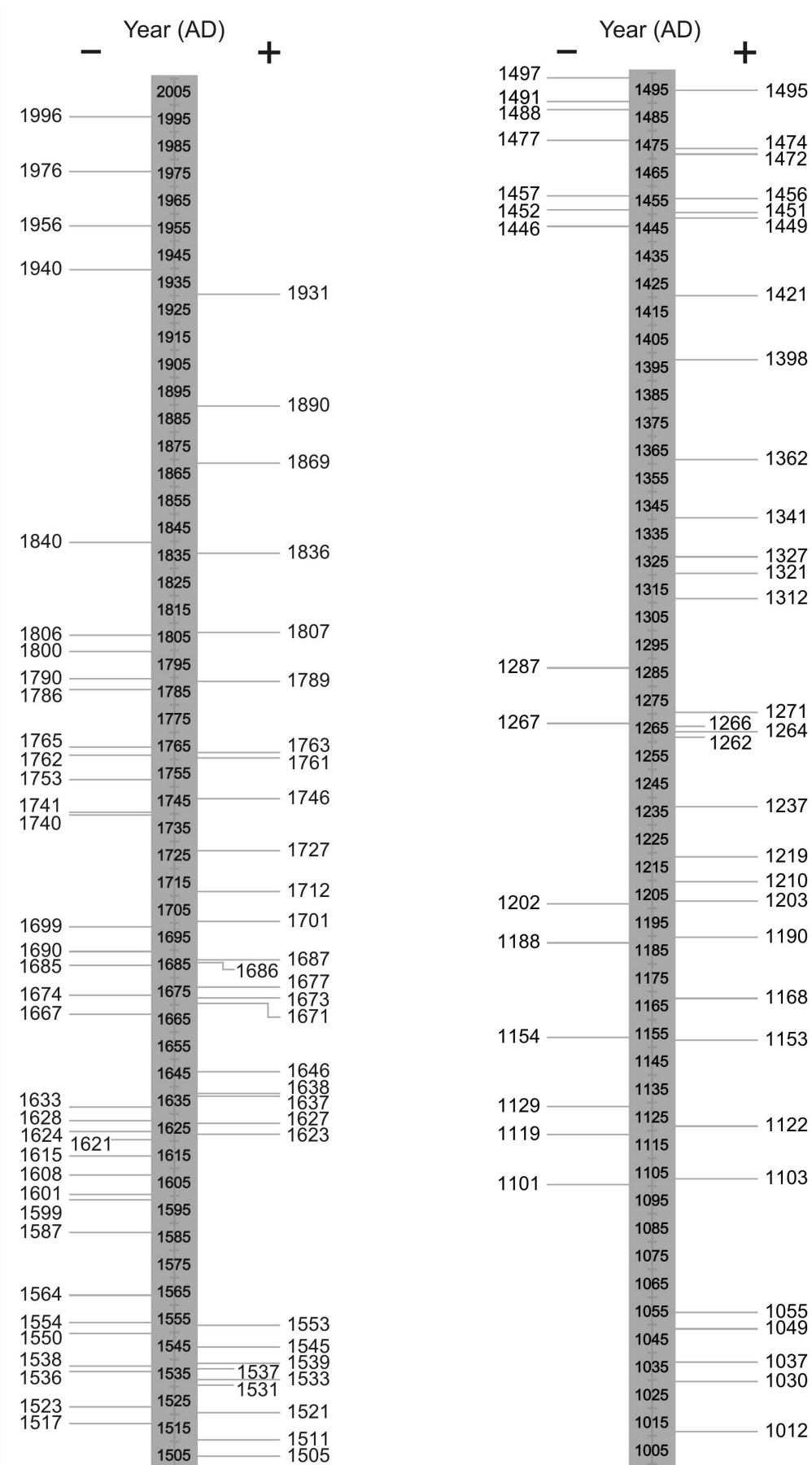


Figure 2.10: Pan-European pointer years for the last two millennia (after Kelly *et al.* 2002).

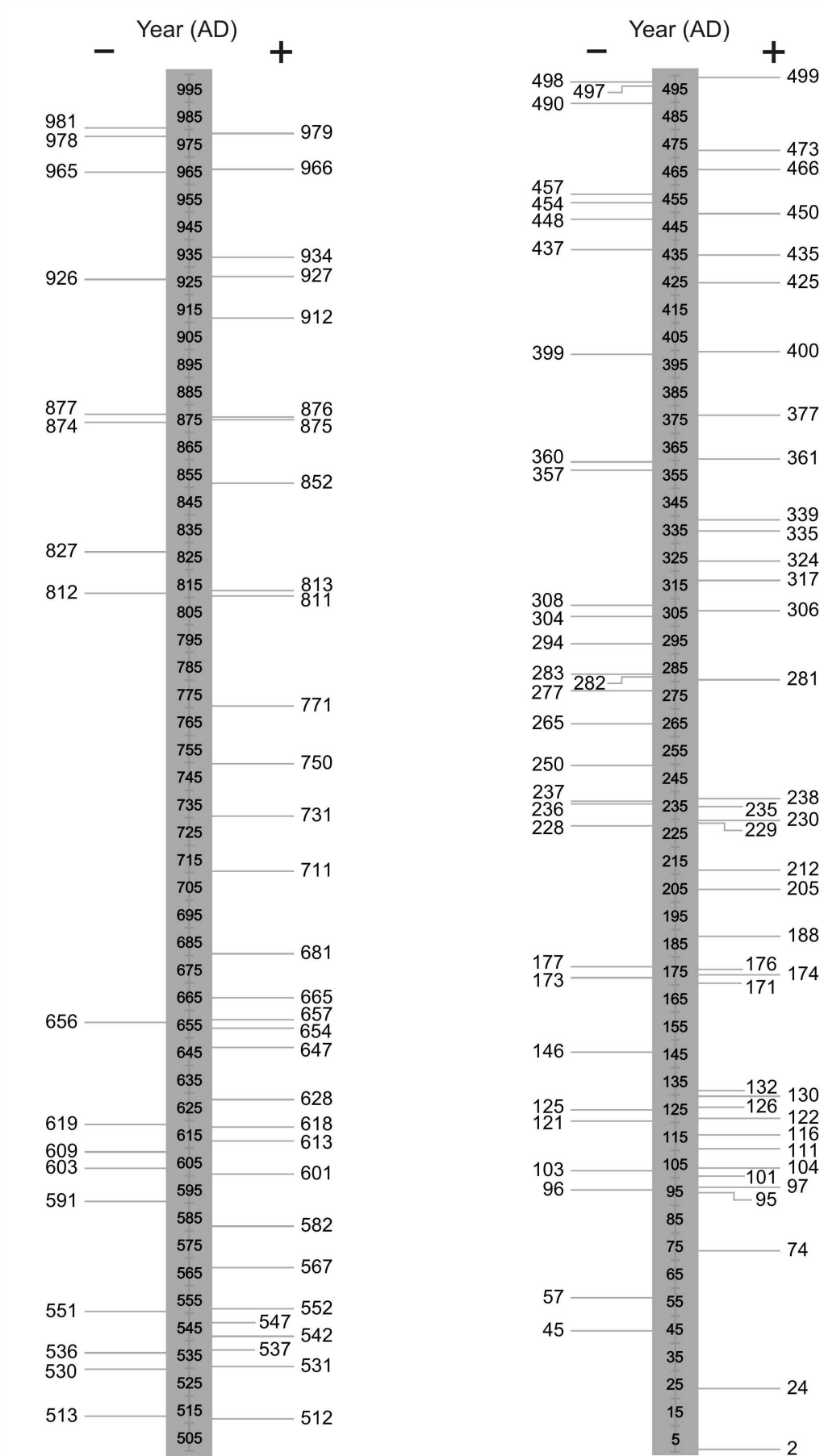


Figure 2.10: (continued)

## 2.6 Applications in historical studies

### 2.6.1 Archaeological and historical sciences

The wooden artefacts of Neolithic settlements are rarely well preserved. The only occasions where wood specimens are found in adequately preserved conditions and in considerable amounts are at abandoned pile dwellings on the shores of lakes. Wooden macro remains are then rapidly covered by sediments and preserved in waterlogged conditions. This allows extensive sampling for tree-ring analysis. Examples of such archaeological sites were found at the Bodensee (Lake Constance) in Germany (Billamboz 1990 and 1996a) or at the Lakes Chalain and Clairvaux in France (Pétrequin 1996; Pétrequin *et al.* 1998). Foundations of the houses are the most prominent wood samples that are suited for further dendrochronological research. Often oak is the most abundant species that was used for construction purposes.

After dendrochronological dating it often becomes possible to distinguish clusters of felling dates. This allows to identify different construction or building phases. In order to identify these construction phases one needs to combine the tree-ring data with the maps drawn from the archaeological excavation or the construction of the building. Wooden remains, arranged in regular geometrical structures often display highly similar felling dates. Reversely, when wooden timbers from one structure, building or construction display completely different felling dates, it even becomes possible to distinguish repairs or adaptations. Bridge and Dobbs (1996) for instance demonstrated a serious repair on the Tudor warship Mary Rose, 27 years after the ships construction.

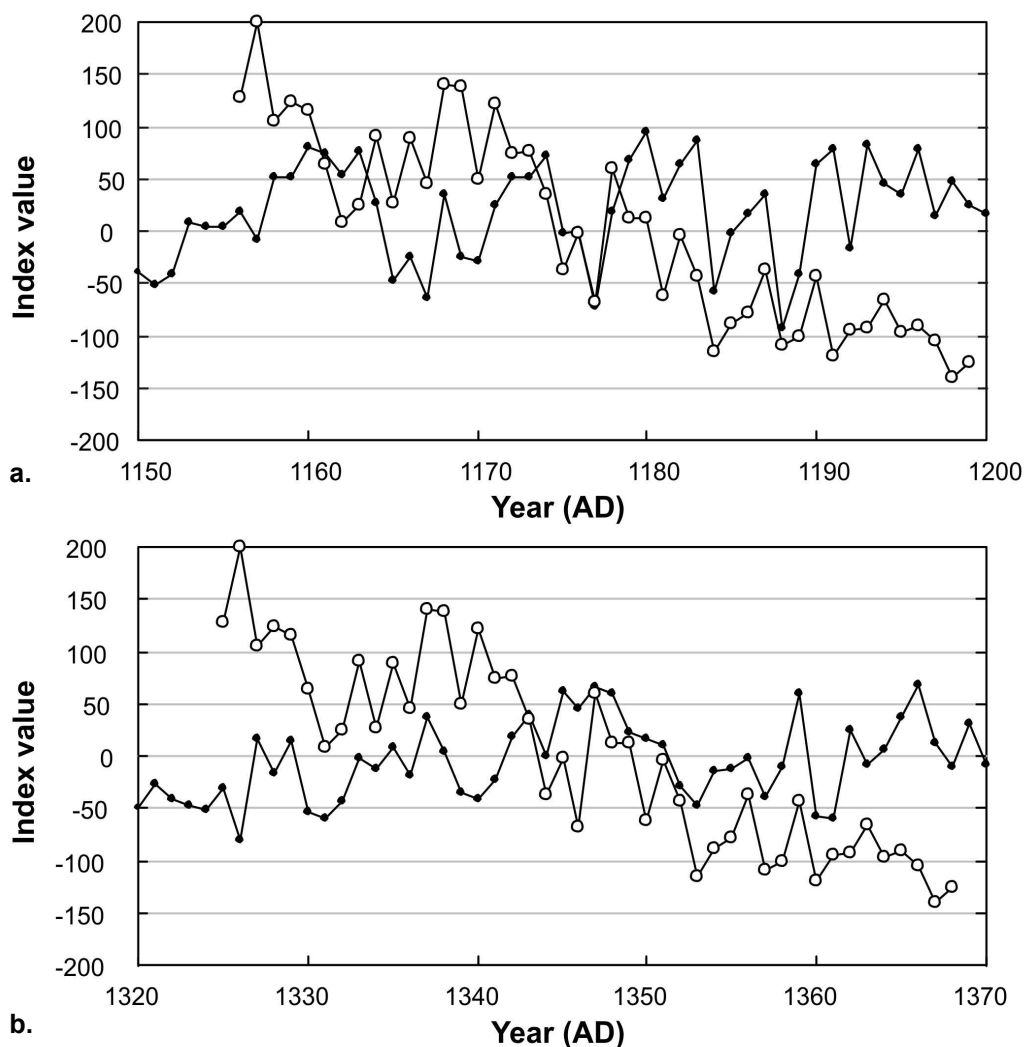
A rapidly rising population often triggered increased forest clearings and a changed attitude towards surrounding woodlands. This often coincides with changes in the choice of the forest products. At the Neolithic settlements around the lakes of Chalain and Clairvaux (France) for instance, young ash trees (*Fraxinus excelsior* L.) from secondary forests, probably resprouted from stumps, were used together with oak for house building when the settlements were small and had few inhabitants. Once the number of inhabitants rose, together with the number of villages around the lakes, almost exclusively large oak poles were used (Pétrequin 1996; Pétrequin *et al.*

1998). This probably indicates that the rising need for agricultural products dramatically increased and induced rapid conversion of the secondary forest to arable land. They suggested that construction timber was then collected in primary forests or old-grown secondary forest, which is also reflected in the increased size of the oak poles. However, a preference for the large oak poles based on the excellent mechanical properties of oak can not be excluded.

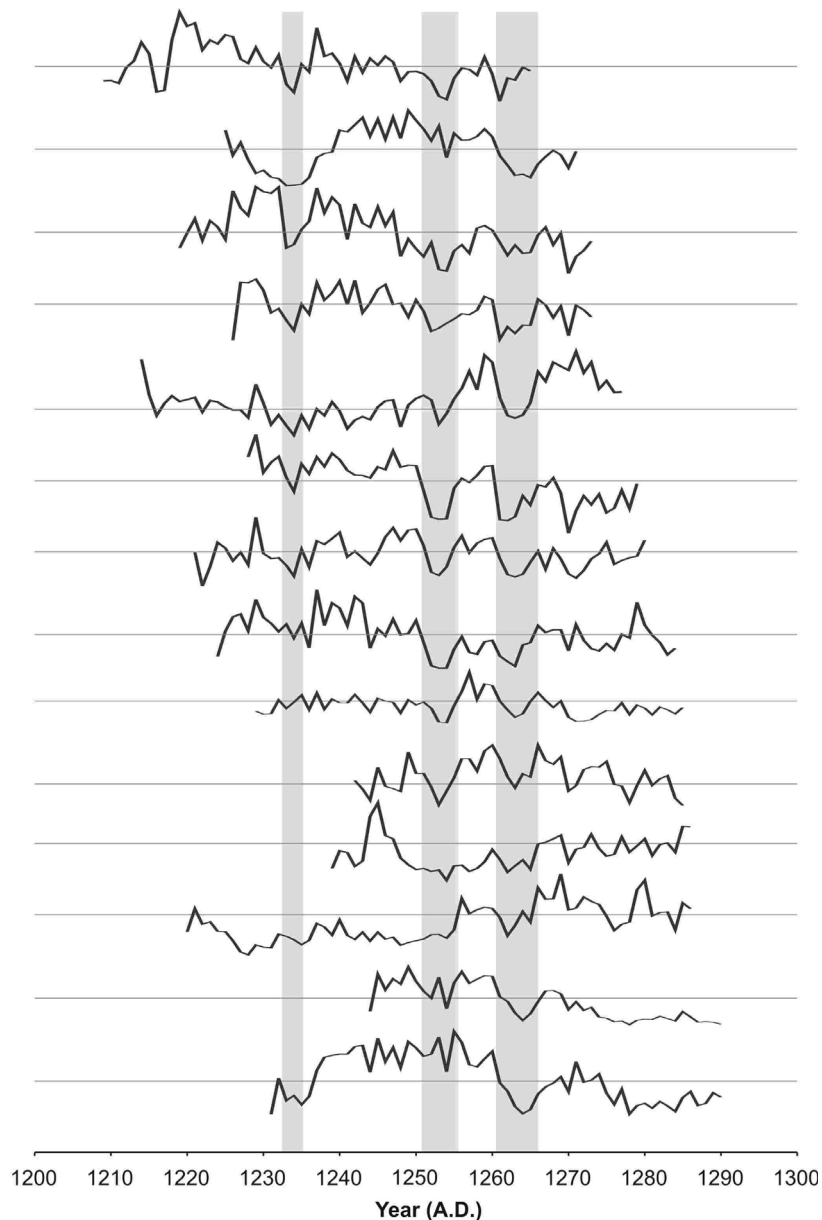
It is clear that such dramatic human impact on forests must have had its consequences on the forest structure. This has been demonstrated repeatedly by the analysis of thousands of tree-ring series from subfossil trees in the vicinity of the Lake Constance (Billamboz 1992, 1996b and 2003). At other locations tree-rings have provided an image of the prevailing forest type and management of the remaining woodland (Haneca *et al.* 2006). 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).

When the demographic pressure rises, selective cutting and harvesting of the available forests and woodland is often replaced by more drastic actions as clear cuttings for conversion to arable land. These interventions in the original vegetation have lead, on the long term, to shortages in timber assortments. One particular silvicultural technique has therefore become very popular during the Roman era and especially during the Middle Ages, i.e. coppice (Bechmann 1990; Rackham 2003; Vera 2000). Resprouting from a stool is considerably faster compared to regeneration from seed. In the short term this yields considerable amounts of small timber. Since coppice became a widely spread technique in forest management, wood from coppiced trees is often found on archaeological sites. Timber from such short rotation systems only yields a limited number of tree rings to be measured. This can hamper further analysis when dating is the main objective. Crossdating becomes very tentative when tree-ring series span only a limited number of years. Such short series, less than 50 to 80 years long, can produce erroneously high correlation measures with a reference chronology. However, on many archaeological sites in Europe a large portion of the wood samples excavated contain less than 50 to 60 rings (Billamboz 1996a; Haneca *et al.* 2006; Hillam and Groves 1996; Hillam *et al.* 1987; Hurni and Orcel 1996; Hurni and Wolf 2001). Excluding such samples from a

dendrochronological analysis could lead to a loss of fine detail (Hillam *et al.* 1987). Nevertheless it is important to realise that tree-ring patterns of less than 50 years might not be unique, and contain a certain element of circularity when compared to a long reference chronology. Different positions along a reference chronology might yield acceptable visual and statistical correlation values (Figure 2.11). This can be encompassed when large numbers of preserved wood are available, allowing extensive sampling for tree-ring measurements. When the recorded, short series match each other as well as a reference chronology, their dating can become reliable, even with relatively low correlation measures (Figure 2.12). Replication within a substantial set of short series from the same site allows to compensate for low correlation with a single reference curve.



**Figure 2.11:** Crossdating of a short (length = 44) ring-width series (sample B566398A) originating from an archaeological excavation near Ypres. It crossdates with a reference chronology from the Meuse valley (Hoffsummer 1995) on two different positions. A first acceptable position was found at 1199 AD ( $t_{BP}$ : 5.2;  $GLK$  69), a second at 1368 AD ( $t_{BP}$ : 4.4;  $GLK$  70). Comparison with other series from the same site revealed that the first position, at 1199 AD is the correct one.



**Figure 2.12:** Short ring-width series from archaeological wood, excavated near the medieval town of Ypres (Haneca *et al.* 2006). The series could be successfully crossdated, despite the low number of tree rings (41 - 67) and low correlation values against reference chronologies. The grey bars highlight the common variance in the dated ring-width series.

### 2.6.2 The study of art-historical objects

For centuries, wood has been one of the preferred raw materials for many artists. Not only wood was used to create objects of art, but it was also used as a functional support. The two most obvious examples of the aforementioned statements are wooden sculptures and panel paintings, respectively. Such objects have been the subject of many wood anatomical and dendro-chronological surveys. Panel paintings have chiefly been produced during the 15<sup>th</sup> to 17<sup>th</sup> century. As from the 16<sup>th</sup> century wooden panels are more and more replaced by canvas. Oak was the preferred raw

material for panels, especially in the Low Countries, England and Germany. Also in Greece many icons were painted on oak panels. In Italy for instance, poplar was more commonly used by panel makers. This hampers current tree-ring dating. Besides these two examples, other wood species like beech (*Fagus sylvatica* L.), lime (*Tilia* spp.), maple (*Acer* spp.), fir (*Abies* spp.), pine (*Pinus* spp.) and spruce (*Picea* spp.) were also used for manufacturing panels. Later, as can be seen from a wood anatomical survey on Rembrandt (1606° - 1669<sup>+</sup>) paintings (Bauch and Eckstein 1981), tropical wood species as *Cedrela odorata* L. and *Swietenia mahogany* Jacq. were used as well.

After the first successful attempts of tree-ring dating by Bauch (1968) on panel paintings made of oak, numerous other works of art have been investigated (Bauch 1978a and 1978b; Bauch and Eckstein 1981; Bauch *et al.* 1978 and 1978; Eckstein *et al.* 1975; Fletcher 1986; Fraiture 2000 and 2002; Haneca *et al.* 2005a; Klein 1986 and 1993; Klein and Wazny 1991; Lavier and Lambert 1996). Also panels made of beech have been dated successfully (Klein and Bauch 1983). The successful application of tree-ring dating on panel paintings benefits from the fact that often quarter sawn boards were used in order to avoid excessive warping and deformation while drying. As a consequence, long series of tree rings can be measured, increasing the chance for successful dating.

It should be clear however that dendrochronologists do not date the art-historical object, but try to approximate the year in which the tree was felled that yielded the wood, used for the creation of the work. Some further estimates of the time needed to process, to transport and to season the wood plus additional storage time should be added to approximate the year in which the object was created. Bauch and Eckstein (1981) suggest an average interval of  $5 \pm 3$  years between the felling of the tree and the creation of the panel painting. By investigating oak panels of paintings from the Cologne School and Flemish paintings that are signed and dated, longer storage times (10 up to 15 years) are observed during the 14<sup>th</sup> to 15<sup>th</sup> century in the Netherlands and Germany (Bauch 1978a; Klein 1986). With 18<sup>th</sup> century panel paintings, tree-ring dating can become more complicated. At that time there was a shortage of high quality oak and some artists started to reuse older oak panels, what can now lead to conflicting dating reports.



Wooden sculptures are another example of fine arts that have a high potential for tree-ring dating. The wood species that is used for carving is highly dependent on the region where the craftsman was working. Oak was most popular in Flanders, the Netherlands and England, where lime is more typical for Germany, and poplar for the Mediterranean area. Most sculptures made of oak that have been the subject of a dendrochronological survey originate from a special type of artwork, i.e. altarpieces. This type of wooden sculptures was mainly produced during the 15<sup>th</sup> and 16<sup>th</sup> centuries, especially in Germany and the Low Countries. An altarpiece consists of several individual sculptures, arranged in a case that is divided into a number of narrative scenes. Often, altarpieces were outfitted with painted wings that could reveal the sculptures from sight when closed. Oak and walnut (*Juglans regia* L.) are two of the most popular species in the creation of South Netherlandish (Flanders and southern part of the Netherlands) sculptures. For oak, most sculptures are carved only from the durable heartwood and only in exceptional cases few sapwood rings will be preserved. Therefore it is often necessary to include several sculptures from one particular altarpiece into the analysis in order to capture the most recent growth ring. If sapwood was not completely removed during the creation process, the analysis can be restricted to a lower number of sculptures when dating is the main objective. It has been observed that the time between felling of the tree and the sculpting is rather short. Approximately 1 to 4 years elapse after logging and the creation of the sculptures (Haneca *et al.* 2005a).

It is clear that there is a large difference between a dendrochronological analysis on an isolated work of art that is created with a single or few pieces of wood and, for instance, an altarpiece or piece of furniture that is made of numerous wooden boards (Lavier and Lambert 1996). Indeed, the analysis of several pieces of wood originating from a similar context permits to obtain more detailed information regarding the exact setting in time, the origin of the wood and the preferences of the artist regarding the quality of the raw material.

Other objects that have been the subject of a tree-ring analysis are for example wooden book covers (Lavier and Lambert 1996). From a collection of medieval books in France it was noticed that oak was the preferred wood species from the 8<sup>th</sup> to the 15<sup>th</sup> century. From early 15<sup>th</sup> century on beech and elm (*Ulmus* spp.) started to

replace oak. Furthermore, music instruments are often the subject of a dendrochronological analysis. However, oak is seldom used to build instruments. In some case oak was used for part of organs, but never for resonation elements of stringed instruments.

### **2.6.3 Ecclesiastical and vernacular architecture**

Due to its excellent mechanical properties and high durability, oak has established itself as one of the preferred wood species for construction purposes. Oak beams have been used extensively for the construction of barns, houses, churches, cathedrals and vernacular buildings throughout Europe. By dating beams, posts and rafters from roof framings it becomes possible to put stylistic evolutions in strict chronological order. This was demonstrated repeatedly by Hoffsummer who investigated roof-framings in Belgium and Northern France (Hoffsummer 1995, 1996 and 2002). A clear evolution in slope of church roofs was observed during the 13<sup>th</sup> century, corresponding with the implementation of Gothic architecture. Also technical advances, the typology of timber jointing, the quality of the construction timber, provenance of the timber, etc. are all features that can be of interest in the study of local and regional architecture.

Besides this, different construction phases can be distinguished within one 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 14<sup>th</sup> century as expected but to the late 15<sup>th</sup> and early 16<sup>th</sup> century.

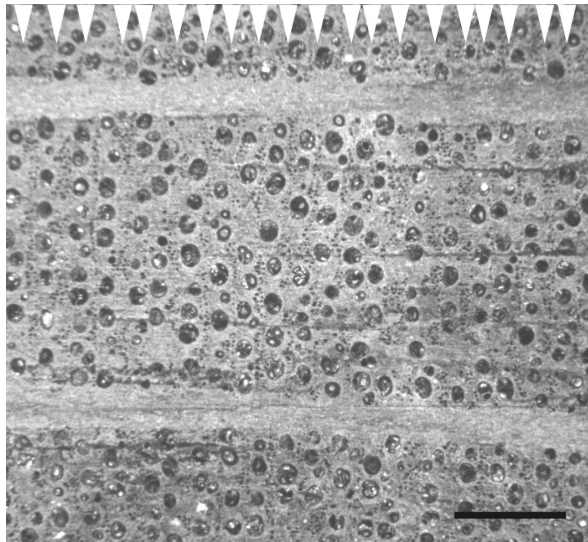
## **2.7 Dendrochronology beyond dating**

### **2.7.1 Palaeoecology of subfossil oaks**

The construction of the Irish and German long oak chronologies mostly relied tree-ring series of subfossil wood, excavated on wetland sites. Most of these oak trees were preserved under anoxic and wet conditions in bogs, river gravels or marine sediments. Two groups can be distinguished when regarding the subfossil oaks; i.e. bog oaks and river oaks. The first group encompasses oak trees that grew in or at the margins of peat bogs. Riverine oaks, on the other hand, were standing on more

mineral soils along a river. Such sites are often characterized by high groundwater levels and recurrent inundations. A peaty substrate is also highly susceptible to long-term changes in the hydro-regime. Hence, trees on both types of wetland sites must have experienced limiting growth conditions, closely related to changes in the local hydrology (Leuschner 1992).

Subfossil oak trees that have been examined in Germany, Ireland and the



**Figure 2.13:** A detailed image of a subfossil oak specimen, ca. 8.000 years old, excavate at Ename (Belgium). The extremely narrow growth rings (indicated by white arrows) with nearly no latewood, result in a diffuse porous appearance. Scale bar represents 5 mm.

Netherlands all display a conspicuous tree-ring pattern, characterized by long and repeated growth depressions. The extremely narrow growth rings with almost exclusively earlywood vessels and no latewood (Figure 2.13), have been observed in absolutely dated ring-width series from oak trees of different age and from different bog sites (Leuschner 1992).

It has been demonstrated that these growth depressions coincide within and between wetland sites, even on a pan-European scale (Leuschner *et al.* 2000 and 2002). Climatological variations on a

regional scale are probably the main cause of these variations in the growth-ring patterns of the subfossil bog oaks (Leuschner *et al.* 2002). The latter demonstrates the potential of these bog oaks to provide proxy data for past palaeoclimate.

Striking is that after 600 AD no bog oaks with the characteristic pattern of small tree rings and long growth depressions have been found in the Netherlands (Jansma 1995; Sass-Klaassen 2004). For Germany the bog oaks are limited to ca. 1000 AD (Spurk *et al.* 1998) and for Ireland to 1596 AD with a gap at 948 BC up to a few years before the AD section. An exploration of modern wetlands revealed that contemporary bog-oaks have no resembling tree-ring pattern with their subfossil predecessors. After a long search, oaks from a stand in NE Ukraine were found, displaying a related pattern. The investigation of those ring-width series identifies site hydrology to be the key factor for the long growth depressions. However, this could

not be confirmed by analysis of isotope ratios in the subfossil trees (Poole *et al.* 2004; Sass-Klaassen *et al.* 2005).

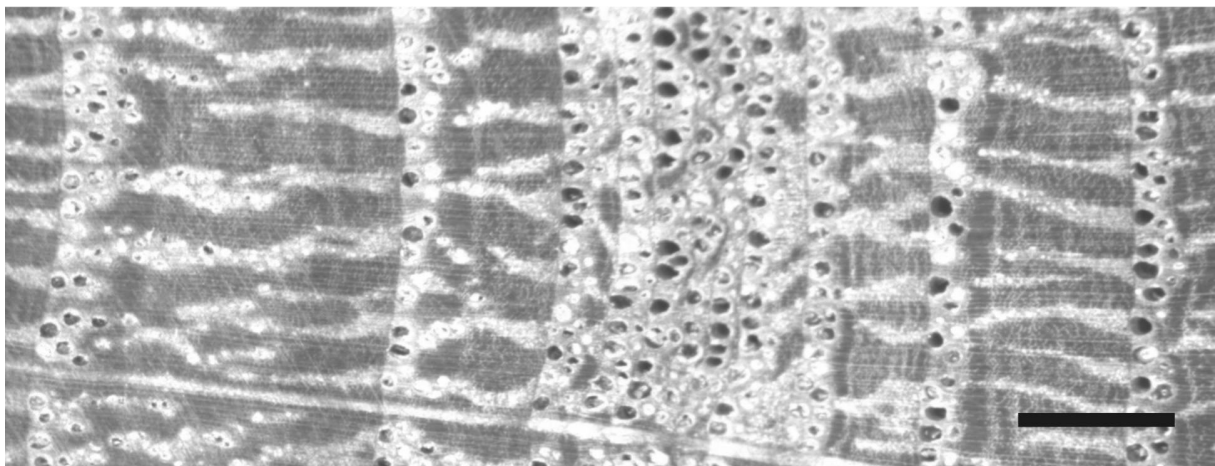
A significant correlation between climatological records and tree-ring series allows to identify periods when favourable growing conditions were prevailing. Such periods can be associated with increased accessibility of the bogs for human activities or induce a clearly identifiable regeneration phase. As opposed to favourable conditions, abundant precipitations during the growing season can induce a sudden die-off in the bog oak population, and might be associated with the construction of track-ways through wet environments. Nevertheless it is quite strange that this vegetation type of oaks on wet sites with a peaty substrate has vanished completely in Central and Northern Europe. Moreover, current phyto-sociological classifications do not mention a vegetation type. A related contemporary vegetation type could be a mixed alder-oak forest (*Lysimachio-Quercetum*), occurring on wet (not permanently!) and poor sandy soils.

### **2.7.2 Forest history and management**

Another method that is able to provide a better image of former woodland development in relation to human occupation was developed by Billamboz (1992) through analysis of tree-ring series from pile-dwellings in southwestern Germany. This method, described as dendrotypology, combines simultaneous tree-ring series into so-called dendro-groups, based on dendrological, and techno-morphological criteria. In practice this means that tree-ring series of the same species with similar cambial age and growth trend are reassembled into a specific group. For each of these groups the average growth rate and cambial age class are then visualised as two proportional sides of a right-angled triangle (average growth rate as the vertical side and cambial age as the horizontal side). Sharp and high triangles then represent young, fast-grown trees whilst flat-lying, low triangles represent slow-grown, old trees. Successive sharp and high triangles suggest the presence of coppice cycles. In combination with the low and flat triangles this could be interpreted as woodland managed as coppice with standards. When a wide variety of triangles in shape and dimensions is encountered, a more natural stand structure, without pronounced human influence, can be identified (Billamboz 1996b and 2003). The results from these analyses helped to identify cycles of forest exploitation (thinning, coppice,...)

and regeneration, both related to demographic evolutions during Bronze Age occupation on the lakeshores of the Bodensee (Billamboz 2002).

Past management interventions are sometimes reflected in the wood anatomy of the trees. For centuries, pollarding of oak trees has been a common practice in Central and Western Europe (Ellenberg 1988; Rackham 2003). This was done in order to stimulate an abundant regeneration of branch wood out of reach of grazing animals. These young shoots could then be used as fodder for animals during the winter months. The effect of pollarding is archived in the anatomy and ring-width pattern of the trees. Abrupt and sustained growth depressions in the ring-width pattern follow a pollarding event (Bernard 1998; Rozas 2005). The earlywood width is not altered the first year after pollarding, but the latewood is reduced considerably. Earlywood width and total ring width decrease in the two following years. Total ring width starts to increase gradually 3 to 4 years after pollarding. The effect of pollarding can be observed in the anatomy of up to seven successive growth rings (Figure 2.14). This particular pattern has been observed in archaeological oak samples as well (Bernard 1998).



**Figure 2.14:** A severe and abrupt growth reduction, observed on a cross-section from the 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.

### 2.7.3 Timber quality

Ring-width series of oak and other ring-porous species provide an image of the density variations within the wood. It has been demonstrated that the density of the individual growth rings is significantly correlated with its cambial age and ring width.

This relationship relies on the difference in density between the different tissues and their proportional distribution within the growth ring (Guilley *et al.* 2002; Guilley and Nepveu 2003; Zhang 1997). The variation in earlywood width along a ring-width series is considerably lower compared to the variation in latewood. As a consequence, total ring-width is more related to the width of the latewood, where the earlywood displays a more constant width in European oak. This indicates that the earlywood width does not increase proportionally with increasing total ring width. Since the density of the earlywood and latewood is ca. 369 - 448 kg/m<sup>3</sup> and 690 - 865 kg/m<sup>3</sup> respectively (Vansteenkiste 2002) it is clear that wood with wide rings, and hence proportionally more latewood, will yield timber of higher densities.

The overall density is linked to a wide variety of technological features that quantify the quality of the wood for a certain application (Zhang 1995). Hence, the study of growth rings can provide an indirect image of the wood quality. Strong variations in the density within a piece of wood will often reduce the overall quality. Therefore, the uniformity of the tree-ring pattern, and hence in density, is desirable in durable applications since it enhances the overall appreciation of the wood (Beeckman 2005). By analyzing tree-ring patterns from archaeological wood or wood from art-historical objects it becomes possible to assess the wood quality in certain periods and yields an image of the assortments available at that time (Haneca *et al.* 2005c; Wazny 2005).

## **2.8 Concluding remarks**

To date, dendrochronology is still the most precise dating method applicable in (pre-) historical studies. The annual resolution of the growth rings, combined with the fact that a lot of cultural objects, historical buildings and archaeological remains are made of wood (especially oak), provides that dendrochronology has a substantial advantage regarding other dating techniques. However, in some cases tree-ring dating fails to offer an accurate felling date for the examined oak specimen, especially when short ring-width series are involved. Therefore, dendrochronologists should always attempt to enhance the methodology involved and gain more expertise in working with such short series. Moreover, the continuously expanding reference frame of absolutely dated site chronologies will probably increase the number of

successful applications of tree-ring dating in the future. As a consequence, dendroprovenancing (see Section 2.4.5) will enable to gain more detailed information on the historical timber trade and the exploitation of (primary) forests during the Middle Ages.

Furthermore, it is clear that dendrochronology has evolved and is currently applied in a wide variety of environmental studies. Tree-rings analysis succeeds in providing relevant information for climate reconstructions, the study of past forest management and structure, etc. The detailed analysis of wood anatomical variables for the construction of time series has not fully been explored yet. However, recent studies demonstrate that the size and distribution of some cell types, e.g. the large earlywood vessel, contain different climatic and environmental signals compared to ring-width measurements. Current advances in image analysis and 3D-computertomography will probably soon create the opportunity to quantify the anatomical feature of wood specimens on a detailed level. This opens new perspectives for the development of new time series that accurately quantify the year-to-year variability in wood anatomy.





**Part I**

**WOOD FROM ART-HISTORICAL OBJECTS**





# **Part I**

## **WOOD FROM ART-HISTORICAL OBJECTS**

### **Preface**

A large portion of Flanders' cultural heritage is made of wood or was constructed by using wood as supportive material. During the Middle Ages, European oak was generally the preferred timber species for construction purposes, due to its excellent physical and mechanical properties. Furthermore, artists and craftsmen highly appreciated oak timber for more delicate applications. Based on the ring-width pattern, often a distinction can be made between the timber that was used for construction purposes (houses, roof structures, storage houses, etc.) and the wood selected by artists and craftsmen. Painters and woodcarvers from 15<sup>th</sup> and 16<sup>th</sup> century, for example, preferred oak for panels and timber with narrow growth rings and a regular growth pattern, whereas oak beams and rafters with wide rings are more common in supporting constructions.

Late Gothic altarpieces are considered as one of the most remarkable examples of visual arts that were produced during the 15<sup>th</sup> and 16<sup>th</sup> century. The individual sculptures, ornaments and the cases were predominantly created in workshops in the Brabantine towns of Antwerp, Brussels and Mechelen. At that time, Brabantine altarpieces were highly appreciated and exported all across Europe. Over the years, many of those altarpieces have become part of museum and private collections worldwide. To date, they provide the opportunity to look at the wooden sculptures from a technological and silvicultural point of view. The growth-ring patterns of the wood from sculptures and panel paintings are potential data sources on the quality of the available wood assortments at their time of creation.

Before the wood arrived in the workshop trees needed to be felled and the wood was processed and traded. It is known that the historical timber trade was not restricted to the local market. The Hanseatic League, which was an assembly of merchants controlling most of the trade in Northern Europe and around the Baltic Sea, had well-established trade agreements with the wealthy Flemish towns during the 15<sup>th</sup> and 16<sup>th</sup> centuries. One of the most important commodities imported were vast amounts of so-called Baltic oak timber. Brabantine altarpieces were mostly carved from the imported high-quality oak timber.

The following two chapters exemplify how the study of our cultural heritage from a dendrochronological and wood anatomical point of view can contribute to a better understanding of the working process and help to document socio-economic phenomena as the historical timber trade. Based on the study of the growth ring pattern and the anatomical features of the wood from altarpieces and altarpiece sculptures from 15<sup>th</sup> and 16<sup>th</sup> century it is attempted to provide data that supports art-historical interpretations and insights into the creation process and medieval workshop practices (**Chapter 3**). The acquired dataset also allows a characterization of the assortments that were preferred by the medieval craftsmen and sculptors. Combined with tree-ring series from 14<sup>th</sup> to 16<sup>th</sup> century panel paintings it is assessed how accurate the original timber source can be identified (**Chapter 4**).



# Late Gothic altarpieces as sources of information on medieval wood use: a combined dendrochronological and art historical survey

# 3

Chapter

## Summary

Wooden altarpieces are important features of European medieval material culture, especially of the Late Gothic Fine Arts from the 15<sup>th</sup> and 16<sup>th</sup> century. Many of them were carved in the Brabantine towns of Antwerp, Brussels and Mechelen in present-day Belgium. Although they were highly esteemed and exported all over Europe, little is known about their production process. In order to understand the context of the creation of the altarpieces, a detailed analysis of the wood has been completed to supplement and confirm historical documentation and art historical approaches.

Tree-ring patterns and anatomical features of 209 wooden sculptures from collections of different museums were analysed. Tree-ring analysis proved the 15<sup>th</sup>-16<sup>th</sup> century origin of the sculptures but also allowed a detailed technical characterization of the carvers' basic material. The striking uniformity of the grain and the sawing pattern revealed that medieval woodcarvers preferred quarter sawn oak lumber, imported from the Baltic area. Stylistic and iconographic hypotheses concerning the current setting of several altarpieces could be founded, based on the wood anatomical and dendrochronological observations. Intensive collaboration between wood biologists and art historians proved to be essential in order to reconstruct the creation process of carved wooden altarpieces.

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### 3.1 Introduction

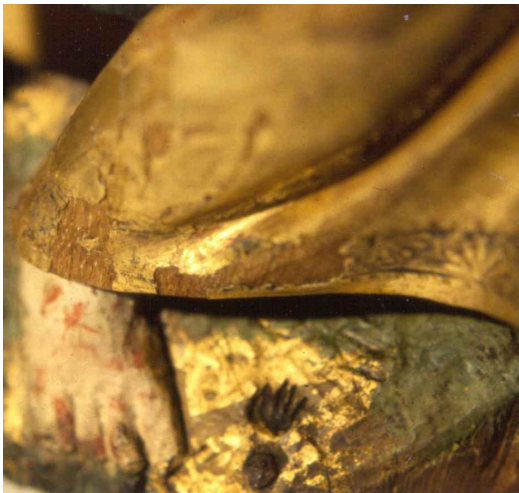
Wood is an omnipresent tissue in nature and has been the resource by far for most of the material culture from early prehistory to our industrial era. While the anatomy of wood provides essential information on the functioning of biological systems, it is also extremely relevant to document cultural studies.

The vast production of Brabantine altarpieces (also called *retables*) during the 15<sup>th</sup>-16<sup>th</sup> century was one of the most remarkable features of Late Gothic Art in Western Europe. These altarpieces exhibit several narrative scenes arranged in an inverted “T”-shaped case, which was usually divided into several compartments. The displayed scenes, predominantly of a religious nature, are composed of separate wooden sculptures. The case itself is mostly outfitted with painted panels that could be used to hide the scenes from view. Important production centres were situated in the Brabantine towns of Antwerp, Brussels and Mechelen (centre of present-day Belgium). The altarpieces were traded and exported to many countries in the Western world. Some authors think that a few thousand were made (Jacobs 1998). Others formulated a more modest estimate of ca. 1000 altarpieces (De Boodt 2004). Approximately 350 examples can still be found in collections from museums and churches all over Europe, from the Baltic countries down to the Iberian Peninsula. Besides complete altarpieces, extensive collections that include dozens of individual sculptures exist that most likely originate from destroyed or dismantled altarpieces.

Usually these sculptures were made of oak (*Quercus* spp.) and, to a lesser degree, of walnut (*Juglans regia* L.). Brabantine altarpieces composed of sculptures from other wood species have yet to be reported. The original case was always made of oak, even when the sculptures themselves were made of walnut. Carved altarpieces have been the subject of many art-historical studies; however, their production process still raises a lot of questions and controversy. In addition, workshop practices and applied woodworking techniques are not fully documented. It is not known how many people were involved and what specific tasks they were assigned. Some authors even suggest that the creation and merchandising of altarpieces can be considered as an example of mass production (Jacobs 1998).



The medieval Antwerp carvers were obliged to become members of the guild of Saint Luke. Guilds were associations of artisans and craftsmen in a particular branch of industry or commerce. The guild representing the woodcarvers, and hence the producers of altarpieces, had detailed guidelines concerning the construction and the quality of the selected wood (De Boodt 2004; Huijgens 1988). When all requirements were met, the wooden sculptures were branded on a clearly visible spot. Such marks guaranteed customers that materials of high quality were used. In Antwerp, for example, an image of a hand was burned into the sculpture with a glowing iron stamp as a warrant for the quality of the wood (Figure 3.1). It should be noted that these marks had no relationship to the artistic value of the sculptures.



**Figure 3.1:** An altarpiece sculpture, branded with the hand of Antwerp (© R. De Boodt).

Since the early 1960's, sporadic collaborations have occurred between art historians, curators and wood scientists. Wood biologists, especially those with a great interest in tree-ring analysis, introduced and developed dendrochronology as a valuable tool for art historians and art collectors (Bauch *et al.* 1978; Eckstein *et al.* 1975). Since then, thousands of panel paintings (e.g. Bauch and Eckstein 1981; Eckstein *et al.* 1986; Klein 1986 and 1993) and sculptures (e.g. Fraiture 2002; Vynckier 1993) have been dated using dendrochronological techniques. This also inspired scientists to look at altarpieces as silvicultural and wood-technological products since it has been known for years that the width and anatomical characteristics of growth rings greatly influence a wide range of wood-technological characteristics (Zhang *et al.* 1994).

It is known that the original configuration of many altarpieces changed over the years. Numerous altarpieces were adapted to the prevailing trend and taste of the time. Other sculptures must have suffered from biological degradation induced by moist conditions and insect attacks. Some deteriorated altarpieces were reassembled into “new” altarpieces. A close inspection of the sculptures' wood anatomical features and tree-ring pattern may provide more detailed information on

their original context. Starting from several case studies on Brabantine altarpieces and collections of individual wooden statues, it is assessed how the combination of art-historical observations, wood anatomy and tree-ring analysis can provide more detailed and well-founded information on the workshop practices in the Brabantine towns during the 15<sup>th</sup> and 16<sup>th</sup> centuries and the original context of the altarpiece production.

## 3.2 Materials and Methods

### 3.2.1 The selected sculptures \*

Two examples, which will serve as case studies throughout this paper, are the Pailhe altarpiece (Figure 3.2), originally from the church of Pailhe (a village in southern Belgium), and the Gaasbeek altarpiece from the collection of the Castle of Gaasbeek (near Brussels, Belgium). The Pailhe altarpiece, now part of the collection of the Royal Museums of Art and History (RMAH) in Brussels, has a maximum height of 260 cm, a width of 238 cm and a depth of 31 cm. The seven narrative scenes are composed of 86 individual blocks of wood, 74 (86%) of which are marked with the Antwerp hand. The original panels of the altarpiece are lost but their former presence is shown by the hinge grooves on the outer post of the case. The scenes display fragments of the life of the Virgin and Christ, and the Passion of the Christ. The Gaasbeek altarpiece is much smaller. It measures 115 cm high, 85 cm wide and 27.5 cm deep. Painted panels are present on both sides. Seven figures, carved out of six different blocks of wood, display a Lamentation scene. However, there are serious doubts that the current state of the altarpiece corresponds with its original presentation (Born and Steyaert 2000; Buyle and Vanthillo 2000).

Collections of isolated groups of sculptures are present, for instance, in the RMAH in Brussels. One of its most splendid examples is the Bassine collection (Huysmans 1999). This group consists of 71 wooden sculptures, 22 of which are stamped with the Antwerp mark of the hand. Except for the fact that they originate from the same private collection, they do not have a clear common origin (e.g. from one former

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\* The titles of all sculptures that were selected for a dendrochronological analysis are mentioned, together with the most relevant features of the recorded tree-ring patterns, in the annex at the end of this chapter.

altarpiece). A similar collection can be found in the Vleeshuis Museum in Antwerp, where a group of 32 sculptures was accessible for a detailed art historical and dendrochronological study. Some of the sculptures display a high similarity in style, but their common origin is questioned. In the Netherlands, the Museum Catharijneconvent (Utrecht) has an extensive collection of South Netherlandish sculptures (Van Vlierden 2004). Many of them probably originate from former altarpieces. The exact production centre of these sculptures is not always clear, but often a Brabantine origin is suggested (Van Vlierden 2004). Fourteen sculptures from the Catharijneconvent collection were available for this study.



**Figure 3.2:** The Pailhe altarpiece (© KIK-IRPA Brussels).

During thorough conservation treatments of the Pailhe and Gaasbeek altarpieces, the separate sculptures and ornamental carvings were disassembled from their framework. Such events provided the opportunity to execute a combined art historical and dendrochronological study. Prior to the selection of sculptures for dendrochronological analysis, a visual inspection verified the overall condition and stability of the polychromy, if present. Also the appearance of the sculptures' underside and the estimated number of growth rings was considered. For the latter criterion a minimum was set at 50. In total, 118 of the 209 accessible objects (= 56.5%) proved to meet all above stated requirements. In order to maximize the statistical reliability, all selected sculptures were submitted to dendrochronological analyses. In addition, five boards from the case of the Pailhe altarpiece were selected for a dendrochronological examination.

### **3.2.2 Pre-treatment for tree-ring analysis**

The wooden blocks from which the individual sculptures were carved, are only roughly finished on the sides that were not visible to the audience. This implies that not all growth-ring boundaries are clearly visible on the underside of the sculptures. Additionally some of the sculptures were submerged in a paraffin wax, as a conservation treatment against woodworm, in the first half of the twentieth century (e.g. the Pailhe altarpiece). Removing the paraffin and accumulated dust by a treatment with solvents can improve the visibility of the growth rings. When this method did not deliver the expected result, a transverse strip of approximately 0.5 cm on the underside of the sculptures needed to be surfaced to make the growth-ring boundaries clearly visible. This appeared to be the most delicate step in the dendrochronological analysis. A procedure with minimal impact on the wood structure was preferred. One of the most appropriate techniques for this purpose is micro-abrasion. With this method spherical particles of glass (45 - 90 µm) are projected (ca. 4 bar) on the transverse section of the wood on the underside of a sculpture. When the particles collide with the wood, accumulated dust is removed, leaving the anatomical structure of the oak wood, in particular the earlywood vessels, clearly visible for the dendrochronologist. A similar method was first introduced by Schultz (1982) and later refined and applied to sculptures by the *Laboratoire de Chrono-écologie* at Besançon (France). Before implementing the micro-abrasion technique, the sculpture needs to be wrapped carefully in order to avoid any contact

of the polychromy with the spherical particles. When the underside is too rough or when the wood fibres and vessels are not aligned transversely, the micro-abrasion technique is no longer able to highlight the growth-ring boundaries sufficiently. In such cases, preparation with a scalpel, razor blade, or a small rotating sanding instrument was considered, in consultation with restorers and curators.

### 3.2.3 Measurements and observations

Using a digital camera (ColorView8) with a resolution of 1280 x 1024 pixels, overlapping digital images were made of the growth rings. Later, the individual images were joined into high-resolution images, and stored in a database. As an alternative, detailed B&W pictures were taken of the sculptures' underside (Hasselblad 500 C/M, Zeiss Planar 150 mm). Digital scans of the negatives then served as a medium to measure the growth-ring pattern. These techniques allow measuring and verification of the tree-ring data, avoiding repeated manipulation of these sometimes fragile medieval sculptures.

In order to quantify the quality of the sculptors' basic material, three main features were considered: the durability, the grain and its uniformity, and the applied sawing pattern.

The most obvious variable that determines the overall durability is the wood species. Within the framework of this study only altarpiece sculptures made of oak were selected. For the genus *Quercus* the distinction between *Q. robur* L. and *Q. petraea* (Matt.) Liebl. is still hard to determine (Feuillat *et al.* 1997; Grosser 1977). According to Feuillat *et al.* (1997) two specific features allow a fast discrimination between *Q. robur* and *Q. petraea*: the number of earlywood vessel rows and the latewood ratio. These features must be measured on four different growth rings approximately 2 mm wide on each unidentified specimen. The selected growth rings also should have formed at least 60 years after the tree began to grow in order to avoid juvenile anatomical features. When the average ranks of earlywood vessel rows are equal or greater than 2 and the average latewood percentage is less than 60, the specimen can be identified as *Q. robur*. On the other hand, for *Q. petraea* the average rank of earlywood vessel rows is equal or less than to 2, combined with an average latewood percentage of more than 70.

Another important feature that highly influences durability is the presence of sapwood. The heartwood of *Q. robur* as well as *Q. petraea* is considered durable to moderately durable (durability class II - III) according to the current European standard EN 350 (EN 350-1/2 1994). Sapwood of oak is highly susceptible to attack by powder-post beetles (*Lyctus* spp.) and the common furniture beetle (*Anobium punctatum* De Geer), and is therefore classified as not durable (durability class V).

The average growth rate and the standard deviation, computed from the original ring-width series, are variables that enable us to quantify the grain. The first-order autocorrelation is the correlation of each value in a time series with the value of its predecessor with a time lag of 1 year (Fritts 1976). High values usually indicate the presence of a distinct growth trend. Combining all growth-ring characteristics permits the quantification of the overall uniformity of the lumber.

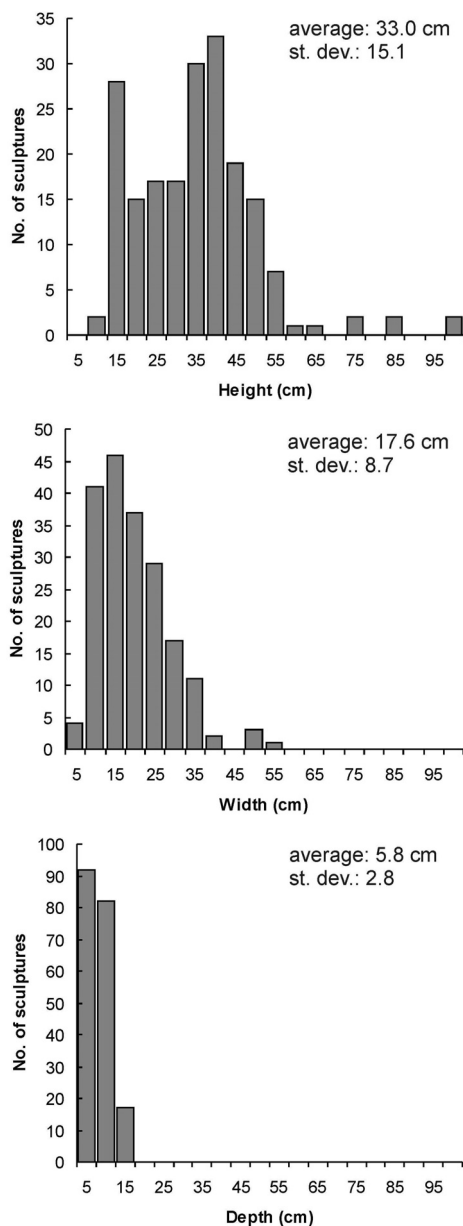
By recording the dimensions and shape of the sculptures, together with the orientation of the growth rings, it becomes possible to obtain a rough image of the original logs the sculptures were carved from. Based on the orientation of the growth rings and wood rays, lumber is considered quarter sawn, i.e. edge-grained lumber, when the growth rings form an angle of 45° to 90° with the widest surface of the timber. When this angle drops below 45°, the wood is considered flat sawn or flat grained. Bastard sawn is the intermediate pattern in which the angle between the growth rings and the largest surface is approximately 45° (Forest Products Society 1999). By recording the orientation of the growth rings on each of the sculptures' underside, all of them were graded into one of the above stated categories.

### 3.2.4 Data processing

In a next step the individual tree-ring series were compared to one another by calculating *t*-values according to the Baillie and Pilcher algorithm (Baillie and Pilcher 1973). After crossdating the individual tree-ring series, object chronologies were computed. An object chronology is defined as the average of all series that belong to one specific group of sculptures, i.e. an altarpiece or a collection of stylistic related sculptures. The object chronologies and all individual sequences were then compared to European reference chronologies. Chronologies composed of tree-ring series from southern Belgium (Hoffsummer 1996), Germany (Becker 1981; Hollstein

1980) and France (Bernard 1998) as well as Baltic/Polish (Wazny 1990b) reference chronologies (Hillam and Tyers 1995) were consulted. For the Baltics, a dense network of local and site chronologies (for definitions see Kaennel and Schweingruber 1995) has recently been assembled (Wazny 2002). All tree-ring series from the Brabantine sculptures, dated against Baltic reference chronologies, were compared with this dataset as well.

### 3.3 Results

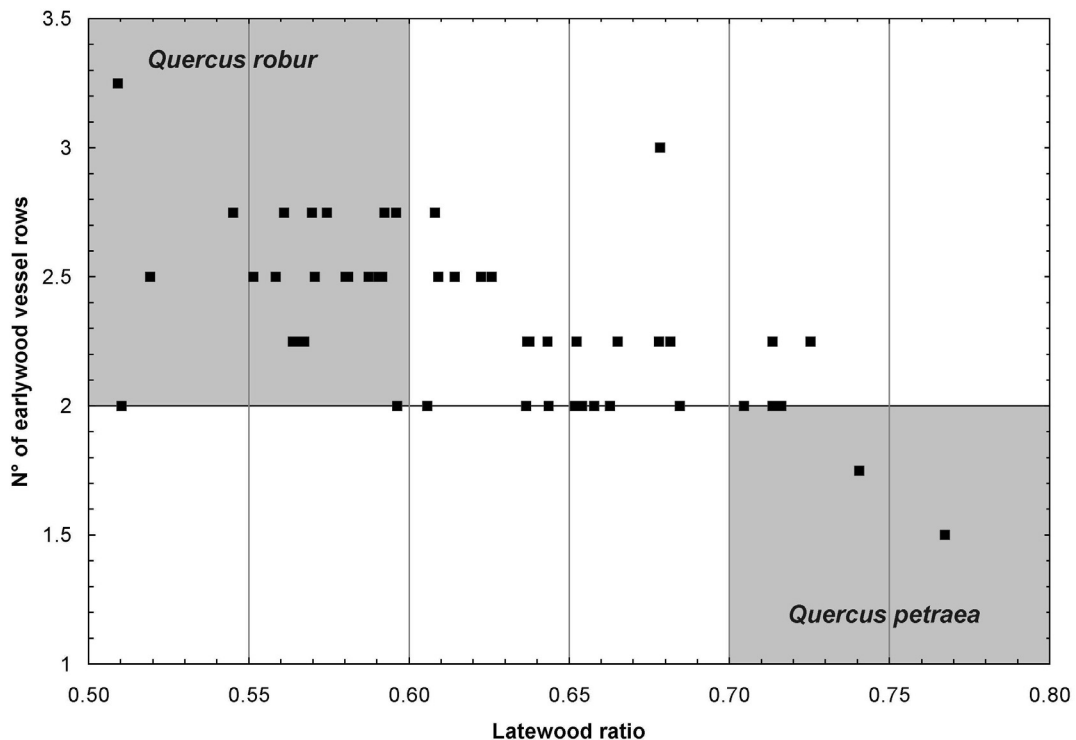


**Figure 3.3-3.5:** Histograms showing the distribution in -3 height, -4 width and -5 depth of 177 Brabantine altarpiece sculptures from 15<sup>th</sup>-16<sup>th</sup> century.

In order to get an impression of the original boards from which the sculptures were carved, two specific features were recorded: the maximal dimensions of the carvings and the shape of the sculptures' underside. The latter usually appeared to be slightly wedge-shaped (trapezoidal) with the narrowest side oriented towards the pith. The pith itself is always removed. The height of the sculptures varies from 6 cm up to 98 cm, the width from 4 cm to 51 cm. From all individual sculptures that were selected for this research, 95% were less than 33 cm in width. The least variable dimension is the depth with a minimum value of 1 cm and a maximum of 15 cm (Figures 3.3 – 3.5).

After transverse strip on the underside of the sculptures had been exposed, wood anatomical features became clearly visible. All sculptures that were selected for this paper were made of oak. From the 118 sculptures that entered the dendrochronological analysis, 50 were submitted to a more detailed anatomical examination, according to the identification key

presented by Feuillat *et al.* (1997). High-resolution images of the tree-ring patterns provided the means to determine the average number of earlywood-vessel ranks and the average percentage of latewood. The remaining tree-ring series either lacked an adequate number of growth rings approximating 2 mm in width, had not reached a cambial age of 60 years, or contained rings in which anatomical detail could not be sufficiently resolved. The wood anatomical observations (Figure 3.6) demonstrate that 44% of all examined sculptures could be identified with a high probability as *Q. robur*. Only 5 (10%) sculptures are most likely made from *Q. petraea* (BASS-03, -14, -61, -70 and VM-AV2602). For all other sculptures the likely species could not be determined.



**Figure 3.6:** Average number of observed earlywood vessel rows and latewood ratio of tree rings, approximately 2 mm wide and at least 60 years in cambial age, from 50 altarpiece sculptures from 15<sup>th</sup>-16<sup>th</sup> century altarpieces.

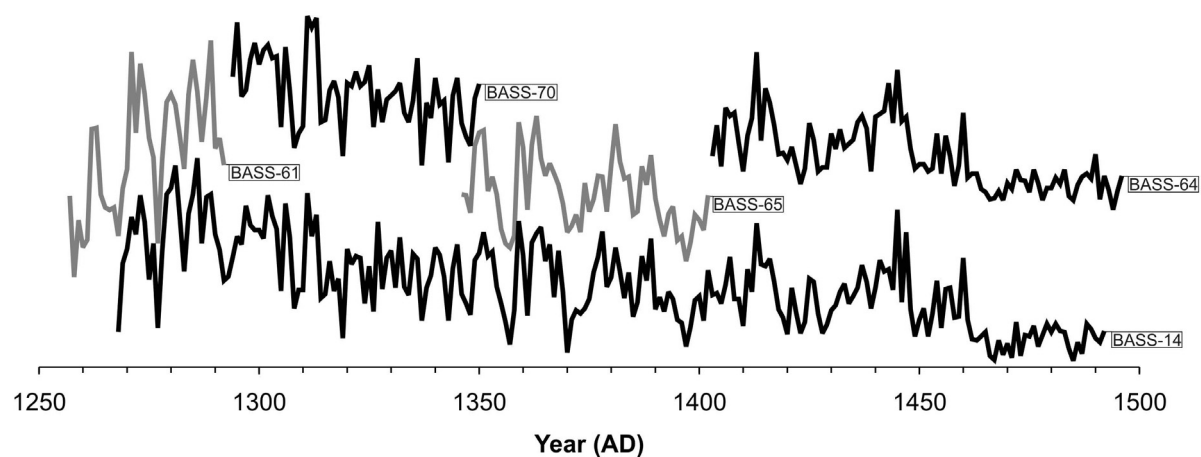
Comparison of the individual growth-ring sequences revealed that some of them exhibit  $t_{BP}$ -values above 7 (Table 3.1) and display an extremely high visual similarity (Figure 3.7). The wood from at least four sculptures (Figures 3.8 – 3.11) possessed highly similar ring-width patterns and anatomical features, suggesting that one tree was the source for each sculpture. All other sculptures were most likely carved from other boards or smaller blocks of wood. The related series were then averaged into one series per tree and compared to each other (Table 3.2). This results in



significantly lower  $t_{BP}$ -values compared to the series that probably originate from the same tree. Nevertheless some of these values peak above 7.0 (tree A and B, tree E and G), but a visual comparison reveals that a different trend can be observed. It was therefore concluded that these series do not originate from the same tree.

**Table 3.1:** Overview of the altarpiece sculptures that were carved from the same tree or log. The correlation between the tree-ring series that originate from the same tree is represented by the average  $t_{BP}$ -value.

| Object (inv. Nr.)             | Collection                            | Average $t_{BP}$ -value | Tree |
|-------------------------------|---------------------------------------|-------------------------|------|
| BASS-69 and -66               | Bassine collection (RMAH – Brussels)  | 12.3                    | A    |
| BASS-03 and -19               | id.                                   | 7.7                     | B    |
| BASS-01, -18 and -48          | id.                                   | 15.87                   | C    |
| BASS-30, -31R and -35         | id.                                   | 8.87                    | D    |
| BASS-14, -64, -65 and -70     | id.                                   | 10.5                    | E    |
| -----                         |                                       |                         |      |
| PAIL-F11 and –E06             | Pailhe altarpiece (RMAH – Brussels)   | 6.6                     | F    |
| PAIL-A01 and –D03             | id.                                   | 20.7                    | G    |
| PAIL-C01 and –C02             | id.                                   | 7.6                     | H    |
| PAIL-D06, –D09 and –D10       | id.                                   | 12.3                    | I    |
| PAIL-A03, –E02, –F01 and –F02 | id.                                   | 10.8                    | J    |
| -----                         |                                       |                         |      |
| GB-A1a, –A2 and –A3           | Gaasbeek altarpiece (Gaasbeek Castle) | 7.5                     | K    |



**Figure 3.7:** Tree-ring patterns from four sculptures (BASS-14, -61, -64, -65 and -70), originating from the same tree.

Dating the individual tree-ring series against the dataset of European reference chronologies was successful in 71.2% of all cases. The majority of the recorded tree-ring patterns (71 out of 84 dated sculptures) display high correlations with the standard Baltic reference chronologies. For instance, the trees that provided the wood for several related sculptures (see Table 3.1) are compared with the Baltic 1 reference chronology (Hillam and Tyers 1995) and a new chronology (Altarpieces)

that is computed as the average series of all recorded tree-ring series that could be dated against Baltic reference chronologies. The corresponding  $t_{BP}$ -values for both reference chronologies are listed in Table 3.2 and are in most cases higher than 6.0. Two particular sculptures (BASS-63 and UM-SMCCb1) could be dated against the reference chronologies that cover the Meuse valley and southern Belgium (Hoffsummer 1995). Two others (UM-RMCCb202 and UM-RMCCb109) display high similarities with both the Meuse valley and the German chronologies, but not with the Baltic references. Nine tree-ring series did not display unambiguous  $t_{BP}$ -values with the available reference chronologies, but showed a sufficiently high correlation ( $t_{BP}$ -values all higher than 4.5) with other tree-ring series from the altarpieces that were already dated against Baltic references.

**Table 3.2:** Correlation matrix ( $t_{BP}$ -values) of the tree-ring series from each tree that was used to carve at least two sculptures (see Table 3.1). The growth pattern of each tree is also compared to the “Baltic1” reference chronology (Hillam and Tyers, 1995) and the “Altarpieces” chronology, which is computed from all tree-ring series that could be dated against the Baltic references.

|                    | Tree A | Tree B | Tree C | Tree D | Tree E | Tree F | Tree G | Tree H | Tree I | Tree J | Tree K |
|--------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| <b>Tree A</b>      | +      |        |        |        |        |        |        |        |        |        |        |
| <b>Tree B</b>      | 7.9    | +      |        |        |        |        |        |        |        |        |        |
| <b>Tree C</b>      | 2.7    | 4.0    | +      |        |        |        |        |        |        |        |        |
| <b>Tree D</b>      | 1.4    | 4.7    | 6.2    | +      |        |        |        |        |        |        |        |
| <b>Tree E</b>      | 5.4    | 5.8    | 0.9    | 3.4    | +      |        |        |        |        |        |        |
| <b>Tree F</b>      | 0.5    | -      | 3.0    | 5.0    | 2.7    | +      |        |        |        |        |        |
| <b>Tree G</b>      | 2.9    | 5.4    | 3.2    | 3.8    | 7.7    | 2.1    | +      |        |        |        |        |
| <b>Tree H</b>      | 1.0    | -      | 2.7    | 4.9    | 1.6    | 3.2    | 5.2    | +      |        |        |        |
| <b>Tree I</b>      | 0.8    | -      | 3.0    | 2.7    | 3.7    | 2.7    | 4.2    | 2.5    | +      |        |        |
| <b>Tree J</b>      | 1.2    | -      | 2.6    | 2.7    | 3.7    | 0.2    | 5.2    | 0.5    | 3.6    | +      |        |
| <b>Tree K</b>      | 3.8    | 3.8    | 6.5    | 4.0    | 4.3    | 4.3    | 3.4    | 1.5    | 2.8    | 0.7    | +      |
| -----              |        |        |        |        |        |        |        |        |        |        |        |
| <b>Baltic1</b>     | 6.0    | 8.7    | 6.0    | 8.7    | 9.5    | 6.4    | 10.1   | 6.9    | 4.9    | 5.2    | 7.3    |
| <b>Altarpieces</b> | 6.1    | 9.9    | 8.8    | 10     | 10.3   | 5.4    | 11.2   | 6.8    | 6      | 7.8    | 8.9    |

Most of the wooden sculptures display a fine and uniform grain, i.e. a tree-ring pattern with relatively small rings and mostly without a strong and pronounced growth trend (Table 3.3). The average ring width of all measured tree-ring patterns that were dated against Baltic reference chronologies is 1.29 mm, which is slightly smaller than the average ring width of the undated series. The reverse holds for the standard deviation. For the 118 tree-ring series from the altarpiece sculptures, an average first-order autocorrelation of  $54 \pm 0.18$  was recorded. In 11 cases this value peaks above 0.75, revealing the presence of a clear and distinct growth trend.

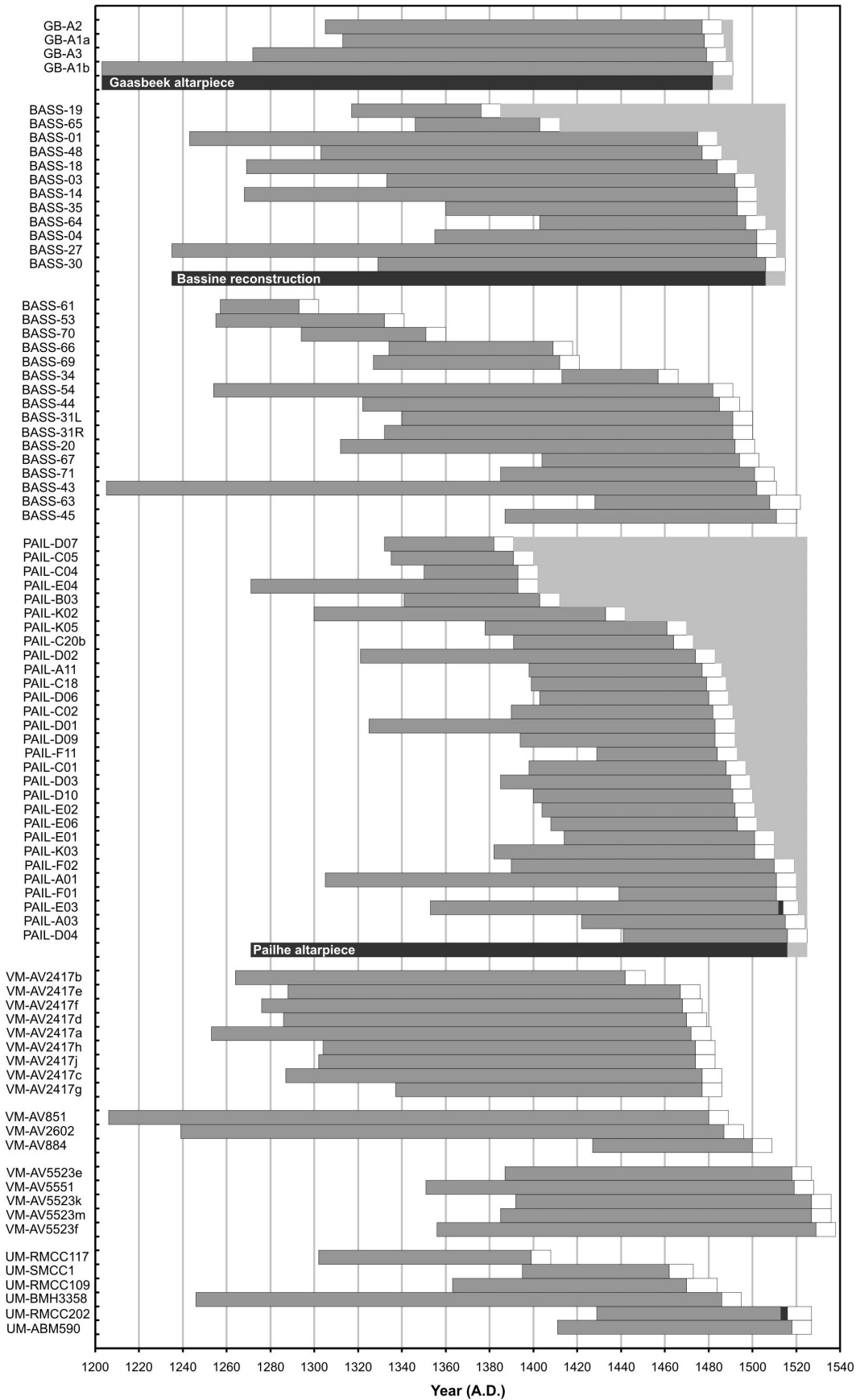


**Figure 3.8-3.11:** Sculptures from the Pailhe altarpiece carved from the wood of the same tree or board. **-8:** PAIL-E02, Kneeling King Melchior. **-9:** PAIL-F01, Shepherd carrying a candle. **-10:** PAIL-F02, Virgin Mary. **-11:** PAIL-A03, Soldier holding a shield and a lance.

**Table 3.3:** Average ring width (mm), standard deviation and first order-autocorrelation for the growth ring patterns measured on 109 medieval oak sculptures.

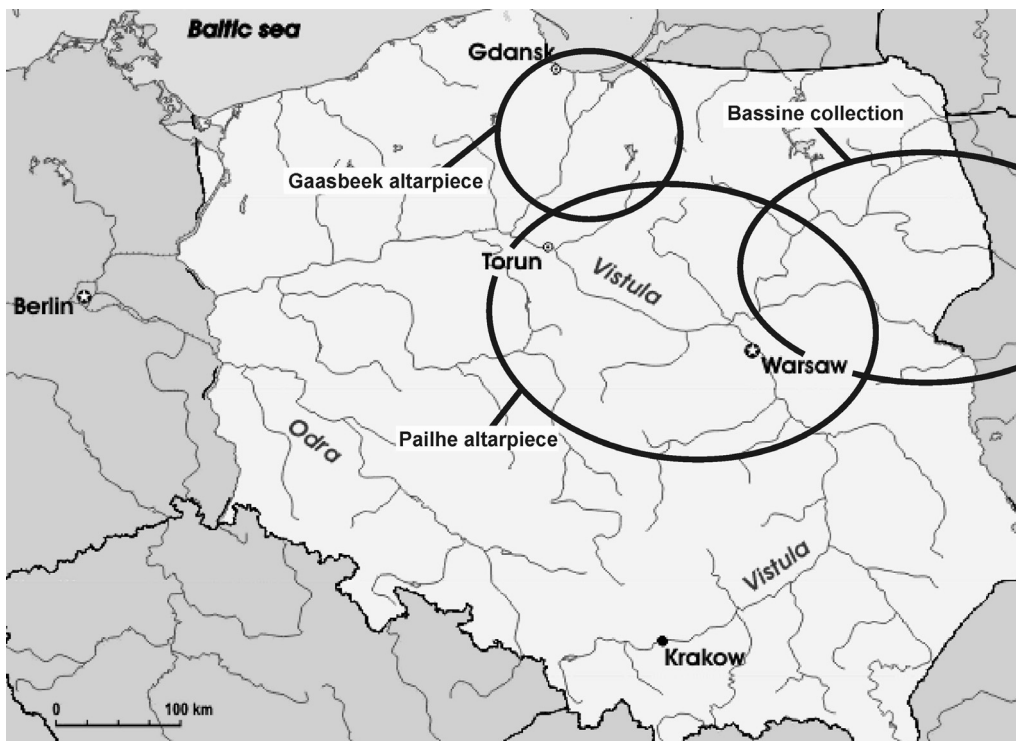
| Collection                                     | Av. ring width | Av. standard deviation | Av. first-order autocorrelation |
|--|----------------|------------------------|---------------------------------|
| Pailhe altarpiece (51)                         | 1.36           | 0.40                   | 0.50                            |
| Bassine collection (34)                        | 1.23           | 0.38                   | 0.59                            |
| Gaasbeek altarpiece (5)                        | 1.29           | 0.38                   | 0.40                            |
| Vleeshuis collection (19)                      | 1.27           | 0.41                   | 0.58                            |
| Catharijneconvent collection (9)               | 1.62           | 0.62                   | 0.61                            |
| -----  |                |                        |                                 |
| Series dated against Baltic ref. chronol. (84) | 1.29           | 0.38                   | 0.54                            |
| Undated series (34)                            | 1.33           | 0.45                   | 0.56                            |
| Total dataset (118)                            | 1.31           | 0.39                   | 0.54                            |

From the dated series, three object chronologies were calculated (Figure 3.12), one for each altarpiece or group of sculptures that are assumed to originate from one former altarpiece; i.e. the Pailhe altarpiece, the Gaasbeek altarpiece and the Bassine collection. The most recent tree ring that was measured served as a starting point to make an estimation of the earliest possible felling date for the entire altarpiece, or group of related sculptures. Since sapwood was removed from nearly all sculptures it can be expected that the tree was felled at least some years after the formation of the last recorded heartwood ring. Therefore an additional number of years should be added to the outermost ring of heartwood as a compensation for the missing sapwood. The median number of sapwood rings from historical and modern oak trees from Poland is 15, with 90% of all cases within the range of 9 to 24 sapwood rings (Wazny 1990b). Oak trees with a more western origin, i.e. from forests in present-day Belgium and Germany, generally include a larger number of sapwood rings that highly depends on the age of the tree (Hollstein 1980). For instance, an oak tree with an age between 100 and 200 years typically forms approximately  $20 \pm 6$  sapwood rings. For all sculptures that show high correlation values with the Baltic reference chronologies, the earliest possible felling date can be approximated by adding 9 years, assuming that only the sapwood and no heartwood was removed. Only one sculpture from the Pailhe altarpiece (PAIL-E03) has two remaining sapwood rings. For this particular sculpture a compensation of only seven sapwood rings was taken into account, resulting in an estimated earliest possible felling date of 1520 AD. This date proved to be the most recent felling date that could be calculated for all sculptures from the Pailhe altarpiece. Likewise, the best approximation of the earliest possible felling date for the sculptures of the Gaasbeek altarpiece is set at 1490 AD.



**Figure 3.12:** Time span of the dated tree-ring series, presented as bar charts, from the 15<sup>th</sup>-16<sup>th</sup> century sculptures. Sapwood rings, indicated in black, are present on sculpture PAIL-E03 and UM-RMCC202. White bars represent the estimated minimal number of missing sapwood rings.

Comparison of the object chronologies with local and site chronologies from present-day Poland (T. Wazny, *personal communication* 2002) showed that the highest  $t$ -values are for the Bassine chronology from eastern Poland. For the object chronology of the Pailhe altarpiece high  $t$ -values did not point towards one specific region. Comparison of the individual tree-ring series from the altarpiece of Pailhe revealed that the majority of the series display the highest correlation with site chronologies from eastern and southeastern Poland. Tree-ring series from the Gaasbeek altarpiece, on the other hand, are highly correlated with site chronologies composed of tree-ring series from archaeological sites in and near the city of Gdansk in northern Poland (Figure 3.13).



**Figure 3.13:** Map of Poland displaying the most probable timber sources of the wood that was used to construct the altarpieces of Pailhe, Bassine and Gaasbeek.

### 3.4 Discussion

Dating results and estimated felling dates clearly demonstrate the 15<sup>th</sup>-16<sup>th</sup> century origin of the sculptures. The major part of the dated tree-ring series is highly correlated with Baltic reference chronologies established by Hillam and Tyers (1995) and Wazny (1990b). It is well-known that vast amounts of timber were shipped from the Baltic region towards the harbours of the Low Countries during the 15<sup>th</sup>-16<sup>th</sup>

century (Bonde 1992; Bonde *et al.* 1997; Tossavainen 1994; Wazny 1990a; Wazny 2002; Wazny and Eckstein 1987; Zunde 1999). Since transport via waterways was the most economical solution at that time (Rackham 1982), forests along the major rivers were the most feasible wood resources. Trees were cut, cleaved and floated down the river towards the shipping port (Wazny 2005). A detailed anatomical analysis suggests that most of the altarpieces are carved of *Q. robur*. Both *Q. robur* and *Q. petraea* are common tree species in Poland, but *Q. robur* is known to have a wider ecological range and is, compared to *Q. petraea*, more typical for the inland plains and large valleys of the big European rivers (Mayer 1980).

Comparison of the object chronologies from all dated sculptures of the Pailhe and Gaasbeek altarpiece and the Bassine collection with Baltic site chronologies shows clear similarities towards particular areas in present-day Poland. These areas can be interpreted as an approximation of the original timber source from where trees were cut, cleaved and transported towards the shipping port. The wood used for the creation of the oldest sculptures (the Gaasbeek altarpiece) originates from northern Poland, most likely from forests in the vicinity of Gdansk, one of the most important harbours of export for the Hanseatic league at that time. On the other hand, the wood that was used to carve the more recent altarpieces of Pailhe and Bassine originates from remote and inland areas. For the object chronology of Pailhe the *t*-values did not point towards a clear region of origin at first sight. This could suggest that the altarpiece was made of mixed material from different regions. Comparison of the individual curves with local and site chronologies showed that a big group of the individual curves was correlated with chronologies from eastern and southeastern Poland.

Four sculptures (BASS-63, UM-SMCCb1, UM-RMCCb202 and UM-RMCCb109) most probably originate from one of the remaining, less remote forests, since the tree-ring patterns display a significant correlation with reference chronologies composed of archaeological wood from the Meuse valley, southern Belgium and Germany. It is striking that three of these sculptures are from the Catharijneconvent Museum. These sculptures are regarded as South Netherlandish and do not display any of the marks (e.g. the branded hand) that are typical for Brabantine sculptures.

From the five sculptures that were probably made out of *Q. petraea*, two certainly originate from the same tree (BASS-70 and BASS-14), because of their highly similar tree-ring pattern. Two other sculptures (BASS-64 and -65), that have not been identified wood anatomically, also originate from this particular tree (Table 3.1). Both sculptures lack a sufficient number of growth rings that approximate 2 mm and therefore are not suited for the identification key of Feuillat *et al.* (1997). The small sculpture (BASS-61) has only 36 tree-rings. This hampered further interpretation of its growth-ring pattern. Nevertheless a strong resemblance was noticed with the tree-ring patterns of BASS-70 and BASS-14, also identified as *Q. petraea*. Since the overlap between the tree-ring series of BASS-61 and BASS-14 is only 25 years, it is hard to interpret the resemblance on statistical grounds. The corresponding *t*-value is only 5.6, so a definite conclusion cannot be made that the sculptures were carved from the same tree or board. The anatomical resemblance provides an additional argument. It strongly suggests that this sculpture was carved from the same log as BASS-14, -70, -64 and -65. So in this case up to five sculptures were carved from one single board (Figure 3.7).

It should be noted that on nearly all sculptures sapwood was removed. This procedure has a strong influence on today's interpretation of dendrochronological data. To compensate for the absence of sapwood, it proved necessary to include as many sculptures as possible in the dendrochronological analysis. Besides the compensation for missing sapwood and heartwood, the time for transportation and seasoning needs to be added to get a more precise estimate of the time of creation. Therefore dendrochronologists can provide only an approximation of the earliest possible year of production. The time needed to transport logs from the Baltic forests, for instance, from the harbour of Gdansk towards Antwerp took about 1 month in those days (Wazny and Eckstein 1987). Before they were shipped from Gdansk the timber was floated down the Vistula river. This probably did not take more than a few weeks. So after cutting, the oak timber could easily have arrived in Antwerp after a few months (Wazny 2005). For panel paintings it is assumed that the drying period for the wood took about  $5 \pm 3$  years (Bauch and Eckstein 1981). It is not clear yet how long this usually was for sculptures. A long drying period could even hamper the carving process since the wood could become harder to work. From historical documents and dendrochronological dating it is known that a large wooden sculpture



like the Triumphal Cross and Screen from the Cathedral of Lübeck (Germany) was carved and installed within one year after the tree was felled (Eckstein 2005). A dendrochronological study on five sculptures with sapwood from the Passion altarpiece in the church of Bouvignes-sur-Meuse (Belgium) resulted in a felling date that is most probably situated around 1552 AD (Vynckier 1993). Historical documents describe the order and installation of the altarpiece in October 1555 AD and March 1557 AD respectively (De Boodt 2002). Hence, the altarpiece was most probably created during 1556 AD. These two case studies suggest a time interval of 1 to 4 years between the logging of a tree and use of the wood for the creation of an altarpiece. Further, dendrochronological analysis on altarpieces that can be dated through historical documents could refine the above stated results.

Besides exact dating, the dendrochronological analyses provided additional arguments that supported further interpretation of the recorded art historical data. For instance, the earliest possible felling date of the sculptures from the Gaasbeek altarpiece (1490 AD) contradicts its actual setting. The current presentation cannot correspond with the original configuration in the late 15<sup>th</sup> or early 16<sup>th</sup> century. The case, which is made of pine instead of oak, is clearly an example of 19<sup>th</sup> century gothic revival, in which medieval sculptures were used and displayed in a new arrangement. Another argument that clearly demonstrates this is the fact that it is impossible to close the panels without touching and damaging the sculptures in their present setting. Nevertheless, dendrochronological evidence proved that three of the six sculptures originate from the same tree. So probably at least these three sculptures originate from one former altarpiece.

A detailed stylistic and iconographic study of the Bassine collection resulted in a selection of sculptures that were probably part of one, lost altarpiece. This resulted in a virtual reconstruction of that former altarpiece (De Boodt *et al.* 2005). Dendrochronological findings, presented in Table 3.1, combined with wood anatomical observations provided additional arguments to add more sculptures to the reconstruction. It was assumed that sculptures carved from wood of the same tree were probably carved in the same workshop that bought the log or board. These suggestions were supported by stylistic links between the sculptures. All of this resulted in a partial reconstruction of that former altarpiece, which now holds about

twenty-two sculptures from the Bassine collection. Without the dendrochronological data and wood anatomical observations only 15 sculptures would have entered the reconstruction, based solely on clear stylistic and iconographic resemblances.

The overall uniformity in technique and style that appears in all sculptures of the Pailhe altarpiece is striking at first sight. When observed more closely, dissimilarities in the proportions, facial type and shape of the sculpted figures become clear. In total probably three or four different hands of craftsmen can be distinguished. Nevertheless, the figures have enough harmony in their style to appear as an ensemble (De Boodt *et al.* 2005). The technical unity of the altarpiece is also confirmed by the dendrochronological data, since several sculptures were carved from the same log. The identification of different carvers combined with these dendrochronological data revealed that often more than one sculptor worked with the wood from one particular log.

Only two of the examined sculptures had two or three sapwood rings left (PAIL-E03 and UM-RMCCb202). Although other dendrochronological investigations have reported the presence of sapwood (Vynckier 1993), the vast majority of the altarpiece sculptures have no sapwood. This conscious use of heartwood by the medieval woodcarvers is probably related to their concern about wood durability. The visual attractiveness of oak heartwood is probably less relevant because of the polychromic staining of the sculptures.

Now, the question arises why medieval woodcarvers preferred the imported, Baltic oak above timber from local forests. One of the most striking features of the imported Baltic oak is the overall uniformity of the wood. The grain can be considered as an important feature that determines wood-technological properties and the quality of the wood (Zhang 1995). The observed fine and uniform grain demonstrates the excellent quality of the imported timber. The growth-ring pattern does not display a strong and pronounced growth trend (Table 3.3). Extreme and abrupt changes in growth rate seldom occur. The latter can be observed by the small average standard deviation of the tree-ring series. Compared to local wood from Ypres (Belgium), a medieval archaeological site from the 12<sup>th</sup>-13<sup>th</sup> century (Haneca, *unpublished data*), it is noticed that the average ring width and average standard deviation is considerably

smaller for the imported oak (Table 3.4). Tree-ring series from wood used in the roof-construction of a warehouse from a medieval abbey (Lissewege, Belgium, ca. 1370 AD) have a comparable average first-order autocorrelation (Haneca, *unpublished data*). This indicates the presence of a rather indistinct growth trend, similar to the tree-ring series from the altarpiece sculptures. The wood used in the construction of this warehouse, and the wood used for the creation of the altarpieces, does not clearly display the characteristic pattern of wide growth rings near the pith that gradually become smaller towards the bark. But, on the other hand, average ring width and standard deviation are considerably higher for the medieval local wood from the warehouse. The difference in wood quality between local oak and imported Baltic oak is probably the result of differences in management or absence of management (Beeckman 2005). Even before the Roman Era, forests in the Low Countries were altered in structure and considerably reduced in size (Buis 1985; Vera 2000). In order to maintain a sustainable source of timber, two management systems became extremely popular during the Middle Ages: coppice and coppice-with-standards. Oak was one of the most prominent species subjected to coppicing, since it re-sprouts easily from a stool after logging. Tree-ring series from modern coppice stands usually display a pronounced growth trend, a high average growth-ring width and a substantial standard deviation (Table 3.4). Timber harvested from such stands will also be limited in dimensions since rotation cycles are considerably shorter compared to high forest systems. Trees from modern forests, dominated by *Q. robur* or *Q. petraea*, which are managed as high forests also exhibit tree-ring patterns with a pronounced growth trend and considerably wide growth rings. Indeed, local wood available on the medieval wood market in Western Europe must have been characterized by wide and variable growth rings with a distinct growth-trend.

**Table 3.4:** Average ring width, standard deviation and first-order autocorrelation of selected, modern and historical, oak stands in Belgium (B) and the Netherlands (NL).

| Stand (location)  | Av. ring width | Av. standard deviation | Av. first-order autocorrelation | <i>n</i> |
|---|----------------|------------------------|---------------------------------|----------|
| Coppice from a modern stand (Kemmel, B)                                     | 1.97           | 1.16                   | 0.74                            | 12       |
| Oak regenerated under pine (Mattemburg, NL)                                 | 1.66           | 0.98                   | 0.69                            | 109      |
| High forest – <i>Q. robur</i> (Soignes, B)                                  | 2.87           | 1.39                   | 0.75                            | 107      |
| High forest – <i>Q. petraea</i> (Buggenhout, B)                             | 2.79           | 1.56                   | 0.77                            | 49       |
| Archaeological wood – 12 <sup>th</sup> /13 <sup>th</sup> century (Ypres, B) | 1.92           | 0.76                   | 0.70                            | 222      |
| Archaeological wood – ca. 1370 A.D. (Medieval warehouse, Lissewege, B)      | 2.79           | 0.94                   | 0.58                            | 38       |

An important feature that determines the dimensional stability of the wood is the applied sawing pattern. It is well known that timber susceptible to moisture fluctuations will display changes in dimension and shape (Forest Products Society 1999; Tsoumis 1991). Sawing timber parallel to the wood rays, i.e. quarter sawn, can minimize such drying defects (Sandberg 1996). Seen from the orientation of the growth rings on the sculptures' underside from the Pailhe altarpiece, it was noticed that for 88.4% of all examined objects the original board was quarter sawn.

All this refers to a specific assortment of edge-grained lumber preferred by the medieval wood carvers. This is also reflected in the guild ordinances. The Saint Luke's Guild, representing the woodcarvers in Antwerp, provided several written instructions and regulations concerning the required quality of wood entering the production process of Brabantine altarpiece sculptures (Van der Straelen 1855). The regulations explicitly stated that the required wood species should be oak (“...eyken hout...”) or walnut (“...nootboemen...”) that is properly dried (“... van drooghen houte...”) and that wainscots (“... wagenschot...”) are preferred. The absence of sapwood is not explicitly stated, but the section “...eyken hout sonder fu...”, meaning oak lumber without any defects, was probably interpreted in that way by the craftsmen. Other regulations dealt with a grade of timber that could be described as “healthy wood”. In this context two specific requirements remain unclear: “...de nyet en slaept...” and “...den rooden ollem nyet en heeft...”. The first statement means, literally translated: wood that doesn't sleep and could refer to wood that is infected by a saprobic fungus (e.g. *Chondrostereum purpureum* (Pers.)). The second statement probably specifies that no abnormal discolouration of the wood should be present that could indicate oxidation or decay by fungi. The whole package of requirements and regulations strongly suggests that wood of the highest possible quality should be selected for the construction of altarpiece sculptures.

As cited by different authors (Bonde *et al.* 1997; Wazny and Eckstein 1987; Zunde 1999) Baltic oak wood was mostly transported as so-called “wainscot” (*wagenschoss*, *waagenschott*, *vanszos*, *wayneskot*, *wagenschot*). The exact meaning of this type of assortment regarding its dimensions and shape evolved through the years (Wazny 2005). For instance, according to Hirsch (Hirsch 1858) wainscots, at the beginning of the 15<sup>th</sup> century, were produced from oak logs without

knots that were 3.04 m to 4.25 m long and up to 75 cm in diameter. A cargo, found on a medieval shipwreck called the “Copper Wreck”, discovered in the Gulf of Gdansk (Litwin 1980) and dated 1405 - 1408 AD via dendrochronology (Wazny and Bonde, *unpublished data*), was composed of edge grained wooden boards and staves. The dimensions of these boards are 2.36 - 2.52 m long and 24 - 30 cm wide, with a trapezoidal cross-section. The smallest surface, oriented towards the pith, has a thickness of 1.5 - 3 cm, and the opposite surface a thickness of 4 - 6 cm (Wazny 2005). Although considerably shorter in length, this assortment approximates the above stated dimensions of wainscot given by Hirsch (1958).

Returning to the dimensions of the investigated sculptures it was noticed that 95% of all sculptures are smaller than 33 cm wide. Dendrochronological analysis suggests that seldom more than four sculptures were carved from the same piece of wood. Adding up the length, combined with the maximum observed width and depth of sculptures originating from one single board (e.g. BASS-01, -18, -48; BASS-30, 31L, -35; PAIL-A3, -E02, -F01, -F02 and GB-A1a, -A2, -A3), results in a virtual approximation of the original board. According to the recorded dimensions, the original boards must have been at least 90 cm up to 143 cm long, 21 cm to 46 cm wide with a maximum thickness of 7 cm up to 15 cm. Compared to the dimensions of the cargo on the “Copper Wreck” it is noticed that the average total length calculated from the related altarpiece sculptures is considerably smaller. The width and thickness correspond much better. Adding up the volume of each individual sculpture, computed by multiplying the maximum value for each dimension, it becomes possible to calculate the minimum volume of wood that was used. For the construction of the Pailhe altarpiece, for instance, a minimum volume of 396.1 dm<sup>3</sup> of oak lumber was needed, including both the case (169.5 dm<sup>3</sup>) and the sculptures (226.6 dm<sup>3</sup>). Additionally the volume of wood that was used for the creation of the shutters, now lost, should be added.

The five sculptures from the Bassine collection that are carved from the same board (BASS-14, -61, -64, -65 and -70) also demonstrate that the wood carvers had a very economical approach towards the use of their basic material. This is obvious when interpreting the arrangement of the tree-ring patterns (Figure 3.7). All five are carved from one particular edge-grained board (wainscot). One sculpture (BASS-14) is

considerably bigger (41 x 30 x 11 cm) than the other four. Assuming that this big sculpture was carved first, the woodcarver(s) must have scrutinized the remaining part of the board before carving the other four sculptures. The tree-ring patterns of the four small sculptures have an overlap of maximum 5 years, or no overlap at all. Consequently, a minimum of wood must have been lost during the creation of these five statues.

### 3.5 Conclusions

Dendrochronological dating not only confirmed the medieval origin of the sculptures, it also provided hard evidence to support stylistic and iconographic observations. Studying medieval sculptures as wood technological products reveals aspects of timber preferences and processing techniques at that time. Medieval wood carvers preferred to use oak imported from the Baltic region, mostly *Quercus robur*, for the creation of the altarpiece sculptures, not a completely free choice since guild regulations imposed the use of high quality timber, which was hardly available on the local wood market. These regulations can be considered as an early grading system. Careful inspection of the growth-ring pattern reveals the consequences of such regulations for medieval wood carvers in the choice of their basic material, i.e. “*drooghen custbaren eyckene hout*” (valuable dry oak wood). This particular grade of timber, characterized by a fine and regular grain, was at that time available on the wood market only as wainscot from the Baltics.

It is clear that our understanding of the altarpiece production benefits from the intensive collaboration between art historians, dendrochronologists, restorers and curators. The interaction between art historians and wood biologists proved extremely fruitful and resulted in a more accurate interpretation of the acquired data from both disciplines. This demonstrates that intensive collaboration between various scientific disciplines is necessary in order to reconstruct the complete working process of the production of wooden sculptures, which was an interdisciplinary task at that time as well.

## Acknowledgements

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Carved wooden altarpieces from 15<sup>th</sup>-16<sup>th</sup> century

**Annex:** All sculptures subjected to a dendrochronological analysis, with indication of the length of the tree-ring series (LE), no. of sapwood rings (SWR), estimated no. of missing sapwood rings (MSWR), average ring width (ARW), standard deviation (SD) and first-order autocorrelation (FOA).

| Title of sculpture                           | DendroCode | LE  | SWR | Date (AD) |      | MSWR       | ARW  | SD   | FOA  |
|--|------------|-----|-----|-----------|------|------------|------|------|------|
|  |            |     |     | start     | end  |            |      |      |      |
| <b>PAILHE ALTARPIECE</b>                     |            |     |     |           |      |            |      |      |      |
| Crucifixion                                  |            |     |     |           |      |            |      |      |      |
| Fainting Virgin                              | PAIL-A01   | 206 | 0   | 1305      | 1510 | 15 (+9/-6) | 1.35 | 0.59 | 0.79 |
| Holy woman                                   | PAIL-A02   | 65  | 0   | -         | -    | -          | 2.12 | 0.56 | 0.49 |
| Soldier                                      | PAIL-A02b  | 82  | 0   | -         | -    | -          | 1.16 | 0.35 | 0.37 |
| Soldier holding a shield and a lance         | PAIL-A03   | 93  | 0   | 1422      | 1514 | 15 (+9/-6) | 1.67 | 0.46 | 0.45 |
| Soldier carrying a sword                     | PAIL-A03b  | 54  | 0   | -         | -    | -          | 1.84 | 0.51 | 0.31 |
| Landscape                                    | PAIL-A07   | 109 | 0   | -         | -    | -          | 1.59 | 0.33 | 0.34 |
| Landscape with two figures                   | PAIL-A08   | 132 | 0   | -         | -    | -          | 1.57 | 0.31 | 0.32 |
| Visitation                                   | PAIL-A10   | 87  | 0   | -         | -    | -          | 1.11 | 0.21 | 0.24 |
| Angel appearing to Joseph                    | PAIL-A11   | 79  | 0   | 1398      | 1476 | 15 (+9/-6) | 1.11 | 0.24 | 0.36 |
| Circumcision                                 |            |     |     |           |      |            |      |      |      |
| Female figures                               | PAIL-B01   | 97  | 0   | -         | -    | -          | 1.29 | 0.56 | 0.76 |
| Virgin, child and high priest                | PAIL-B02   | 310 | 0   | -         | -    | -          | 1.14 | 0.39 | 0.67 |
| Male figure                                  | PAIL-B03   | 62  | 0   | 1341      | 1402 | 15 (+9/-6) | 1.89 | 0.53 | 0.64 |
| Female figure                                | PAIL-B04   | 69  | 0   | -         | -    | -          | 1.39 | 0.34 | 0.66 |
| Male figure                                  | PAIL-B05   | 113 | 0   | -         | -    | -          | 0.69 | 0.26 | 0.54 |
| Marriage of Mary and Joseph                  | PAIL-B07   | 61  | 0   | -         | -    | -          | 1.37 | 0.23 | 0.16 |
| Tree of Jesse                                |            |     |     |           |      |            |      |      |      |
| Prophet wearing a cape                       | PAIL-C01   | 90  | 0   | 1398      | 1487 | 15 (+9/-6) | 1.53 | 0.43 | 0.67 |
| Prophet carrying a purse                     | PAIL-C02   | 92  | 0   | 1390      | 1481 | 15 (+9/-6) | 1.66 | 0.47 | 0.62 |
| Prophet carrying a book                      | PAIL-C04   | 43  | 0   | 1350      | 1392 | 15 (+9/-6) | 2.26 | 0.46 | 0.41 |
| Prophet carrying a purse and a turban        | PAIL-C05   | 56  | 0   | 1335      | 1390 | 15 (+9/-6) | 2.01 | 0.46 | 0.7  |
| Annunciation                                 | PAIL-C18   | 80  | 0   | 1399      | 1478 | 15 (+9/-6) | 1.06 | 0.18 | 0.15 |
| The massacre of the innocents                | PAIL-C19   | 74  | 0   | -         | -    | -          | 1.13 | 0.21 | 0.23 |
| Floorboard                                   | PAIL-C20a  | 45  | 0   | -         | -    | -          | 1.60 | 0.56 | 0.7  |
| Floorboard                                   | PAIL-C20b  | 73  | 0   | 1391      | 1463 | 15 (+9/-6) | 1.38 | 0.36 | 0.43 |
| Death of the Virgin                          |            |     |     |           |      |            |      |      |      |
| Apostle carrying a book in a pocket          | PAIL-D01   | 158 | 0   | 1325      | 1482 | 15 (+9/-6) | 0.89 | 0.25 | 0.61 |
| Praying apostle                              | PAIL-D02   | 153 | 0   | 1321      | 1473 | 15 (+9/-6) | 1.14 | 0.32 | 0.53 |
| Apostle leaning on a prayer desk with a book | PAIL-D03   | 105 | 0   | 1385      | 1489 | 15 (+9/-6) | 1.61 | 0.52 | 0.61 |
| Virgin and two apostles                      | PAIL-D04   | 75  | 0   | 1441      | 1515 | 15 (+9/-6) | 1.57 | 0.47 | 0.56 |
| Bed  | PAIL-D04b  | 290 | 0   | -         | -    | -          | 0.98 | 0.46 | 0.86 |
| Apostle carrying a censer                    | PAIL-D05   | 74  | 0   | -         | -    | -          | 1.32 | 0.52 | 0.66 |
| Apostle wearing long hair                    | PAIL-D06   | 77  | 0   | 1403      | 1479 | 15 (+9/-6) | 1.02 | 0.35 | 0.57 |
| Apostle with arms crossed                    | PAIL-D07   | 50  | 0   | 1332      | 1381 | 15 (+9/-6) | 1.77 | 0.57 | 0.62 |
| Apostle wearing headgear                     | PAIL-D08   | 78  | 0   | -         | -    | -          | 1.18 | 0.37 | 0.58 |
| Apostle without arms                         | PAIL-D09   | 89  | 0   | 1394      | 1482 | 15 (+9/-6) | 1.03 | 0.35 | 0.67 |
| Blessing apostle                             | PAIL-D10   | 91  | 0   | 1400      | 1490 | 15 (+9/-6) | 1.03 | 0.35 | 0.62 |
| Angel appearing to Joseph                    | PAIL-D11   | 82  | 0   | -         | -    | -          | 1.15 | 0.20 | 0.38 |
| Adoration of the Magi                        |            |     |     |           |      |            |      |      |      |
| King Caspar                                  | PAIL-E01   | 87  | 0   | 1414      | 1500 | 15 (+9/-6) | 1.36 | 0.50 | 0.45 |
| Kneeling King Melchior                       | PAIL-E02   | 88  | 0   | 1404      | 1491 | 15 (+9/-6) | 1.72 | 0.47 | 0.2  |
| Virgin with child                            | PAIL-E03   | 161 | 2   | 1353      | 1513 | 15 (+9/-6) | 1.24 | 0.41 | 0.77 |
| King Balthasar                               | PAIL-E04   | 122 | 0   | 1271      | 1393 | 15 (+9/-6) | 1.12 | 0.48 | 0.71 |
| Joseph                                       | PAIL-E06   | 85  | 0   | 1408      | 1492 | 15 (+9/-6) | 1.26 | 0.32 | 0.44 |

Carved wooden altarpieces from 15<sup>th</sup>-16<sup>th</sup> century

| Title of sculpture   | KeyCode  | LE  | SWR | Date (AD) |      | MSWR       | ARW  | SD   | FOA   |
|--|----------|-----|-----|-----------|------|------------|------|------|-------|
|  |          |     |     | start     | end  |            |      |      |       |
| <b>Nativity</b>  |          |     |     |           |      |            |      |      |       |
| Shepherd carrying a candle                                 | PAIL-F01 | 72  | 0   | 1439      | 1510 | 15 (+9/-6) | 1.57 | 0.34 | 0.37  |
| Virgin Mary  | PAIL-F02 | 120 | 0   | 1390      | 1509 | 15 (+9/-6) | 1.67 | 0.45 | 0.29  |
| Saint Joseph   | PAIL-F04 | 151 | 0   | -         | -    | -          | 1.12 | 0.25 | 0.46  |
| Shepherd with a bagpipe                                    | PAIL-F05 | 88  | 0   | -         | -    | -          | 1.16 | 0.38 | 0.75  |
| Female figurer   | PAIL-F11 | 55  | 0   | 1429      | 1483 | 15 (+9/-6) | 1.30 | 0.30 | 0.32  |
| <b>The Presentation in the Temple</b>                      |          |     |     |           |      |            |      |      |       |
| Female figure  | PAIL-G01 | 104 | 0   | -         | -    | -          | 1.12 | 0.40 | 0.78  |
| <b>Case</b>  |          |     |     |           |      |            |      |      |       |
| Post   | PAIL-K01 | 220 | 0   | -         | -    | -          | 0.95 | 0.33 | 0.41  |
| Post   | PAIL-K02 | 133 | 0   | 1300      | 1432 | 15 (+9/-6) | 1.41 | 0.54 | 0.5   |
| Board from the back of the case                            | PAIL-K03 | 119 | 0   | 1382      | 1500 | 15 (+9/-6) | 1.53 | 0.45 | 0.44  |
| Board from the back of the case                            | PAIL-K04 | 56  | 0   | -         | -    | -          | 1.17 | 0.31 | 0.34  |
| Board from the back of the case                            | PAIL-K05 | 83  | 0   | 1378      | 1460 | 15 (+9/-6) | 0.87 | 0.24 | -0.03 |
| <b>BASSINE COLLECTION</b>                                  |          |     |     |           |      |            |      |      |       |
| Annunciation   | BASS-01  | 232 | 0   | 1243      | 1474 | 15 (+9/-6) | 1.14 | 0.42 | 0.73  |
| Visitation   | BASS-03  | 159 | 0   | 1333      | 1491 | 15 (+9/-6) | 1.30 | 0.38 | 0.58  |
| Nativity   | BASS-04  | 147 | 0   | 1355      | 1501 | 15 (+9/-6) | 1.51 | 0.37 | 0.41  |
| Two shepherds of the Nativity                              | BASS-05  | 119 | 0   | -         | -    | -          | 1.79 | 0.58 | 0.65  |
| Shepherd of the Nativity                                   | BASS-06  | 101 | 0   | -         | -    | -          | 1.26 | 0.54 | 0.81  |
| Adoration of the Magi                                      | BASS-14  | 225 | 0   | 1268      | 1492 | 15 (+9/-6) | 1.21 | 0.42 | 0.64  |
| Kneeling Magus of the Adoration                            | BASS-15  | 209 | 0   | -         | -    | -          | 0.77 | 0.19 | 0.59  |
| Circumcision   | BASS-18  | 215 | 0   | 1269      | 1483 | 15 (+9/-6) | 1.18 | 0.38 | 0.68  |
| Virgin and Child of a Presentation in the Temple           | BASS-19  | 59  | 0   | 1317      | 1375 | 15 (+9/-6) | 1.24 | 0.28 | 0.31  |
| Joseph and a female figure of a Presentation in the Temple | BASS-20  | 180 | 0   | 1312      | 1491 | 15 (+9/-6) | 0.87 | 0.23 | 0.5   |
| Christ bearing the cross                                   | BASS-21  | 180 | 0   | -         | -    | -          | 0.86 | 0.25 | 0.7   |
| Virgin and Saint John                                      | BASS-27  | 267 | 0   | 1235      | 1501 | 15 (+9/-6) | 0.93 | 0.29 | 0.65  |
| Two talking soldiers under the cross                       | BASS-30  | 177 | 0   | 1329      | 1505 | 15 (+9/-6) | 1.25 | 0.40 | 0.7   |
| Holy women and soldiers of a Crucifixion                   | BASS-31L | 151 | 0   | 1340      | 1490 | 15 (+9/-6) | 1.24 | 0.42 | 0.72  |
| Holy women and soldiers of a Crucifixion                   | BASS-31R | 159 | 0   | 1332      | 1490 | 15 (+9/-6) | 1.28 | 0.43 | 0.64  |
| Magdalen   | BASS-34  | 44  | 0   | 1413      | 1456 | 15 (+9/-6) | 2.68 | 0.65 | 0.56  |
| Veronica   | BASS-35  | 133 | 0   | 1360      | 1492 | 15 (+9/-6) | 1.17 | 0.31 | 0.71  |
| Descent from the cross                                     | BASS-43  | 297 | 0   | 1205      | 1501 | 15 (+9/-6) | 0.96 | 0.31 | 0.6   |
| Holy woman   | BASS-44  | 163 | 0   | 1322      | 1484 | 15 (+9/-6) | 0.85 | 0.19 | 0.27  |
| Holy woman   | BASS-45  | 124 | 0   | 1387      | 1510 | 15 (+9/-6) | 1.08 | 0.37 | 0.49  |
| Three female background figures                            | BASS-48  | 174 | 0   | 1303      | 1476 | 15 (+9/-6) | 1.16 | 0.33 | 0.65  |
| Altar  | BASS-53  | 77  | 0   | 1255      | 1331 | 15 (+9/-6) | 1.45 | 0.40 | 0.52  |
| Landscape with the source of life                          | BASS-54  | 228 | 0   | 1254      | 1481 | 15 (+9/-6) | 1.04 | 0.42 | 0.81  |
| Dream of Abraham or Eliah in the desert                    | BASS-61  | 36  | 0   | 1257      | 1292 | 15 (+9/-6) | 1.67 | 0.48 | 0.59  |
| Jonah returned by the whale                                | BASS-62  | 66  | 0   | -         | -    | -          | 1.18 | 0.45 | 0.66  |
| Moses receiving the Tables of the Law                      | BASS-63  | 80  | 0   | 1428      | 1507 | 20(+/-6)   | 1.05 | 0.30 | 0.56  |
| Isaac bearing firewood                                     | BASS-64  | 94  | 0   | 1403      | 1496 | 15 (+9/-6) | 0.95 | 0.32 | 0.65  |
| Abraham's sacrifice  | BASS-65  | 57  | 0   | 1346      | 1402 | 15 (+9/-6) | 1.28 | 0.35 | 0.58  |
| Baptism  | BASS-66  | 75  | 0   | 1334      | 1408 | 15 (+9/-6) | 1.18 | 0.30 | 0.46  |
| Confirmation   | BASS-67  | 90  | 0   | 1404      | 1493 | 15 (+9/-6) | 0.92 | 0.26 | 0.68  |
| Confession   | BASS-68  | 80  | 0   | -         | -    | -          | 1.17 | 0.45 | 0.74  |
| Eucharist  | BASS-69  | 85  | 0   | 1327      | 1411 | 15 (+9/-6) | 1.21 | 0.35 | 0.46  |
| Extreme unction  | BASS-70  | 57  | 0   | 1294      | 1350 | 15 (+9/-6) | 1.57 | 0.34 | 0.27  |
| Magdalen   | BASS-71  | 116 | 0   | 1385      | 1500 | 15 (+9/-6) | 1.32 | 0.51 | 0.71  |

Carved wooden altarpieces from 15<sup>th</sup>-16<sup>th</sup> century

| Title of sculpture                                       | KeyCode    | LE  | SWR | Date (A.D.) |      | MSWR       | ARW  | SD   | FOA  |
|--|------------|-----|-----|-------------|------|------------|------|------|------|
|  |            |     |     | start       | end  |            |      |      |      |
| <b>GAASBEEK ALTARPIECE</b>                               |            |     |     |             |      |            |      |      |      |
| Joseph of Arimathea supporting Christ (I)                | GB-A1a     | 165 | 0   | 1313        | 1477 | 15 (+9/-6) | 0.94 | 0.18 | 0.25 |
| Joseph of Arimathea supporting Christ (II)               | GB-A1b     | 279 | 0   | 1203        | 1481 | 15 (+9/-6) | 0.75 | 0.17 | 0.54 |
| Magdalen   | GB-A2      | 172 | 0   | 1305        | 1476 | 15 (+9/-6) | 0.98 | 0.21 | 0.22 |
| Virgin and Saint John                                    | GB-A3      | 207 | 0   | 1272        | 1478 | 15 (+9/-6) | 1.03 | 0.25 | 0.48 |
| Nicodemus with crown of thorns                           | GB-A4      | 32  | 0   | -           | -    | -          | 2.44 | 1.06 | 0.51 |
| <b>VLEESHUIS COLLECTION</b>                              |            |     |     |             |      |            |      |      |      |
| Five male figures  | VM-AV2417a | 219 | 0   | 1253        | 1471 | 15 (+9/-6) | 1.79 | 0.45 | 0.49 |
| Three male figures                                       | VM-AV2417b | 178 | 0   | 1264        | 1441 | 15 (+9/-6) | 1.37 | 0.47 | 0.63 |
| Three male figures                                       | VM-AV2417c | 190 | 0   | 1287        | 1476 | 15 (+9/-6) | 0.99 | 0.22 | 0.64 |
| Three male figures                                       | VM-AV2417d | 184 | 0   | 1286        | 1469 | 15 (+9/-6) | 1.00 | 0.25 | 0.54 |
| Christ with four male and one female figures             | VM-AV2417e | 179 | 0   | 1288        | 1466 | 15 (+9/-6) | 1.49 | 0.54 | 0.59 |
| Virgin, Saint John and three other male figures          | VM-AV2417f | 192 | 0   | 1276        | 1467 | 15 (+9/-6) | 1.43 | 0.49 | 0.46 |
| Three male figures                                       | VM-AV2417g | 140 | 0   | 1337        | 1476 | 15 (+9/-6) | 0.91 | 0.30 | 0.55 |
| Three male figures                                       | VM-AV2417h | 170 | 0   | 1304        | 1473 | 15 (+9/-6) | 1.04 | 0.37 | 0.69 |
| Christ with two male figures                             | VM-AV2417i | 165 | 0   | -           | -    | -          | 1.38 | 0.48 | 0.67 |
| Four male figures in a landscape                         | VM-AV2417j | 172 | 0   | 1302        | 1473 | 15 (+9/-6) | 1.04 | 0.31 | 0.59 |
| The crowning with thorns                                 | VM-AV2602  | 248 | 0   | 1239        | 1486 | 15 (+9/-6) | 1.08 | 0.38 | 0.53 |
| Young male saint in boiling oil                          | VM-AV5523a | 178 | 0   | -           | -    | -          | 1.43 | 0.50 | 0.74 |
| Ruler and servant  | VM-AV5523e | 131 | 0   | 1387        | 1517 | 15 (+9/-6) | 1.57 | 0.70 | 0.71 |
| Ruler and servant on a stage                             | VM-AV5523f | 173 | 0   | 1356        | 1528 | 15 (+9/-6) | 1.30 | 0.51 | 0.79 |
| Two horsemen in a landscape                              | VM-AV5523k | 135 | 0   | 1392        | 1526 | 15 (+9/-6) | 1.34 | 0.28 | 0.34 |
| Horseman in a landscape with buildings and a dog         | VM-AV5523m | 142 | 0   | 1385        | 1526 | 15 (+9/-6) | 1.30 | 0.25 | 0.19 |
| Young male saint handing out bread and money to the poor | VM-AV5551  | 168 | 0   | 1351        | 1518 | 15 (+9/-6) | 0.80 | 0.28 | 0.79 |
| Three Marys and the angel at the tomb of Christ          | VM-AV851   | 274 | 0   | 1206        | 1479 | 15 (+9/-6) | 1.04 | 0.36 | 0.51 |
| Chained Christ with male figure                          | VM-AV884   | 73  | 0   | 1427        | 1499 | 15 (+9/-6) | 1.86 | 0.58 | 0.59 |
| <b>CATHARIJNECONVENT COLLECTION</b>                      |            |     |     |             |      |            |      |      |      |
| Magdalen   | UM-ABM323  | 114 | 0   | -           | -    | -          | 1.14 | 0.53 | 0.5  |
| The preaching of Saint Peter                             | UM-ABM590  | 107 | 0   | 1411        | 1517 | 15 (+9/-6) | 1.07 | 0.20 | 0.5  |
| The descent from the cross                               | UM-ABM259  | 157 | 0   | -           | -    | -          | 1.57 | 0.48 | 0.41 |
| Kneeling canon   | UM-RMCC117 | 97  | 0   | 1302        | 1398 | 15 (+9/-6) | 0.97 | 0.54 | 0.56 |
| The martyrdom of Pope Clement                            | UM-RMCC202 | 87  | 3   | 1429        | 1515 | 19 (+/-6)  | 0.85 | 0.54 | 0.52 |
| Magdalen and mourning female figure                      | UM-SMCC2   | 95  | 10  | -           | -    | -          | 0.95 | 1.63 | 0.90 |
| Veronica   | UM-SMCC1   | 67  | 0   | 1395        | 1461 | 16 (+/-5)  | 0.67 | 0.92 | 0.71 |
| Mourning female figure                                   | UM-RMCC109 | 107 | 0   | 1363        | 1469 | 20 (+/-6)  | 1.07 | 0.36 | 0.60 |
| Christ bearing the cross and Veronica                    | UM-BMH3358 | 240 | 0   | 1246        | 1485 | 15 (+9/-6) | 2.40 | 0.38 | 0.78 |



# Provenancing the original source of timber, imported during the Middle Ages

# 4

## Chapter

### Summary

During the Middle Ages northern Belgium and the Netherlands were gradually deforested. A steadily rising demand for quality timber obliged merchants to look for new timber sources. From the 13<sup>th</sup> century onwards, large volumes of timber were imported from surrounding regions and, despite the remote supply area, merchants of the Hanseatic League managed to organize a huge timber trade from towns around the Baltic Sea.

Trees from forests along the Vistula River seem to have been exported via Gdansk, first to Bruges and later to Antwerp. At their final destination the imported wood assortments were highly appreciated for shipbuilding and construction purposes, but also by woodcarvers and famous painters.

Over the last decade dendrochronologists have established a dense network of historical site chronologies for northern and central Poland. These site chronologies are supposed to reflect local growth conditions and may allow the identification of the provenance of the wood of many art historical objects made out of Baltic timber.

Tree-ring patterns of panel paintings and sculptures, mainly from the 14<sup>th</sup>-16<sup>th</sup> centuries, were measured and compared to this dataset of site chronologies. An evaluation of the accuracy of sourcing medieval Baltic timbers using standard correlation techniques was made. The identification of provenance enriches historical information on logging activity and timber trade around the Baltic Sea during the Middle Ages.

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## 4.1 Introduction

Forests in the Low Countries experienced a long and complex history of exploitation and degradation. An increasing anthropogenic pressure during the Middle Ages resulted in a drastic deforestation. Major parts of the remaining primary forests were logged and converted to arable land (Buis 1985; Tack *et al.* 1993). As well as a dramatic reduction in forest-cover, management interventions often altered the structure of the residual forests. Sylvicultural systems such as coppice or coppice-with-standards became gradually more popular during the Middle Ages (Rackham 2003; Vera 2000). These two structural interventions were often implemented for oak (*Quercus robur* L. and *Q. petraea* (Matt.) Liebl.). Such forests provided a sustainable and diverse assortment of timber but were chiefly appreciated for their vigorous production of acorns, which was the most essential source of fodder for pig husbandry.

These changes in forest-cover and structure also had a significant influence on the availability and quality of timber products. The mounting demographic evolution during the Middle Ages resulted in a rising need for construction timber (Buis 1985). Local forests could no longer cope with this increased demand. As a consequence, merchants started to explore more remote areas to replenish their supplies. Firewood and wood for carpentry was generally still dependent on the local wood supply, but high quality construction timber was imported from more distant regions.

In general the most viable wood resources were located along the major rivers of northern Europe (Figure 4.1). Water transport was the most economical way to deliver goods. Transport of wood assortments over land, on the other hand, was too laborious and expensive (Rackham 1982). Trees from forests near a river were cut, cleaved and floated down the river towards a town with the status of staple town and the right to stock and distribute all imported timber passing through (de Vries 1994). In the Low Countries the Meuse and the Rhine were the most important trade-routes for the shipment of timber products. Forests in Northern France and Germany were the most obvious timber resources since these were the nearest forests where quality timber could be found. However, traditionally Flemish towns have always relied more on overseas transport for their commodities on the international market

than transport along the rivers. Timber importation was more convenient by boat, due to the cities close location to the North Sea, than importation of timbers floated along the Rhine or the Meuse that then needed additional transport over land. Also important were the advances in navigation and shipbuilding during the 15<sup>th</sup> and 16<sup>th</sup> century. The Hanseatic cog and hulk, which could carry a cargo of ca. 100 and 300 tons respectively, enabled the transportation of goods at a massive scale. Political reasons may also have played an important role in the establishment of trading-routes.



**Figure 4.1:** Major rivers of northern Europe. Primary forests along these waterways are possible historical timber sources. Trunks were floated down the river towards the nearest staple town or exporting harbour.

During the Middle Ages the Hanseatic League slowly evolved from a loose network of traders to a disciplined organization, controlling most of the trade in Northern Europe. Although exploiting remote areas around the Baltic Sea, the Hansa towns of Lübeck and Gdansk managed to organize a huge trade in Baltic timber (Tossavainen 1994). Forests situated along the Vistula River, the main waterway of the medieval Kingdom of Poland and Teutonic Order, were the most important exploitation areas for this trade. After logging, stems were cleaved and floated towards the harbour of export. Transportation of semi-products (confirmed e.g. by the records from custom

chambers of Wloclawek and Weissberg (Rybarski 1958), both located along the Vistula River) was much more convenient and faster than floating complete logs, especially in the case of relative heavy oak stems. During the 14th-15th centuries Gdansk became one of the most important export harbours (Bonde 1992; Wazny and Eckstein 1987). Later, during the second half of the 16th century, the centre of the timber trade shifted further eastwards, towards Königsberg/Kalinigrad, the Duchy of Courland and Riga (Zunde 1999).

From early 13<sup>th</sup> century on, oak from the Baltic area was imported into Flanders (northern Belgium). Wood was shipped from the harbour of Gdansk to the harbour of Bruges. At that time Bruges was the commercial centre of Western Europe. It was the meeting point for traders from Italy and Northern Europe (Tossavainen 1994; Wazny and Eckstein 1987). Later Antwerp gradually started to play a more important role in the timber trade. The oldest physical proof of Baltic timber in Flanders was found on archaeological sites as herring vessels, with felling dates situated at the end of the 14<sup>th</sup> century (Houbrechts and Pieters 1996). Although shipbuilding was the main branch of industry that used imported timbers, famous painters such as Jan van Eyck (ca.1395°-1441<sup>†</sup>), Hiëronimus Bosch (ca.1450°-1516<sup>†</sup>), Pieter Bruegel the Elder (ca.1525°-1569<sup>†</sup>) and Pieter Paul Rubens (1577°-1640<sup>†</sup>) highly appreciated the imported oak panels for their paintings (Bauch *et al.* 1978a; Eckstein *et al.* 1975). Also wood carvers during the 15<sup>th</sup> -16<sup>th</sup> century mostly used imported massive planks, referred to as *wainscots*, to carve their sculptures from. Oak imported from forests covering the Baltic countries was characterized by a slow and regular growth that results in wood with a fine grain (i.e. a narrow tree-ring structure). This has implications regarding the woods' technological properties. A fine grain, combined with a sawing pattern perpendicular to the growth rings (i.e. quarter-sawn timber), delivers boards and panels with a high dimensional stability. In addition to the superior quality, a wide spectrum of different assortments was available. Only a few artists still used local material (Fraiture 2000).

Several methods display a high potential for producing information on the original timber source. Recent developments in genetic research have shown the potential of DNA analysis to identify the geographical origin of wood specimens (Deguilloux *et al.* 2002). Optimisation of the *polymerase chain reaction* (PCR) allows extraction and



amplification of short and degraded DNA sequences from modern and ancient oak wood (Dumolin-Lapègue *et al.* 1999). In the case of *Q. robur* and *Q. petraea* detailed reference maps of chloroplast variants exist for Europe (Csaikl *et al.* 2002; Petit *et al.* 2002b), and could help to determine the geographical origin of the oak wood. Notwithstanding the new developments, routine implementation of these new techniques to analyse the degraded DNA remains in old, dry wood has yet to be established.

Using dendrochronology to determine the origin of timber has been successfully applied since the development of regional oak chronologies in Europe. This so-called *dendro-provenancing* is mostly used for wood from an archaeological or art historical context (Bonde 1992; Bonde *et al.* 1997; Crone *et al.* 2000). Within the framework of dendro-provenancing different types of tree-ring chronologies can be distinguished. A site chronology is composed of synchronised tree-ring series from one particular site, where a site is defined on ecological grounds (Kaennel and Schweingruber 1995). For historical studies, tree-ring series originating from archaeological sites should be incorporated into this definition. Master or regional chronologies are composed from archaeological, art historical and/or modern tree-ring series. They span long periods and reflect the average growth conditions over a vast area. They are computed by averaging several site chronologies into one series. The master and regional chronologies are mostly used to date new tree-ring series.

When examining tree-ring patterns from art-historical objects, up to now the *Baltic region* was often designated as the original timber source. Although these statements make sense and are well confirmed by historical documents and toll records, they refer to a vast region along the Baltic Sea. Over the last 15 years, the network of site and regional chronologies has been significantly enhanced for countries around the Baltic Sea. Northern and central Poland is now particularly well represented by a large number of historical site chronologies (Wazny, *unpublished data*). These site chronologies are derived from oak samples found on archaeological sites. They cover a time span between 952 AD and 1670 AD. It is assumed that this wood, used in constructions and foundations, is likely to be local wood. While wood for export was floated down the Vistula, directly towards the towns of the Hanseatic League, wood for local use was cut and cleaved in the nearest forest. These historical site

chronologies are supposed to reflect local growth conditions in contrast to the frequently used master chronologies that are composed of tree-ring series from a distinct, but vast area. Well known *Baltic* master chronologies, computed from tree-ring series of art historical objects, were built by Bauch (1978a) and Eckstein *et al.* (1975). Using tree-ring series measured on panel paintings Hillam and Tyers (1995) established the *Baltic1* and *Baltic2* chronologies. For dating purposes these master chronologies have proved to be extremely useful. The *Gdansk-Pomerania* chronology (Eckstein *et al.* 1986) was the first regional chronology for the Baltic region. It is composed of tree-ring series from buildings and archaeological sites in northern Poland, particularly from the area around Gdansk.

More detailed information on the provenance of Baltic oak, used for the construction of art-historical objects, would enrich historical information on logging activity and timber trade in the Baltic region during the Middle Ages. The question arises whether dendrochronology could serve as a tool to determine the original timber source of art-historical objects and, most of all, how accurately this timber source can be identified.

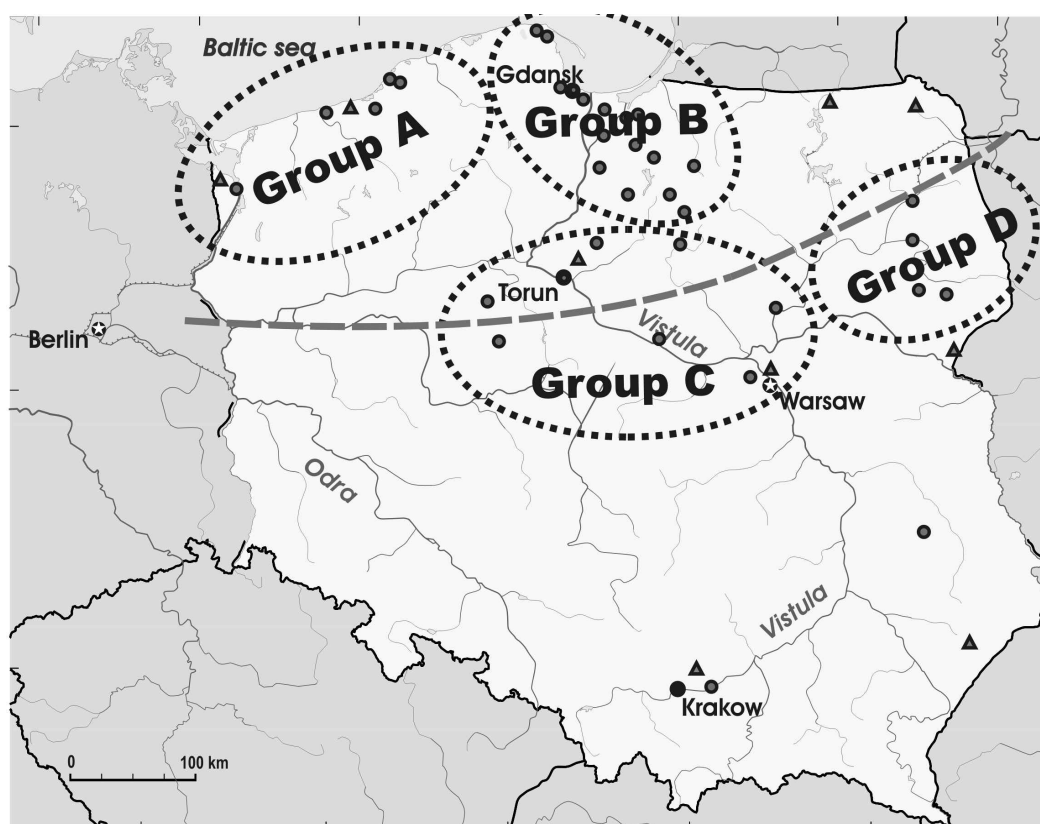
## 4.2 Materials and methods

### 4.2.1 Site and regional chronologies

Over the last decade dendrochronologists have established a dense network of regional and site chronologies in particular parts of the Baltic region (Wazny 2002). Archaeological excavations are often the main source of wood samples that are suitable for dendrochronological research. Oak was usually one of the most prominent species used for construction purposes. It is believed that on many of these archaeological sites local forests were the main timber source. This assumption that most of the wood comes from the vicinity of that archaeological site implies that each of the historical site chronologies reflect the local forest dynamics and growth conditions over a certain period. They are supposed to represent the average growth pattern from a single locality.

Site chronologies for 36 archaeological sites (Figure 4.2), in present-day Poland, are available for further investigation. The historical site chronologies cover different periods and are derived from a variable number of tree-ring series. Often less than

15 specimens per site were available to compute the site chronology (Table 4.1). The archaeological sites are mainly situated in northern and central Poland. Tree-ring data from southern Poland is only available for a few sites.



**Figure 4.2:** Location of the archaeological sites (•) and the selected modern forests (▲), plus a visualization of the four dendro-groups. The hatched line indicates the division between northern and southern Poland suggested by Wazny and Eckstein (1991).

#### 4.2.2 Dendrochronological database of art-historical objects

During an interdisciplinary research project more than one hundred wooden sculptures from Brabantine altarpieces, all made out of oak, were submitted for tree-ring analysis (De Boodt *et al.* 2005). These sculptures were carved during the 15<sup>th</sup>-16<sup>th</sup> century, mainly in the towns of Antwerp and Brussels. Rich collections of such altarpieces are still preserved in museums all over Europe (De Boodt 2004). This dataset of tree-ring series was increased by approximately one hundred similar measurements on altarpieces from that period (Bonde, *pers. comm.*; Vynckier 1993). In addition more than 300 tree-ring series, from panel paintings, were added to this dendrochronological dataset of tree-ring series from art-historical objects (Table 4.2). All the selected works of art were created during the period in which vast amounts of Baltic timber were imported into the Low Countries. In total 390 tree-ring series were available for further analysis.

**Table 4.1:** Description of the selected historical and modern site chronologies from present-day Poland.

| Site code   | Site location | Covered time period (AD/BC) | Length | Sample depth | Author     |
|---|---------------|-----------------------------|--------|--------------|------------|
| <b><i>Historical site chronologies</i></b>                |               |                             |        |              |            |
| PI-07   | Bielsk Podl.  | 1262-1503                   | 242    | 5            | T. Wazny   |
| PI-16   | Bransk        | 1247-1427                   | 181    | 16           | T. Wazny   |
| PI-11   | Darlowo       | 1477-1670                   | 194    | 5            | T. Wazny   |
| PI-15   | Dabrowno      | 1079-1344                   | 266    | 10           | T. Wazny   |
| PI-31   | Elblag        | 980-1347                    | 368    | 74           | T. Wazny   |
| PI-42   | Gdansk        | 1121-1398                   | 278    | 6            | T. Wazny   |
| PI-03   | Izdebno       | 1182-1294                   | 113    | 16           | T. Wazny   |
| PI-36   | Jeziernik     | 1151-1363                   | 213    | 12           | T. Wazny   |
| PI-22b  | Kolobrzeg     | 1509-1664                   | 156    | 6            | T. Wazny   |
| PI-22a  | Kolobrzeg     | 1084-1393                   | 310    | 154          | T. Wazny   |
| PI-01b  | Koszalin      | 1276-1478                   | 203    | -            | T. Wazny   |
| PI-01a  | Koszalin      | 1139-1297                   | 159    | 3            | T. Wazny   |
| PI-12   | Krupy         | 1209-1401                   | 193    | 7            | T. Wazny   |
| PI-34   | Kwidzyn       | 1343-1587                   | 245    | 6            | T. Wazny   |
| PI-35   | Kwietniewo    | 1439-1638                   | 200    | 8            | T. Wazny   |
| PI-08   | Lodygowo      | 1206-1308                   | 103    | 2            | T. Wazny   |
| PI-29   | Lubawa        | 1476-1610                   | 135    | 4            | T. Wazny   |
| PI-10   | Lublin        | 1240-1374                   | 135    | 10           | T. Wazny   |
| PI-05   | Malbork       | 1185-1320                   | 136    | 5            | T. Wazny   |
| PI-06   | Nowy Dwor     | 1144-1252                   | 109    | 3            | T. Wazny   |
| PI-38   | Gdansk Oliwa  | 1375-1599                   | 225    | 12           | T. Wazny   |
| PI-19   | Ostroda       | 1157-1346                   | 190    | 4            | T. Wazny   |
| PI-09   | Ostrowite     | 1133-1299                   | 167    | 2            | T. Wazny   |
| PI-20   | Plock         | 1177-1364                   | 188    | 2            | T. Wazny   |
| PI-37   | Pruszcz       | 1151-1431                   | 281    | -            | T. Wazny   |
| PI-39   | Przezmark     | 1140-1390                   | 251    | 10           | T. Wazny   |
| PI-30   | Puck          | 1408-1568                   | 161    | 8            | T. Wazny   |
| PI-41   | Puck          | 1111-1407                   | 297    | 7            | T. Wazny   |
| PI-27   | Pultusk       | 1192-1452                   | 261    | -            | M. Krapiec |
| PI-04   | Rusiec        | 1236-1447                   | 212    | 23           | T. Wazny   |
| PI-40   | Starzyno      | 1147-1374                   | 228    | -            | T. Wazny   |
| PI-18   | Szczecin      | 952-1272                    | 321    | 74           | T. Wazny   |
| PI-44   | Torun         | 1225-1445                   | 221    | -            | A. Zielski |
| PI-17   | Trzemeszno    | 1218-1300                   | 83     | 2            | T. Wazny   |
| PI-02   | Tykocin       | 1293-1477                   | 185    | 4            | T. Wazny   |
| PI-28   | Vistula       | 1100-1529                   | 430    | 25           | M. Krapiec |
| PI-14   | Zalewo        | 1194-1361                   | 168    | 3            | T. Wazny   |
| <b><i>Tree-ring series from actual Polish forests</i></b> |               |                             |        |              |            |
| pola007   | Goldap        | 1871-1980                   | 110    | 22           | T. Wazny   |
| pola008   | Hajnowka      | 1720-1984                   | 265    | 19           | T. Wazny   |
| pola009   | Kosobudy      | 1782-1988                   | 207    | 22           | T. Wazny   |
| pola010   | Koszalin      | 1782-1986                   | 205    | 22           | T. Wazny   |
| pola011   | Krakow        | 1792-1985                   | 194    | 29           | T. Wazny   |
| pola013   | Suwalki       | 1861-1986                   | 126    | 19           | T. Wazny   |
| pola014   | Torun         | 1713-1986                   | 274    | 21           | T. Wazny   |
| pola015   | Warszawa      | 1690-1984                   | 295    | 19           | T. Wazny   |
| pola016   | Wolin         | 1554-1986                   | 433    | 23           | T. Wazny   |

**Table 4.2:** Overview of the art historical database.

| Object   | Total number | Dated          | Undated       | Covered time period (AD) | Author(s)                                  |
|--|--------------|----------------|---------------|--------------------------|--|
| <b>Sculptures from altarpieces</b>   |              |                |               |                          |  |
| Altarpieces of Bassine, Pailhe and Gaasbeek (Belgium-Brussels)                   | 91           | 62             | 29            | 1203-1515                | K. Haneca & H. De Pauw                     |
| Altarpiece fragments from the Royal Museum of Art and History (Belgium-Brussels) | 11           | 4              | 7             | 1188-1502                | K. Haneca                                  |
| Altarpiece fragments from the Museum Vleeshuis (Belgium-Antwerp)                 | 19           | 17             | 2             | 1206-1526                | K. Haneca                                  |
| Altarpieces of Holstebro and Ulkebol (Denmark)                                   | 7            | 7              | -             | 1181-1495                | N. Bonde                                   |
| Other altarpiece fragments   | 91           | 74             | 17            | 1137-1534                | J. Vynckier                                |
| Total number of tree-ring series from altarpiece sculptures                      | 219          | 164<br>(74,8%) | 55<br>(25,2%) |                          |  |
| <b>Panel paintings</b>   |              |                |               |                          |  |
| Rubens   | 19           | 14             | 5             | 1272-1601                | J. Vynckier                                |
| Jan Van Eyck   | 11           | 11             | -             | 1136-1407                | J. Vynckier                                |
| Rogier van der Weyden  | 5            | 4              | 1             | 1231-1444                | J. Vynckier                                |
| Hans Memling   | 16           | 15             | 1             | 1099-1525                | J. Vynckier                                |
| Pieter Bruegel the Elder   | 3            | 3              | -             | 1212-1551                | J. Vynckier                                |
| Pieter Bruegel the Younger   | 5            | 5              | -             | 1239-1592                | J. Vynckier                                |
| Dirk Bouts   | 15           | 14             | 1             | 1173-1543                | J. Vynckier                                |
| Various artists  | 247          | 200            | 47            | 1023-1640                | J. Vynckier;<br>H. Beeckman<br>& K. Haneca |
| Total number of tree-ring series from panels of panel paintings                  | 321          | 266<br>(82,9%) | 55<br>(17,1%) |                          |  |

### 4.2.3 Confronting individual series and references

In order to compare the individual tree-ring series from the art historical database with the historical site chronologies from Poland,  $t$ -values were calculated according to the Hollstein algorithm (Hollstein 1980). While calculating these correlation measures, the initial tree-ring data undergo a logarithmic transformation to eliminate age trends.

$$y_i(\text{Holl}) = \log\left(\frac{y_i}{y_{i+1}}\right) \quad (4.1)$$

The corresponding  $t_H$ -value between the art historical tree-ring series (sample) and the site chronology (reference) is then calculated as:

$$t_H = \frac{r \times \sqrt{n-2}}{(1-r^2)} \quad (4.2)$$

with:  $y_i$  = ring-width value at year  $i$

$y_{i(Holl)}$  = tree-ring indices at year  $i$ , after Hollstein transformation

$r$  = correlation coefficient between sample and reference

$n$  = number of overlapping years between sample and reference

The resulting correlation matrix of  $t_H$ -values is supposed to provide more detailed information on the provenance of the wood. Theoretically a high correlation value should be observed when comparing an individual tree-ring series with a site chronology that is composed of tree-ring series originating from the same area. A threshold value can be set arbitrarily, supported by personal experience, or by consulting tree-ring series from modern trees, growing under comparable conditions in the same climatological region. Modern tree-ring series were selected from 9 different sites scattered all over present-day Poland (Figure 4.2), but within the same geographical range of the historical sites chronologies. For each site the average  $t_H$ -value was computed by calculating the  $t_H$ -values for all possible combinations between trees. The average  $t_H$ -value for all of the 9 modern sites could be used as a threshold for the comparison of medieval tree-ring series with the historical site chronologies.

Nevertheless it is possible that, while comparing an individual tree-ring series with several site chronologies, more than one  $t$ -value exceeds the selected threshold. In such cases it is important to take into account the geographical distribution of the matching sites. If one individual site chronology, or a small group of neighbouring sites, display  $t$ -values higher than the selected threshold, it is assumed that these locations approach the original timber source. On the other hand, if high  $t$ -values are associated with widely dispersed sites, no further conclusions or interpretation can be made.

#### 4.2.4 Grouping sites and individual series

It is expected that in some cases the comparison of site chronologies with individual tree-rings series will result in correlation values lower than the selected threshold.

This could indicate that (a) the original timber source is not represented by one of the site chronologies, (b) the period spanned by the site chronology does not overlap with the individual series, (c) the presence of growth anomalies within the individual tree-ring series from the database with art-historical objects, or (d) that the average growth conditions for that specific area are not well represented by the available site chronology. The latter could be a consequence of a site chronology being composed of only a low number of individual series. To address this problem, neighbouring site chronologies can be grouped into a regional chronology, reflecting average growth conditions for a more extensive region.

When grouping neighbouring site chronologies into one regional chronology it is possible to use all the individual samples incorporated in the separate site chronologies, or treat the site chronologies as individuals and calculate the regional chronology as the arithmetic mean of all site chronologies. In this case the latter should be preferred since the number of tree-ring series that constitute the individual site chronologies from Poland is highly variable and ranges from 3 up to more than 150 (Table 4.1). Averaging all individual series into one regional chronology would bias the resulting chronology towards the site with the largest number of individual series. This method should increase the strength of the common signal in the calculated chronology, but implies a loss of detail, since these regional chronologies are now supposed to represent a larger area.

While the regional chronologies now cover a larger area, it becomes more likely that individual series show high similarities with more than one regional chronology. When trying to interpret the provenance of an oak specimen it is necessary that the  $t_{H-}$ -value calculated with one of these regional chronologies should pass a certain threshold, but more important, the  $t_{H-}$ -value should be significantly higher compared to the other values calculated with the remaining chronologies. There should be only one  $t_{H-}$ -value that clearly points towards one region.

#### **4.2.5 Missing sapwood and felling date estimates**

The majority of the art historical objects lack sapwood, which is more vulnerable to biological degradation by insects and fungi. When the heartwood/sapwood boundary can be identified or when a few sapwood rings are preserved a more precise felling

date can be calculated using sapwood estimates for the Baltic area. In all other cases, where all sapwood and an unknown number of heartwood rings have been removed, only a *terminus post quem* can be calculated by adding the lower limit of the sapwood estimates. Oaks from present day Poland contain approximately 15 (9 - 24 in the 90% confidence interval) sapwood rings (Wazny 1990b).

This average number should be added to complete the number of missing sapwood rings on the individual series. For altarpieces it is assumed that all sculptures were carved during the same tight time interval. Therefore the most recent felling date or *terminus post quem*, calculated from one particular sculpture from an altarpiece, should be attributed to all sculptures from that altarpiece. This is of course a generalisation and will not be correct for all elements in all objects. Nevertheless this could be considered an acceptable approximation since the time needed for transportation, seasoning and storage is thought to be short. According to Wazny and Eckstein (1987) the time required for a ship to sail from Gdansk to London, and to deliver their goods was less than 1 month, though this was highly dependent on the political situation. Although the medieval guilds prescribed the use of dry timber (De Boodt 2004; Haneca *et al.* 2005), sculptors preferred freshly cut oak wood to carve their sculptures from. Therefore the drying period was often reduced to a minimum or neglected at all (Eckstein 2005). In general no more than 1 to 4 years elapsed between the logging of a tree and the creation of an altarpiece with wood from that tree (Haneca *et al.* 2005). For panel paintings this is usually  $5 \pm 3$  years (Bauch and Eckstein 1970).

### 4.3 Results

In total 540 tree-ring series from art-historical objects from 5<sup>th</sup>-16<sup>th</sup> century were collected. Nearly 80% (430 out of 540) of all the tree-ring series from this art historical database could be dated against standard Baltic master chronologies *Baltic1* and *Baltic2* (Hillam and Tyers 1995), and *East-Pomerania* (Eckstein *et al.* 1986). Averaging tree-ring series from the same tree, displaying high inter-correlation and excellent visual agreement, reduced the original dataset down to 390 series. The total time-period covered by the dated series ranges from 1023 AD - 1640 AD. The

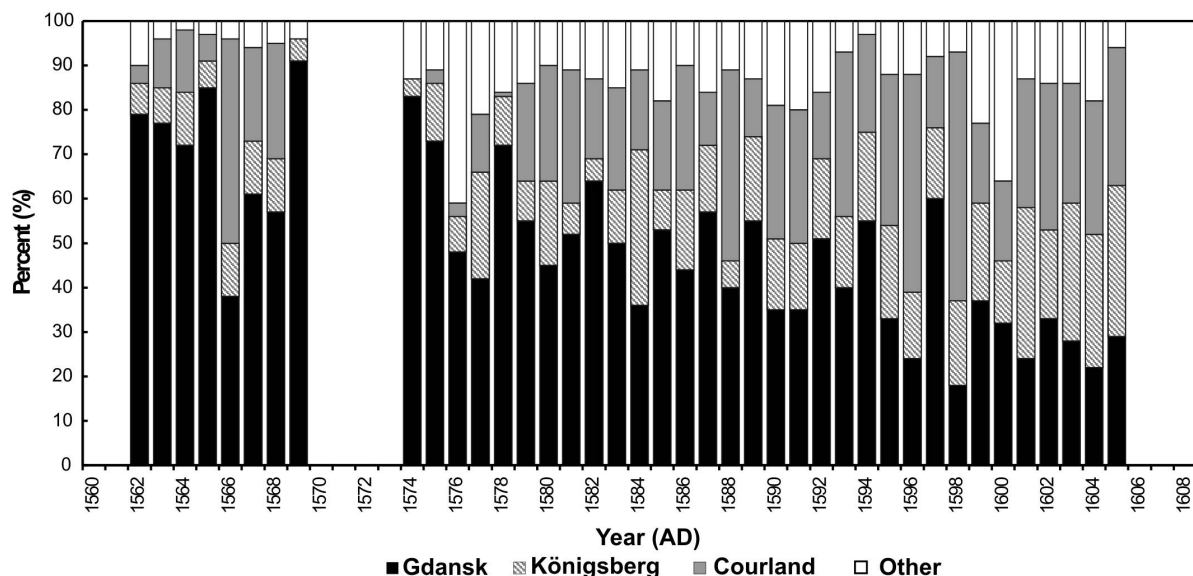


remaining tree-ring series have yet to be dated against any other available master chronology.

In addition to the dendrochronological data, historical records dealing with commerce and politics need consulting. Written documents providing more details on the trade in forest products from the Baltic region before 1562 AD are rare. One of the most important sources that can help to quantify the Baltic timber trade are the *Books of the Sound Dues* (Bonde *et al.* 1997). In these toll books, the cargo of vessels passing through the Sound of Denmark was recorded, from 1562 AD onwards. Together with the type of cargo the harbour of export was also recorded. The most important commodity that was shipped from the Baltic area was grain, but forest products were the second most important commodities exported towards the staple towns of the Hanseatic League (Tossavainen 1994). According to these historical toll records most of the so-called wainscots were shipped from Gdansk, Königsberg and the Duchy of Courland, i.e. the part of present-day Latvia west of the Daugava River up to the Baltic Sea. Gdansk in particular, at the mouth of the Vistula River, took a dominant position in the timber trade. In 1565 AD up to 85% of all the wainscots that passed through the sound of Denmark towards the North Sea were shipped from Gdansk (Figure 4.3). This percentage dropped to 73% in 1575 AD and only 53% in 1585 AD (Bonde *et al.* 1997; Wazny and Eckstein 1987). It is probable that large quantities of wood, logged after this date, originate from regions further to the northeast. At present, only a few, short and poorly replicated reference chronologies for oak are available from the Baltic States (Estonia, Latvia, Lithuania) for the period of intensive trade in forest products (Pukiené 2002). This hampers further attempts to locate the timber source in the period after 1585 AD when harbours other than Gdansk become more important. In order to maximize the probability that the original timber source is represented by the dataset of site chronologies from present-day Poland, all tree-ring series from the art historical database with felling dates later than 1585 AD were removed. After this elimination process, a total of 348 tree-ring series were available for further analysis.

Tree-ring series from modern forests were used to compute the average  $t$ -value observed between trees within one forest in Poland. The average  $t_H$ -value within the 9 selected sites ranges from 4.96 to 7.39, with an overall average value of 5.93 for

Poland. This value, rounded to 6.0, will be considered as a guide value, which should be exceeded by the  $t_H$ -values before any further interpretations will be made concerning the original timber source. The tree-ring series from the modern forest were also averaged into site chronologies. In Table 4.3 an overview is presented of the correlation, expressed as  $t_H$ -values, between the modern site chronologies for their common time interval 1871 - 1984 AD. The overall correlation is very low, and does not seem to depend solely on the geographical proximity of the sites. Only a few neighbouring sites have a considerably high  $t_H$ -value (e.g. Goldap and Suwalki), whilst other neighbouring sites have a very low  $t_H$ -value (e.g. Koszalin and Wolin). It is probable that other factors, such as soil type, slope, etc., play a more significant role in the explanation of differences in tree-ring pattern between different sites. This corresponds with a similar comparison of site chronologies from Britain (Bridge 2000). A more exhaustive study on the differentiation between forest sites in Poland, with special interest in dendrochronology, has been made by Wazny (1990b) and Ufnalski (1996).



**Figure 4.3:** Percentage of wainscots passing through the Sound of Denmark, shipped from the various Baltic harbours according to Bonde *et al.* (1997).

Comparison of the selected series from the art historical database with the site chronologies from Poland resulted in a 348 (no. of individual tree-ring series) by 36 (no. of site chronologies) correlation matrix of  $t$ -values. In general, the calculated  $t_H$ -values are rather low. The  $t_H$ -values peaked above the threshold of 6.0 in only a few

cases. Since such a multiple comparison increases the risk for false positive values (i.e. statistical type II errors), it is important to interpret the  $t$ -values very critically, even when they are high. Therefore, when the high  $t$ -values are scattered without any geographical order over several sites, no further attempt was made to interpret these. It was observed that in 8.9% (i.e. for 31 out of 348 series) of all series from the art historical database a high and unique correlation was found with one of the historical site chronologies from Poland.

**Table 4.3:** Correlations, expressed as  $t_r$ -values, between modern site chronologies from present-day Poland.

| Site code | Pola-007 | Pola-008 | Pola-009 | Pola-010 | Pola-011 | Pola-013 | Pola-014 | Pola-015 | Pola-016 |
|-----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Pola-016  | 2.5      | 1.5      | 1.5      | 1.7      | 2.5      | 2.6      | 3.3      | 2.1      | -        |
| Pola-015  | 1.4      | 3.9      | 4.9      | 0.7      | 2.6      | 3.5      | 2.9      | -        |          |
| Pola-014  | 2.4      | 3.8      | 3.5      | 3.4      | 3.2      | 2.8      | -        |          |          |
| Pola-013  | 5.1      | 2.8      | 1        | 0.7      | 0.3      | -        |          |          |          |
| Pola-011  | 0.9      | 3        | 5.9      | 1.9      | -        |          |          |          |          |
| Pola-010  | 1.2      | 0.5      | 1.4      | -        |          |          |          |          |          |
| Pola-009  | 0.3      | 3.9      | -        |          |          |          |          |          |          |
| Pola-008  | 1.9      | -        |          |          |          |          |          |          |          |
| Pola-007  | -        |          |          |          |          |          |          |          |          |

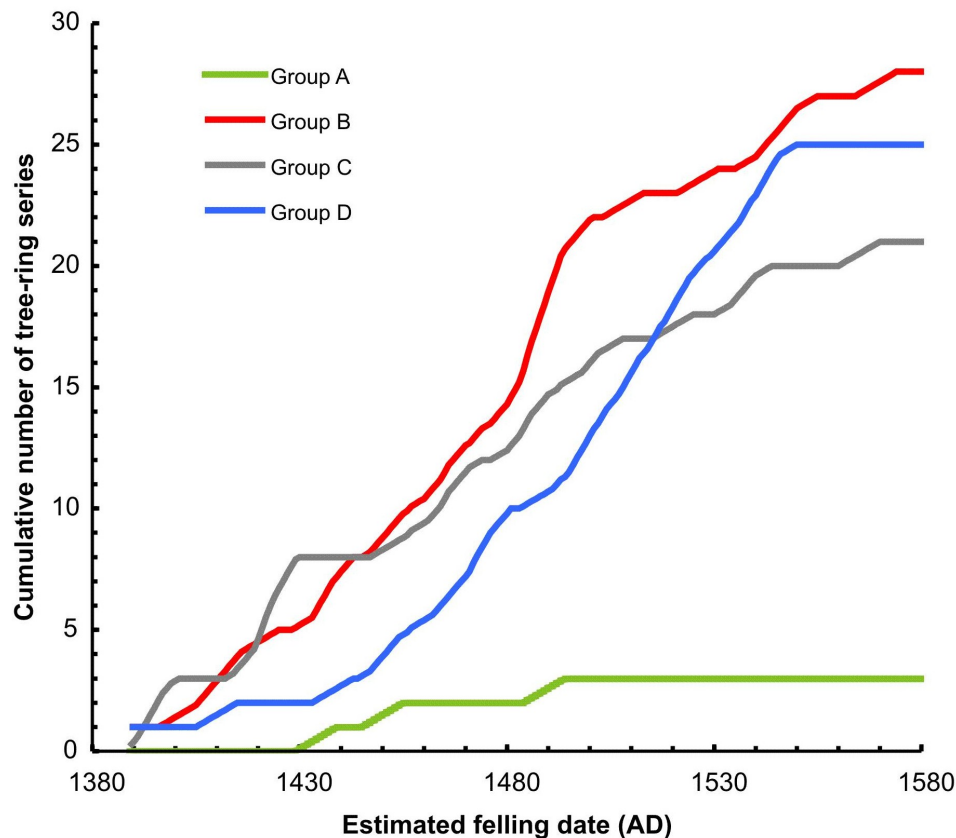
A wide variety of both hierarchical (between- and within-group linkage, centroid clustering, Ward's method) and non-hierarchical (K-means) statistical clustering techniques have been performed on the modern site chronologies, in order to obtain a statistically reliable grouping of the different sites. All applied statistical procedures delivered very disordered results that were not suited for further interpretation. Therefore, four groups were defined arbitrarily, based on the sites' geographical distribution and associated phytogeographical characteristics (Figure 4.2). Group A and B represent the coastal region of Poland with, adjacent to the south, the lake district called Pomerania. Characteristic for this region is the high humidity, an annual rainfall above 600 mm, mild winters and rare scorching summers. The eastern part encloses Gdansk, the region's commercial, political and cultural centre, located in the mouth of the Vistula River. Group C covers the basin of the middle Vistula and the Mazovian Lowland. In the Middle Ages most of this huge plain was covered by primeval woods. Group D represents the Podlasie Lowland at the confluence of the Narew, Biebrza and Bug Rivers, with large flood plains and Europe's largest natural

forest, Puszcza Bialowieska. Characteristic for this part of Poland is the climate's strong continental component, which increases eastward.

For each group a regional chronology was computed by calculating the arithmetic mean of all site chronologies enclosed by that group. The regional chronologies now represent a larger and more diverse area than the individual site chronologies. For further comparison, the minimum  $t_H$ -value was lowered down to 5 (i.e. the lowest average  $t_H$ -value found for modern forest sites in Poland, see above), but more important, other  $t_H$ -values should be at least 25% lower than the highest  $t_H$ -value. Only upon meeting both requirements are tree-ring series supposed to be related to a group or region. After comparison of the individual tree-ring series with these chronologies, a further 14 series could be assigned to a certain region. This adds up to 12.9% of all series that show a distinct correlation with one specific regional or site chronology.

According to the survey of Wazny and Eckstein (1991), Poland can be divided into a northern and a southern part. This is based on a difference in the climatological response of oak trees from the coastal region and the more continental inland. Again, the site chronologies from northern and southern Poland were averaged into two regional chronologies, one for the north and one for the south (Figure 4.2). Here 13.8% (48 out of 348) of all single series showed a significantly high and distinct correlation with one of the two regional chronologies.

The tree-ring series that demonstrated a clear tendency towards one of the four regional chronologies or 36 site chronologies were set aside for further analysis. For each individual series the most precise estimate of the actual felling date was calculated. According to the calculated felling dates, the cumulative number of tree-ring series associated with one regional chronology was computed. These cumulative numbers were plotted on a time axis (Figure 4.4). Most of the selected tree-ring series show a clear tendency towards groups B, C or D. Particularly the regional chronology of group B, which is composed of tree-ring series from forests in the vicinity of Gdansk, is often designated as the original timber source for several tree-ring series from art historical objects. Only in a few cases were high and unique  $t_H$ -values for group A found.



**Figure 4.4:** Cumulative number of art historical tree-ring series attributed to one of the four different groups (see Figure 4.2) in Poland.

#### 4.4 Discussion

All dated tree-ring series from the art historical database showed high  $t_H$ -values with standard Baltic reference chronologies. For instance, the average  $t_H$  value for all dated art historical tree-ring series with the *Baltic1* chronology is 6.62. The estimated felling dates from the dated tree-ring series fall within the era of intensive timber trade from regions around the Baltic Sea towards staple towns in England, Flanders and in a later stage Holland. Comparison with other master chronologies from Germany, France, the Netherlands, Denmark or Great Britain did not result in higher  $t$ -values for any of the series. This suggests that the tree-ring series from the art historical database originate from the same area as the tree-ring series that were used to construct the Baltic reference chronologies. More detailed information on the original timber source can not be obtained by further comparison with standard Baltic references since these chronologies reflect the growth conditions over vast areas.

Only 8.9% of the art historical sequences were strongly correlated with only one or few site chronologies in a certain region. It is probable that comparison of individual tree-ring series with site chronologies is too detailed and is a strategy that only in a few cases could lead to the correct interpretation. After grouping site chronologies from four characteristic regions, 12.9% of the art historical tree-ring series showed a high and distinct correlation with one of the group chronologies. These chronologies represent a larger area, and should have a stronger common signal in their average ring width patterns. When trying to distinguish only between northern and southern Poland, 13.8% of the individual series could clearly be attributed to one of these regions. So this final distinction between northern and southern Poland does not result in a significantly higher number of tree-ring series that could be attributed to a specific region.

The cumulative numbers demonstrate that the majority of the tree-ring series that display a significantly high and distinct correlation are associated with groups B and C (Figure 4.2). The more or less constant slope of the fitted curves illustrates that these regions were a regular supply area during this period of intensive timber trade. The number of tree-ring series that highly correlate with group D shows a strong increase after 1450 AD. Before that period it is only rare that one of the art historical samples shows a clear tendency towards this area. Another successful application of dendrochronology as a tool to determine the original timber source of imported Baltic oak was reported by Wazny (2002). Tree-ring series of oak panels from the painted ceiling of Guthrie Aisle in Scotland, dated by Crone (1998), were also compared with site chronologies from Poland. This resulted in extremely high  $t$ -values ( $t_{BP} > 9$ ; calculated according to the Baillie and Pilcher (1973) algorithm with historical chronologies, composed of wood specimens that probably represent regions adjoining the Bialowieska forest in eastern Poland, near the border with Belarus. This region is covered by the regional chronology of group D. The exact felling date for the painted panels could not be determined, but the trees were certainly felled after 1450 AD. Wood from the northwestern part of Poland, covered by the group A chronology, is seldom found in the art historical database.

The provenance of 45 objects from a set of 348 art-historical objects can now be defined more accurately. Their original timber source was previously described as

the Baltic region. Now it is possible to be more specific and narrow the source to a particular region in present-day Poland. For the majority of the dataset it was not possible to locate more accurately the origin of the timber source. The lack of a sufficient number of site chronologies from southern Poland in this analysis could be one of the main reasons why more tree-ring series could not be attributed to a certain region. However southern Poland was not the only major timber source. Regions outside present-day Poland, both the Baltic States (Estonia, Latvia and Lithuania) and Belarus have also been major suppliers for the Baltic timber trade (Zunde 1999).

In order to maximize the potential of dendrochronology as a tool to determine the original timber source, often referred to as *dendro-provenancing*, there are still some aspects that need to be addressed. Despite the progress that has been made during the last decade, more site and regional chronologies that cover the period of the Hanseatic timber trade are needed in countries around the Baltic Sea. Such regional oak chronologies, especially in the Baltic States and Belarus, should allow the application of dendrochronology for provenancing purposes in a more detailed and comprehensive way. Unpublished historical documents from archives, dealing with the Hanseatic trade could also help to quantify the amounts of forest products that were transported and document the origin of the traded products. At present, site chronologies cover narrow periods and sometimes hamper clear characterization of the original timber source. Extension of existing site and regional chronologies should facilitate the interpretation of the generated correlation values.

### **Acknowledgements**

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**Part II**  
**ARCHAEOLOGICAL WOOD**





## Part II

# ARCHAEOLOGICAL WOOD

### **Preface**

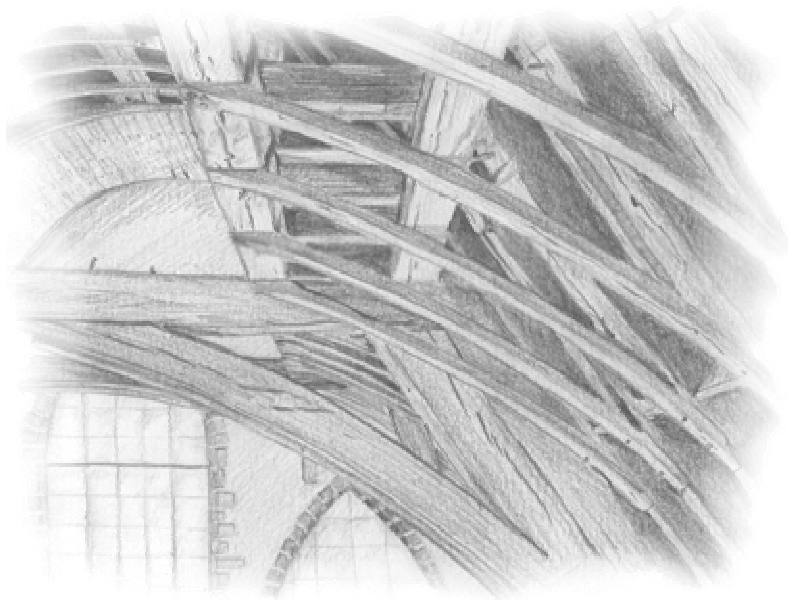
As demonstrated in the previous chapters, medieval wood carvers and craftsmen were keen on the imported assortments of Baltic timber. They preferred oak timber with narrow growth rings and few abrupt growth variations. This contrasts the wood often encountered on archaeological sites in Flanders. Water wells, sheet pilings, foundations, roof constructions, houses and storage buildings are mostly constructed with oak timber, characterized by wide rings and a conspicuous growth trend. Consequently, cross-sections excavated during archaeological campaigns or recovered from historical buildings, usually display only a low number of growth rings.

It should be clear that short ring-width series are not the ideal material to work with when tree-ring dating is the main goal. The recorded short growth-ring series may not be characteristic enough or unique. This means that, when shifted along a long reference chronology, it is possible to find several positions with a good visual and statistical agreement, which lead to unreliable and questionable dating results.

However when short series would be excluded from dendrochronological analyses, this would dramatically reduce the number of samples accessible for further investigations and only few long-lived specimens would be left. Construction of a robust and well-replicated reference chronology would possibly be jeopardized due to a low number of available dated tree-ring series. Therefore it is of the uttermost importance to assess the potential of those relatively short ring-width series for tree-ring dating and chronology building.

Moreover, ring-width series are also considered to archive changes in their direct environment and growing conditions. This includes pulses due to human activities in forests and woodlands. Such activities could be related to logging, pollarding, grazing by livestock, etc. or other silvicultural management practices. In this context, the question arises whether it is possible to gain more insights on the structure and management of former forests and woodlands where timber was logged, by analysing the recorded ring-width patterns. Here, no distinction should be made according to the length of the ring-width series. All recorded growth patterns are of interest when regarding stand structure and management.

In the following two chapters, ring-width series of wood specimens, collected during archaeological excavations and restoration projects, are examined. Special attention is paid to the short ring width series, so often encountered on timbers from archaeological sites in Flanders. It is to be evaluated if such series are useful for dating purposes and whether they can contribute to the creation of a robust and well-replicated reference chronology (**Chapter 5**). Furthermore, the recorded ring-width patterns are examined with respect to gain more information about past forest structure and management. This is assessed in detail in **Chapter 6** by comparing the growth patterns of wood specimens from Roman and Medieval archaeological sites with the growth patterns of contemporary trees from stands with a well-known structure and management.



# Dendrochronology of medieval oak from Flanders: the information content of short ring-width series

# 5

Chapter

## Summary

Throughout the Middle Ages forests in Flanders (northern Belgium) experienced a dramatic human influence. Forests were logged for wood supply and converted to arable land. The structure of the remaining forests was altered. This, combined with the tempering influence of the Atlantic climate, this results in conditions that are suboptimal for dendrochronological research. Tree-ring series of *Quercus robur* and *Q. petraea* of timber from medieval archaeological sites are often short, show abrupt growth-rate variations and are complacent. The question arises whether tree-ring series of this type are potential records of past management and whether they could constitute the basis of a reference chronology for archaeological dating. During six archaeological excavations in and around the medieval town of Ypres, cross-sections were collected. The tree-ring series could be dated back to the 12<sup>th</sup>-14<sup>th</sup> centuries, using reference chronologies from surrounding regions. The growth pattern of the short sequences displays a high similarity to tree-ring series from modern coppice. For the first time, it has been confirmed that dendrochronological analysis in Flanders is possible and can provide valuable information on medieval forest use and structure.

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K. Haneca, I. Boeren, J. Van Acker and H. Beeckman (2006). Dendrochronology in suboptimal conditions: tree rings of medieval oak from Flanders (Belgium) as dating tool and archives of past forest management. *Vegetation History and Archaeobotany* 15(2): *in press*.

## 5.1 Introduction

Over the last 30 years, dendrochronology has become one of the standard dating techniques in archaeology, especially in Europe (e.g. Kuniholm 2001). The chance of successful dating depends strongly on a few, clear features. For example long sequences with high environmental sensitivity for instance, generally have a higher potential for dating purposes than short and complacent series. When analysing tree-ring series from archaeological wood in Flanders (northern Belgium), long and sensitive series are rare. There, a low number of tree rings depending on diameter and abrupt variations in growth rate due to anthropogenic influences, are common. This hampers the crossdating process, which is one of the basic steps in dendrochronological analysis. In addition, averaging raw tree-ring data with strong pulses of endogenous disturbances can bias the resulting chronology (Cook *et al.* 1990).

Even before the Roman era forests in present-day Flanders were heavily exploited and degraded. During the Dark Ages (4<sup>th</sup> to 7<sup>th</sup> centuries AD), a period of forest recovery started (Tack *et al.* 1993). Migrating Germanic tribes disrupted the organisation of local communities, exploiting the local forest resources. The conversion to arable land was interrupted and the forests could regenerate. From the 7<sup>th</sup> century onwards, this recovery phase was halted due to a growing need for staple food and fodder crops. This caused an increasing pressure on the remaining woodlands and forests. A demographic explosion during 10<sup>th</sup>-13<sup>th</sup> century accelerated the exploitation of forests for wood supply and deforestation for conversion to arable land. These processes resulted in the lowest forest cover ever in Flanders by the end of the 13<sup>th</sup> century.

Together with the progressing deforestation, the structure of the remaining forests was altered. Two management systems gradually became more popular in England, Northern France and Flanders: coppice and coppice-with-standards (Bechmann 1990; Vera 2000; Rackham 2003). The main goal of these interventions was to create a sustainable wood supply for construction and fuel, and fodder for pig breeding.



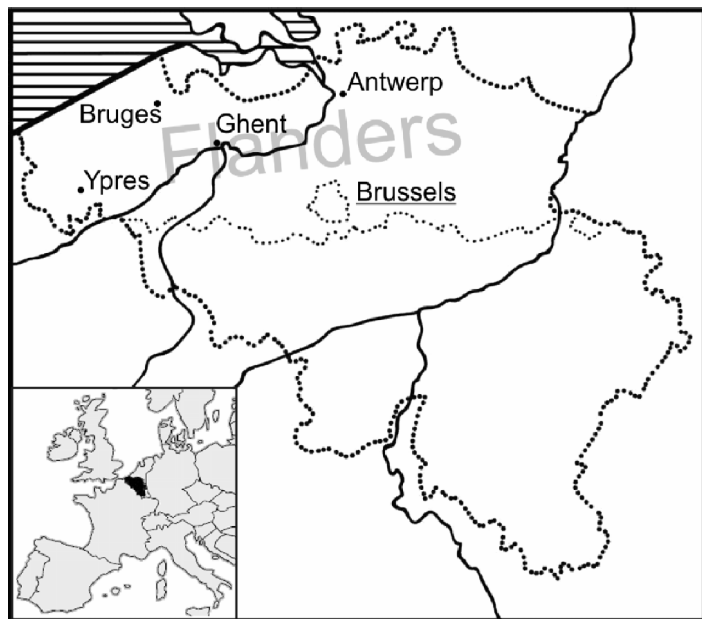
The combination of high anthropogenic pressure with the tempering influence of the Atlantic climate results in conditions that are considered as suboptimal for dendrochronological research. In this regional climate temperate deciduous forest is the climax vegetation, in which oaks (*Quercus robur* L. and *Q. petraea* (Matt.) Liebl.) occupy an important position. These oaks experience climate conditions favourable for growth, expressed in wide growth rings and ring-width series with a low sensitivity to climate.

In order to support the interpretation of archaeological findings, one of the main goals of a dendrochronological analysis is the exact dating of excavated wood specimens. The lack of reference chronologies composed of local tree-ring series from Flanders is a drawback in the application of dendrochronology as a dating tool. As a result, master chronologies from surrounding regions must be consulted.

For dating purposes in an archaeological context, it is important to report the exact felling date of wood specimens. This is only possible when all the sapwood rings are still present in a transverse section. When sapwood is absent, only a *terminus post quem* can be calculated (Eckstein *et al.* 1984; Baillie 1995). When part of the sapwood is preserved, the felling date is estimated using a mean number of sapwood rings. This mean number is considered dependent on two main factors: the age of the tree and its geographical location (Hollstein 1980; Hillam *et al.* 1987). Such standard sapwood estimates are available for different regions throughout Europe. Sapwood estimates for oak from Belgium most frequently rely on the age-dependent standards for Western Europe. A subdivision is made by 100 year age classes. For trees up to 100 years  $16 \pm 5$  is considered as the mean number of sapwood rings. This number is increased for a tree with an age between 100 and 200 years to  $20 \pm 6$ . Trees older than 200 years are expected to have  $26 \pm 8$  sapwood rings (Hollstein 1980). All these estimates are based on the 68.3% confidence level and are derived from tree-ring series originating mainly from trees within primary forests. Since primary forests were obviously no longer present in medieval Flanders, the relevance of the sapwood estimates is questionable.

Extensive dendrochronological datasets can form the basis for a reconstruction of forest dynamics and structure (Billamboz 1996b; Leuschner *et al.* 2000; Billamboz 2003). Information on stand structure and internal competition is embedded in the individual tree-ring series (Cook 1990), but usually hard to extract. Therefore, characteristic tree-ring series from a stand with a specific structure or management system are useful for comparison with tree-ring series from archaeological excavations. By collecting tree-ring series from forests with a well-known structure and management system, it becomes possible to characterize the average growth pattern for an individual tree in such a stand. This characterization will include information on average ring width and growth rate. Such datasets also permit verification of the standards quoted above for sapwood estimates and the relevance of these into Flanders.

During six archaeological excavations in and around the medieval town of Ypres (Figure 5.1), cross-sections of timber were collected for dendrochronological research. The question arose as to the observed growth-ring patterns were suitable for dating purposes and chronology building. Therefore correlation measures needed to be sufficiently high and the resulting chronology would have



**Figure 5.1:** Map of Belgium with the location of Ypres

to show a strong common signal. To evaluate whether these tree-ring series were potential records of past management, growth-pattern analyses were performed. Characteristic growth curves were selected and compared with curves from living oaks. Analysis and comparison of such characteristic growth-ring series can yield an impression of the forest structure and dynamics at that time.

## 5.2 Site description

All the archaeological excavations were situated in or near the town of Ypres. The name of this town was first cited in 1066 AD. At that time two residential areas were located along a branch of the Ieperlee, a tributary of the Yzer River. Due to the success of the textile industry the population grew considerably and the two settlements merged. From 1214 AD, the rapidly growing town was walled. The suburbs however, remained outside the defensive wall. In 1383 AD, during the Hundred Years' War between England and France (1337 – 1453 AD), an English army supported by soldiers from Ghent, in the 14<sup>th</sup> century one of the most powerful cities north of the Alps, attacked the town and destroyed the suburbs. Although the town itself was never taken, the suburbs were never rebuilt.

## 5.3 Material and methods

From 1993 up to 2002, several archaeological “rescue” excavations took place. During two field campaigns, dozens of well-preserved wooden structures, parts of medieval residences and patrician and craftsmen's houses, sheet pilings from rivers and a wind mill were recovered. Timber specimens were sampled by taking cross-sections. Prior to sampling, no distinction was made based on dimension or diameter, which ranged from 4 to 50 cm. The cross-sections collected were all saturated with water at the time of sampling. To avoid excessive shrinking, the disks were stored in humid conditions using plastic bags. With scalpel and razor blades, a transverse strip was surfaced to make the tree-ring structure clearly visible. Ring widths were measured to the nearest 0.01 mm using a positioning table (Lintab) with associated software (TSAPWin; Rinn 2003) and a stereomicroscope (Olympus SZX12).

In Flanders only a few dendrochronological analyses have been made and are available for comparison/dating purposes. Therefore, master chronologies from surrounding regions and countries had to be used: i.e. chronologies covering the Meuse valley (*Meuse5*) and southern Belgium (*Ardennes4*) (Hoffsummer 1995), the standard chronologies from Germany (Hollstein 1965; Hollstein 1980; Becker 1981),

northern France (Bernard 1998), southern England and East Anglia (Bridge 1988), and the southern part of the Netherlands (Jansma 1995).

To assess the signal strength in the resulting chronology the common variance in synchronised series was analysed. A widely used parameter to quantify the chronology's strength is the *Expressed Population Signal* (EPS) (Wigley *et al.* 1984; Briffa and Jones 1990). The EPS is based on the mean correlation between all series included in the chronology and has a possible range from zero to one.

$$EPS(t) = \frac{n \bar{r}_{bt}}{n \bar{r}_{bt} + (1 - \bar{r}_{bt})} \quad (5.1)$$

with:  $\bar{r}_{bt}$  = the average correlation between all tree-ring series

$n$  = the number of correlated trees

The EPS increases with sample size and with the strength of the mean correlation. Wigley *et al.* (1984) suggested a minimum value of 0.85 in order to obtain a sufficiently replicated chronology.

At four locations in Flanders, stands with coppiced oaks were selected. Using an increment borer, cylinders of wood were extracted from 2-3 shoots of 15 coppice stools. Using the same technique, 93 cores from naturally regenerated oaks in a forest reserve dominated by *Pinus sylvestris* L. were collected in Mattemburg (the Netherlands). As seedlings, these oaks had been strongly suppressed by the conifers for years. This resulted in very low growth rates and narrow growth rings. Finally, 120 cross-sections from recently cut oaks from two high forests near Brussels (Soignes and Buggenhout) were collected. On each core or cross-section from the three different forest types, ring widths were measured. Cumulative growth-ring patterns were calculated and compared to the series from the Ypres dataset. The total number of sapwood rings was recorded and the associated descriptive statistics, such as range and standard deviation, were calculated.

## 5.4 Results

Descriptive statistics of the recorded ring-width series for each archaeological site are listed in Table 5.1. The average ring width and average standard deviation for the

individual series do not differ significantly between the different archaeological sites. The same holds for the mean sensitivity of the tree-ring series. This justifies the consideration of the tree-ring series from the five archaeological sites as one dendrochronological dataset.

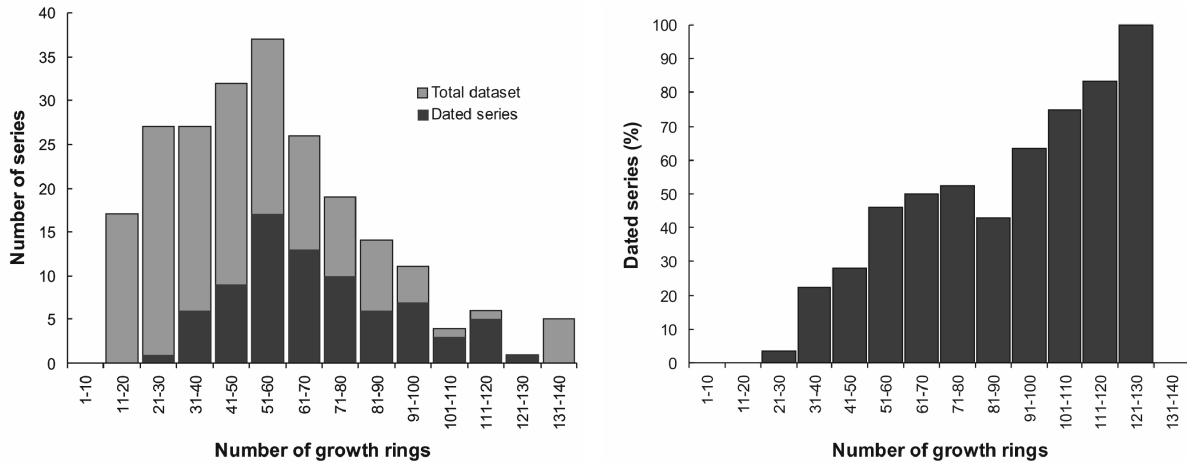
**Table 5.1:** Descriptive statistics of the tree-ring series from the different archaeological sites.

|                            | N° of samples | Average ring-width (mm) | St. dev. | Range (mm)  | Mean sensitivity | Mean series length (years) |
|----------------------------|---------------|-------------------------|----------|-------------|------------------|----------------------------|
| Sint Michiel 1             | 120           | 2.11                    | 0.75     | 0.18 - 9.67 | 0.213            | 43.9                       |
| Sint Michiel 2             | 56            | 1.66                    | 0.68     | 0.15 - 9.71 | 0.230            | 68.8                       |
| Sint Michiel (windmill)    | 4             | 1.44                    | 0.76     | 0.24 - 5.55 | 0.223            | 80.0                       |
| Ypres, historical centre 1 | 21            | 1.58                    | 0.83     | 0.17 - 7.13 | 0.240            | 82.8                       |
| Ypres, historical centre 2 | 21            | 1.94                    | 1.02     | 0.55 - 7.00 | 0.228            | 84.8                       |
| Total dataset              | 222           | 1.92                    | 0.76     | 0.15 - 9.71 | 0.225            | 57.8                       |

The average ring width of all individual series within the Ypres dataset is 1.92 mm, with an average standard deviation of 0.76. The large range of observed ring-widths is striking. Ring widths of less than 0.2 mm as well as values up to nearly 1 cm are recorded.

Comparison of the individual series results in low and unreliable correlation values. Short sequences especially disrupt the crossdating process. These short series often show an acceptable visual agreement with longer series at several positions. In only a few cases, the correlation values satisfactorily support one of the synchronisation positions. All doubtful synchronisation positions were rejected, and in the next step the individual tree-ring series were compared directly with the selected reference chronologies. Although statistical measures like  $t$ -values (Baillie and Pilcher 1973) and coefficients of parallel variation (*Gleichläufigkeit*, *GLK*; Eckstein and Bauch 1969) are still rather low (e.g. an average  $t$ -value of 3.71 for all dated series compared to *ZD-Becker*), they are acceptable due to the fact that the same match positions occur on different reference chronologies. Following this procedure, 74 series (= 33.3% of the total dataset) could be absolutely dated. The percentage of successful dating events strongly relies on the number of measured tree rings (Figure 5.2a, 5.2b). Samples with more than 60 rings could be dated in 50% of all cases. Nevertheless, several series with 30 to 60 growth rings could also be dated.

Standardization with a negative exponential curve, a *cubic spline* or combination of both does not ameliorate the dating results. There is no improvement in correlation values, nor in the number of series that can be dated.



**Figure 5.2a:** Histogram showing the distribution of the number of growth rings on the collected cross sections.

**Figure 5.2b:** Percentage of dated series according to the total number of growth rings on the cross sections.

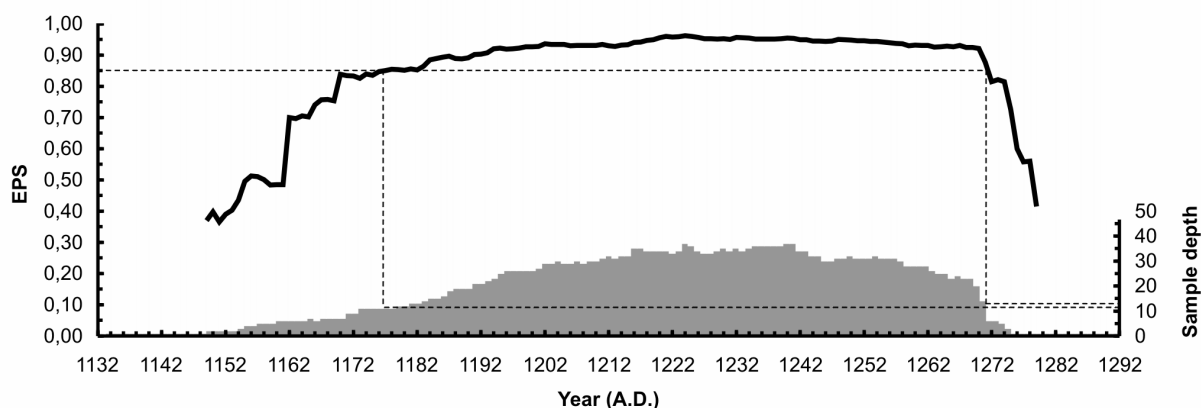
After standardizing the individual tree-ring series with a negative exponential curve, a chronology was calculated by averaging the resulting indices. This chronology spans the period 1132-1362 AD and shows high correlation with the selected references (Table 5.2). The highest correlation values are found with master chronologies from southern Belgium (*Meuse5* and *Ardennes4*) and the southern part of the Netherlands. Comparison with chronologies from Southern England (*S-Engl* and *E-Englia*) provides the lowest correlation values. The Ypres chronology also displays a significant correlation with ring-width chronologies from archaeological sites near St. Omer and Calais (C. Lavier, *pers. comm.*), 60-80 km southwest of Ypres, just across the border with France; however the correlation values are lower than those with the German references. Nevertheless, the surroundings and climatological conditions at these locations in France are highly similar to these in Flanders.

To assess the signal strength of the resulting chronology, EPS values were calculated. Instead of computing one single EPS value to characterize the whole chronology, running  $EPS(i)$  values were computed for fixed time intervals of 31 years, on each year  $i$  of the Ypres chronology. At each point of the chronology a 31-year

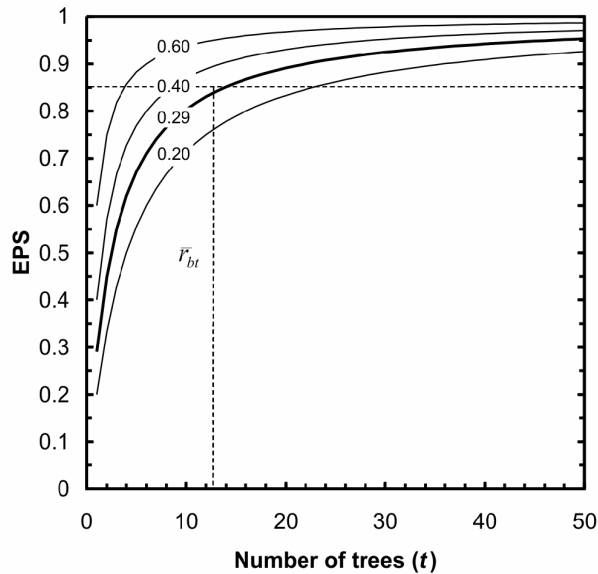
**Table 5.2:** Percent of parallel variation (*Gleichläufigkeit*, *GLK*), *t*-values according to Baillie and Pilcher ( $t_{BP}$ ) and *cross-date index* (CDI) between the Ypres chronology and reference chronologies from surrounding regions, and the Ypres chronology built exclusively with short series of less than 60 growth rings (<60).

| Reference (author)                       | Overlap  |     | GLK      |     | $t_{BP}$ |      | CDI      |     |
|--|----------|-----|----------|-----|----------|------|----------|-----|
|  | Ypres-ne | <60 | Ypres-ne | <60 | Ypres-ne | <60  | Ypres-ne | <60 |
| Meuse5 (Hoffsummer 1995)                 | 231      | 231 | 78       | 78  | 13.6     | 12.1 | 104      | 94  |
| NL-Zuid (Jansma 1995)                    | 231      | 223 | 77       | 70  | 13.0     | 11.7 | 93       | 83  |
| Arden4 (Hoffsummer 1995)                 | 217      | 217 | 71       | 71  | 12.9     | 11.5 | 86       | 78  |
| WD-Eiche1 (Hollstein 1980)               | 231      | 231 | 72       | 73  | 10.0     | 9.3  | 73       | 70  |
| WD-Eiche2 (Hollstein 1980)               | 231      | 231 | 72       | 73  | 9.5      | 8.4  | 65       | 59  |
| BasPar8 (Bernard 1998)                   | 231      | 231 | 68       | 69  | 8.0      | 7.6  | 56       | 55  |
| SD-Eiche (Becker 1981)                   | 231      | 231 | 70       | 72  | 8.4      | 6.9  | 55       | 47  |
| LCE-StOmer (Lavier, <i>pers. comm.</i> ) | 125      | 120 | 63       | 61  | 6.5      | 3.0  | 31       | 21  |
| LCE-Calais (Lavier, <i>pers. comm.</i> ) | 169      | 164 | 70       | 68  | 4.6      | 5.5  | 32       | 37  |
| S-Engl (Bridge 1988)                     | 231      | 231 | 59       | 56  | 5.2      | 4.4  | 33       | 28  |
| E-Anglia (Bridge, <i>pers. comm.</i> )   | 231      | 231 | 57       | 58  | 3.2      | 3.0  | 21       | 20  |

wide window was superimposed on all synchronised series. The computed  $EPS(i)$  value was then assigned to the central point of the time window (Figure 5.3). When more than 14 samples are included in the calculation, the  $EPS$  value exceeds the 0.85 threshold suggested by Wigley *et al.* (1984). At one position this level is reached with only 10 samples. A total of 14 samples can be interpreted as the minimum number of samples required when calculating a medieval ring-width chronology for Flanders. The minimum sample depth that should be included in a chronology can also be calculated from the formula defining the  $EPS$  by inserting the 0.85 threshold value in the equation. For the samples from the Ypres dataset, the  $\bar{r}_{bt}$  has a value of 0.29 in the interval with the largest number of overlapping series. This results in a theoretical minimum sample depth of approximately 14 trees to reach an  $EPS$  of 0.85 (Figure 5.4).



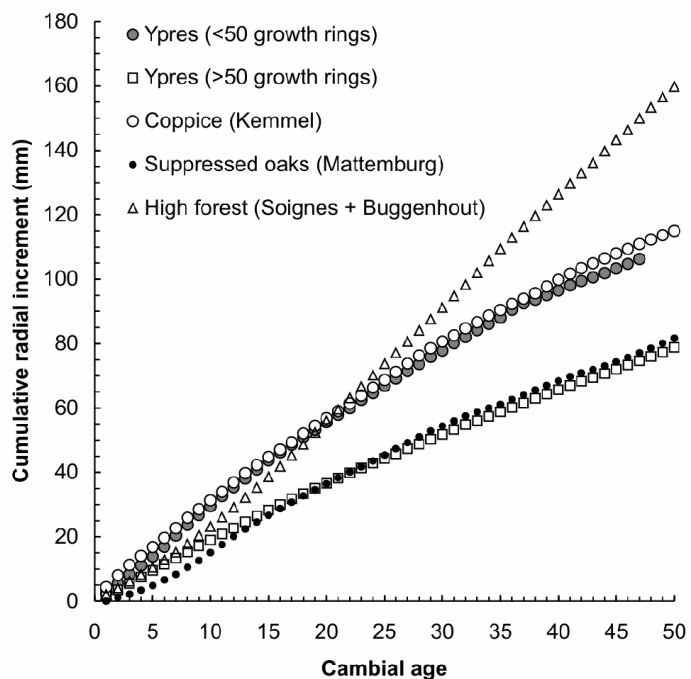
**Figure 5.3:** Running  $EPS$  values and sample depth for the Ypres chronology.



**Figure 5.4:** Theoretical EPS values for different numbers of trees and several levels of average correlation.

Of the cross-sections that were collected from the archaeological sites, 60.4 % had less than 60 growth rings. After filtering all samples with less than 60 growth rings out of the dataset a new chronology was calculated, using only these short series. Comparison of this new chronology with the selected references still results in high  $t$ -values and coefficients of parallel variation (Table 5.2). EPS values could not longer be calculated since the sample depth was reduced considerably.

The growth rate of the short sequences from the Ypres dataset differs significantly from that of the longer series. All samples with pith, partly preserved sapwood or bark and an estimated number of less than 50 growth rings were selected. The cumulative radial increment was calculated based on the cambial age. The cumulative radial increment was also calculated for all series with pith and more than 50 growth rings (Figure 5.5). Significant differences between these two types of series can be seen in their growth curves. As early as in the juvenile stage, a considerable difference in growth rate is noticed. The difference in growth rate slowly decreases with increasing age of the trees. Adding similar series of tree-ring data from modern coppice, high forest and suppressed oaks, it is obvious that the short Ypres sequences show a



**Figure 5.5:** Cumulative radial increment of samples with less and more than 50 growth rings from the Ypres dataset, compared with radial increment of modern coppice, suppressed oaks and oaks from high forest.



very high similarity with the coppice. The growth curve of the longer Ypres series on the other hand corresponds best to the suppressed oaks.

The number of sapwood rings was recorded from contemporary oaks from three specific types of woodland: shoots of a coppice stool, high forest and suppressed oaks in a stand dominated by *Pinus sylvestris* (Table 5.3). According to the total number of growth rings, each individual was assigned to an age class of 50 years. Within these age classes the mean number of sapwood rings was calculated and plotted against the widely applied standards for Western Europe. In the age class with the youngest trees, i.e. up to 50 years old, a considerable difference is noticed between the standard of 16 sapwood rings and the observed number of sapwood rings, only 6.6. When shoots are allowed to grow beyond 50 years, the number of sapwood rings rises up to the standard estimate. For older trees, up to 200 years, the mean number never differs more than six years from the standards, and falls within the range of the standard deviation.

**Table 5.3:** Average number of sapwood rings for oaks growing under specific conditions, compared to the prevailing standards for Western Europe.

| Age class                   | Coppice   | High forest | Oak under pine | Standards for Western Europe |
|-----------------------------|-----------|-------------|----------------|------------------------------|
| <b>Average +/- st. dev.</b> |           |             |                |                              |
| 1-50                        | 6.6 ±2.3  | 13.0 ±5.3   | 19.5 ±2.5      | 16 ±5                        |
| 51-100                      | 16.9 ±4.6 | 19.7 ±5.9   | 18.1 ±4.8      | 16 ±5                        |
| 101-150                     | -         | 26.7 ±7.8   | 16.7 ±5.2      | 20 ±6                        |
| 151-200                     | -         | 22.2 ±6.1   | -              | 20 ±6                        |
| 201-250                     | -         | -           | -              | 26 ±8                        |
| <b>Range (min - max)</b>    |           |             |                |                              |
| 1-50                        | 5 - 13    | 7 - 20      | 17 - 22        |                              |
| 51-100                      | 10 - 26   | 9 - 37      | 9 - 31         |                              |
| 101-150                     | -         | 13 - 47     | 12 - 23        |                              |
| 151-200                     | -         | 15 - 34     | -              |                              |
| 201-250                     | -         | -           | -              |                              |
| <b>Sample depth</b>         |           |             |                |                              |
| 1-50                        | 13        | 4           | 3              |                              |
| 51-100                      | 20        | 47          | 87             |                              |
| 101-150                     | -         | 53          | 3              |                              |
| 151-200                     | -         | 16          | -              |                              |
| 201-250                     | -         | -           | -              |                              |

With all dated series, a chronology was built for the archaeological sites in and around Ypres. This Ypres chronology now spans 231 years starting from A.D. 1132.

The earliest felling date, calculated from the oldest wood sample with completely preserved sapwood, is A.D. 1199. The most recent felling date from a similar sample, where the bark is still attached, is A.D. 1316. This indicates that, at least during a period of 117 years, construction activity took place at these locations. According to the distribution of the felling dates, this construction activity was most intense from A.D. 1240 up to 1290. After this last date, there is a significant reduction in the number of dated tree-ring series.

## 5.5 Discussion

Up to now, only a few dendrochronological projects have been undertaken in Flanders for dating archaeological wood. Successful dating was almost completely restricted to imported timber from the Baltic (e.g. Houbrechts and Pieters 1996; Haneca 2005). The potential for such dendrochronological research on Flemish oak was unclear and had been discussed. The combination of the lack of reference chronologies for this specific area, the high anthropogenic influence on forests since the Roman era and the tempering influence of the Atlantic climate made investments in dendrochronology as a dating tool risky. Moreover, the amount of preserved wood from archaeological excavations is often rather low. The rich collection of wood recovered during archaeological excavations in Ypres, provided the opportunity to verify the potential of dendrochronology as a dating tool for medieval archaeological sites in Flanders and for the development of a procedure for a dendrochronological approach adapted to the reality of Flanders and comparable regions throughout Europe.

The average ring width of 1.92 mm suggests that these oaks experienced favourable conditions, resulting in a high growth rate. The typical weather patterns in Flanders, with mild winter temperatures, moderately warm summer temperatures and abundant precipitation (approx. 750 mm), rarely lead to stressful conditions for oaks. Mathematically, this is expressed in the low mean sensitivity of the tree-ring series from the Ypres dataset (Table 5.1). Mean sensitivity can be considered as an indicator of the responsiveness of trees to the prevailing environmental conditions (Fritts 1976). Since these hardly ever limit growth, response to the mild Atlantic

climate is hard to quantify. Additionally, soil fertility and especially stand density must also have had a considerable influence on radial growth.

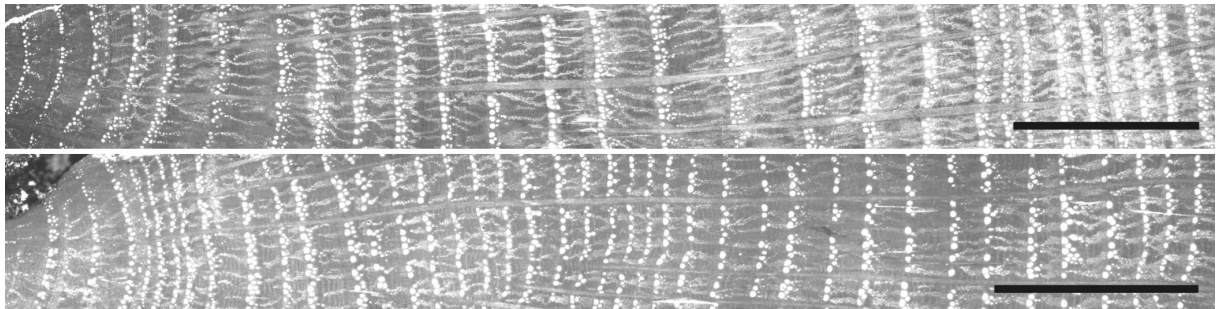
The large range of ring widths (0.2 – 9.7 mm) is probably influenced by the many abrupt growth changes that are observed in a large number of series. Since man intensively exploited medieval forests in Flanders, these abrupt variations are likely to be related to logging activity or management interventions.

It has been demonstrated that even short sequences with less than 60 growth rings can be dated. Nevertheless, a strong correlation between the number of measured tree rings and successful dating was observed (Figure 5.2b). Only when an oak sample has more than 60 growth rings does the chance of successful dating rise above 50%. Nevertheless it needs to be emphasised that dendrochronological dating in these specific conditions is laborious and needs a sufficient number of wood specimens to lead to a successful and acceptable dating of the tree-ring series.

According to Briffa and Jones (1990), an EPS value of 0.85 can be achieved by as few as four trees in semi-arid conifer stands in western USA. On the other hand a sample depth of at least 25 trees can be necessary in deciduous sites in the UK. For Flanders at least 14 dated medieval wood samples ought to be available to calculate a robust chronology. Combined with the calculated percentage of dated series according to the total number of growth rings (Figure 5.2b), an estimate can be made of the minimum number of wood specimens that should be collected from each construction phase on an archaeological site, when chronology building is one of the main goals. For example if most wood samples show 61-70 growth rings, at least 28 samples ( $= 14 / 0.50$ ) should be collected and measured. When the observed tree-ring series are longer, e.g. 91-100 years, this number decreases to 22 ( $= 14 / 0.64$ ).

Growth patterns of shoots from modern coppice are the most similar to the growth pattern of short series from the Ypres dataset. In particular the first growth rings of the short series from Ypres and the modern coppice display a vigorous growth (Figure 5.6). This contrasts with the low growth rate of the longer series from Ypres and the oaks generated from acorns (suppressed oaks from Mattemburg). It is obvious that shoots from a coppice stool (vegetative regeneration) will demonstrate a

larger growth rate compared to that from generative germination from a seed. In the first year, seedlings of pedunculate and sessile oak reach an approximate height of respectively 20 cm and 16 cm, while a shoot on an oak stool grows up to 2 m, and reaches a thickness of 2.5 cm (Vera 2000). These data suggest that the timber with short tree-ring series from Ypres comes from shoots from coppice stools. The first growth rings of the longer series from Ypres demonstrate that these trees probably regenerated from acorns, and not from a coppice stool. All this agrees with written sources on medieval woodland and forest use (e.g. Buis 1985; Rackham 2003). During the Middle Ages coppicing became a popular silvicultural technique (Bechmann 1990, Rackham 2003). Cutting trees and shrubs like oak (*Quercus* spp.), hazel (*Corylus avellana* L.), ash (*Fraxinus excelsior* L.) and willow (*Salix* spp.) to ground level allowed a vigorous re-growth, resulting in a sustainable supply of timber. An adaptation of this technique is coppice-with-standards, a two-storey woodland with coppice and some trees left to grow as large size timber, called *standards*. This type of woodland management yields a large spectrum of forest and timber products.



**Figure 5.6:** Ring-width patterns of two cross-sections from the archaeological excavations at Ypres that display different growth trends. The growth pattern of the upper image shows wide rings, while the other cross-section displays a more uniform growth pattern of smaller rings. Earlywood vessels were filled with chalk in order to highlight the growth-ring boundaries. The scale bar represents 1 cm.

The anomalous growth-rate changes that are observed in the tree-ring series from the Ypres dataset might be a result of logging activity. Bridge *et al.* (1986) measured the growth pattern of oaks in the Bradfield woods (Suffolk, UK). This stand is described as coppiced woodland. Oak trees are treated as standards while the understorey of ash, hazel, birch (*Betula* spp.) and alder (*Alnus glutinosa* L.) is coppiced on a regular basis. Bridge *et al.* observed that after coppicing the understorey, the growth rate of the retained oaks increased suddenly by 20% compared to the year prior to coppicing.

When calculating the mean number of sapwood rings, management practices and growth ratios are hardly ever considered. If in medieval times, forest structure differed significantly from the present, sapwood estimates could be biased when using tree-ring series exclusively from primary forests. Comparison of sapwood counts from modern oaks with the prevailing standards for Western Europe does not show large differences, except in one situation. Based on the available data, sapwood estimates differ significantly for young shoots (less than 50 years old) from coppice stools. Here a mean of  $7 \pm 2$  sapwood rings is the best estimate, in contrast to the prevailing standard of  $16 \pm 5$ . An important factor that emphasizes the observed difference is the fact that only one sapwood estimate is available for a broad age class of 100 years. The recorded sapwood counts demonstrate that age classes of 50 years are more appropriate for sapwood estimates, especially for trees less than 100 years old.

Although conditions in Flanders are suboptimal for dendrochronology, these results show that tree-ring analysis can help to document historical records of forest management and structure. From raw tree-ring series, impressions of medieval forest structure and dynamics can be derived. Furthermore, successful application of dendrochronology as a dating technique is demonstrated. This should encourage further combined dendrochronological and archaeological research in regions with a high historical anthropogenic influence on the original forest cover. In particular the creation of a regional reference chronology for Flanders would increase the potential of dendrochronology for dating purposes.

### **Acknowledgements**

The authors owe their gratitude to Marc De Wilde, Anton Eryvynck (Flemish Heritage Institute) and their co-workers on the field for providing the opportunity to analyse a rich collection of medieval oak from archaeological sites in Flanders. Also, we are grateful to Catherine Lavier (Laboratoire de Chrono-écologie, Besançon) for providing related tree-ring data. Furthermore, we would like to thank the dendro-laboratory in Hamburg (Dieter Eckstein, Sigrid Wrobel and co-workers) for the opportunity to use their chronologies and for helping us with the sample preparation.



# Growth trends provide an image of forest structure and management during Roman and Medieval times

# 6

## Chapter

### Summary

At some point in time, man has influenced nearly all forests in Western Europe. Most of the original forest cover has been converted to arable land and pastures, or has been cut for the supply of firewood and construction timber. In order to secure a sustainable source of firewood, the structure of the remaining forests was often altered. Especially coppice of European oak became increasingly popular during the Roman era and the Middle Ages.

Ring-width series of oak trees from Roman times and Medieval settlements were recorded. In order to extract more detailed information regarding past forest structure and management, those series were compared to growth patterns of contemporary oak. The modern oaks were selected on forests sites in Flanders (northern Belgium) with well-known structure and management.

Some remarkable similarities in growth patterns were observed. These findings yield tentative assumptions regarding past forest structure and management.

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K. Haneca, H. Beeckman and J. Van Acker (2005). Growth trends reveal the forest structure during Roman and Medieval times in Western Europe: a comparison between archaeological and actual oak ring series (*Quercus robur* and *Quercus petraea*). *Annals of Forest Science* 62(8): *in press*.

## 6.1 Introduction

In Europe, man, at some point in time, has influenced almost all forests and woodlands (Buis 1985; Rackham 2003; Tack *et al.* 1993). During Roman times the original vegetation in Western Europe was converted on a large scale. Forests were cleared and converted to arable land and pastures, or were cut for the supply of firewood and construction timber. Later, during the Middle Ages, the remaining forests were further reduced in their dimensions. For instance, in Flanders (northern Belgium), it is estimated that the lowest forest cover ever was encountered as early as in the second half of the thirteenth century (Tack *et al.* 1993). In order to secure a sustainable source for firewood, forests were often altered in structure. Coppice, especially of European oak (*Quercus robur* L. and *Q. petraea* (Matt.) Liebl.), became one of the most popular and widely dispersed short rotation systems (Bechmann 1990; Rackham 2003). Coppiced oak trees regenerate fast (Vera 2000) and provide small-dimension timber, and in addition the acorns were used as fodder for pig husbandry.

The reconstruction of past environments and biological communities has become an interesting topic for archaeobotanists, archaeologists and historians over the last few decades. For the reconstruction of past woodland and forest composition palynology, anthracology and the examination of macro remains are the most obvious proxies. Analyses of pollen grains, charcoal and fruits provide valuable information on the species composition and on changes in vegetation cover, but fail to provide detailed information on forest structure and dynamics.

Changes in the environmental conditions experienced by trees and shrubs trigger physiological processes that modulate the development of the secondary xylem, i.e. wood. Trees record such changes in their growth pattern (Fritts 1976; Schweingruber 1983). Tree-ring width and series of ring-width measurements are therefore potential archives of changes in the local or global environment. Gradual or abrupt changes in ring width that occur simultaneously in many trees growing at the same environment are often related to changing growth conditions (Fritts and Swetnam 1989). Silvicultural intervention is an example of a process that can modulate the growth-ring pattern of the majority of trees in the affected stand. Therefore growth patterns



from large collections of wood specimens, found during archaeological excavations, on waterlogged sites and from architectural objects can be considered as suitable proxies for the reconstruction of past forest architecture (Billamboz 2003; Wrobel and Eckstein 1993).

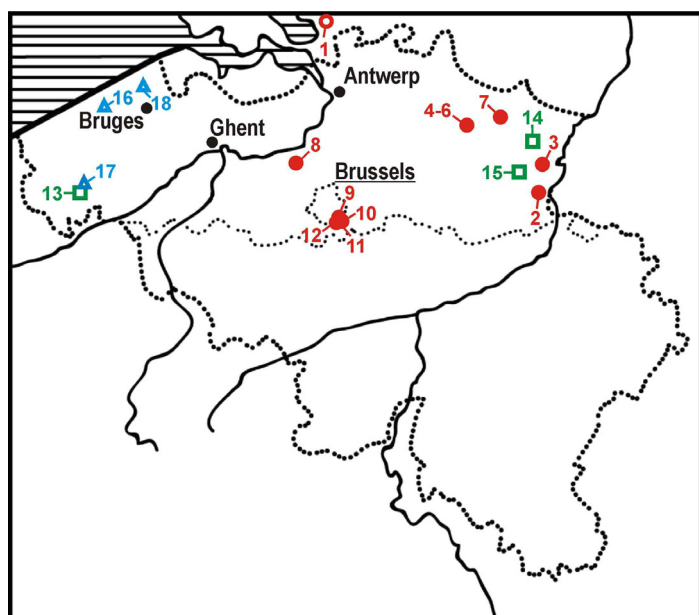
Most silvicultural interventions aim to modulate the growth rate of trees and hence influence the width of the tree-rings. For ring-porous species in general and European oak more specific, it has been demonstrated repeatedly that tree-ring width and cambial age (i.e. the number of the growth ring starting from the pith) highly determine the wood density. The latter variable is significantly related to the overall quality and the mechanical properties of the wood (Kollman and Côté 1968; Tsoumis 1991). Fast grown oaks provide high-density wood (650-850 kg/m<sup>3</sup>), while low-density oak (550-750 kg/m<sup>3</sup>) is often characterized by small rings (Rijsdijk and Laming 1994). High-density oak timber has better strength properties compared to low-density oak, while the latter has better physical characteristics and is more easily worked.

The question arises whether it is possible to distinguish between forest types based on a study of the ring-width patterns. It will be examined if characterization of the growth patterns from modern stands with well-known structure and management could help to reconstruct past forest structure from growth patterns of archaeological wood specimens. Moreover, the recorded ring-width series of modern, archaeological and historical trees will be compared with regard to wood quality. This could provide more information on the available wood assortments in a historical context.

## **6.2 Materials and methods**

### **6.2.1 Selected contemporary forest sites**

Fifteen contemporary forest sites in Flanders with well-known management and stand structure were selected for this study (Figure 6.1 and Table 6.1). Three main forest management systems can be distinguished: high forest, coppice and coppice-with-standards. Forest managed as high forest is focussed on the production of high-quality construction timber and logs for the veneer industry. Examples of such sites, with an abundance of European oak, are found southeast of Brussels in the Zoniën



**Figure 6.1:** Location of the selected forest stands with well-known structure (□ coppice stands; ● high forest; ○ oak under pine) and of the archaeological sites (△).

forest and at Buggenhout, in the Flemish region. Both locations are characterized by loamy soils. From the Tervuren Xylarium oak specimens from these forests have been selected: 107 cross sections (*Q. robur*) from four different sites (Epeler, Groenendaal, Zevenster and Kwekerij) in the Zoniën forest and 49 from Buggenhout (*Q. petraea*). The stem disks were always sawn as close as possible to the ground level to get the

maximum number of rings, from stumps of recently felled trees. In six other high forests, on dryer and more sandy soils in the north-eastern part of Belgium, two additional increment cores per tree were taken from four or five standing trees per site. On two other sites in the same area, both managed as a coppiced oak stand, increment cores were taken as well. Only one site (Kemmel), located in the south-western part of Flanders, was managed as coppice-with-standards. On this site increment cores from 17 trees were collected, i.e. increment cores from 12 coppiced trees and 5 widely spaced standards.

**Table 6.1:** Description of –a the selected contemporary forest stands –b and of the archaeological sites, with *Quercus* spp. (QUSP), *Q. robur* (QURO) and *Q. petraea* (QUPE).

#### a. Contemporary forest stands

| Nr. | Site            | Species | Management system                                     | No. of trees |
|-----|-----------------|---------|---|--------------|
| 1   | Mattemburg      | QURO    | Natural regeneration under <i>Pinus</i> spp.          | 97           |
| 2   | Eisderbos       | QUPE    | High forest (natural regeneration) + regular thinning | 5            |
| 3   | Kleine Homo     | QURO    | High forest (natural regeneration) + regular thinning | 5            |
| 4   | Gemeentebos 12a | QURO    | High forest (plantation) + regular thinning           | 5            |
| 5   | Gemeentebos 21a | QUPE    | High forest (plantation) + regular thinning           | 4            |
| 6   | Gemeentebos 28a | QUPE    | High forest (plantation) + regular thinning           | 4            |
| 7   | Pijnven         | QUPE    | High forest (plantation) + regular thinning           | 5            |
| 8   | Buggenhoutbos * | QUPE    | High forest (plantation) + regular thinning           | 49           |
| 9   | Epeler *        | QURO    | High forest (plantation) + regular thinning           | 18           |
| 10  | Groenendaal *   | QURO    | High forest (plantation) + regular thinning           | 20           |
| 11  | Zevenster *     | QURO    | High forest (plantation) + regular thinning           | 45           |
| 12  | Kwekerij *      | QURO    | High forest (plantation) + regular thinning           | 24           |
| 13  | Kemmelberg      | QURO    | Coppice-with-standards                                | 17 (12+5)    |
| 14  | Gruitrode *     | QURO    | Coppice   | 5            |
| 15  | Klaverberg      | QUPE    | Coppice   | 10           |

Table 6.1: Continued.

| <b>b. Archaeological sites</b> |                                 |                |  |                       |
|--------------------------------|---------------------------------|----------------|--|-----------------------|
| <b>Nr.</b>                     | <b>Site</b>                     | <b>Species</b> | <b>Description</b>   | <b>No. of samples</b> |
| 16                             | Oudenburg<br>(ca. 350-450 A.D.) | QUSP           | Roman settlement with two well-preserved water wells, constructed with wooden logs | 22                    |
| 17                             | Ypres<br>(1250-1300 A.D.)       | QUSP           | Wooden poles and boards from several medieval constructions                        | 111                   |
| 18                             | Lissewege<br>(1365-1370 A.D.)   | QUSP           | Medieval storage house   | 33                    |

The cross sections from locations marked with a \* are part of the Xylarium of the Royal Museum for Central Africa (Tervuren, Belgium).

In addition, one forest site with natural regeneration of oak (*Q. robur*) under pine (*Pinus sylvestris* L. and *Pinus pinaster* Aiton) was selected as well. Within the 106 ha forest reserve Mattemburgh, in the municipality of Woensdrecht (the Netherlands) close to the Belgian border, increment cores of 97 naturally regenerated oak trees were collected.

### 6.2.2 Archaeological and historical wood

Wood samples were collected on two archaeological sites and from one historical building (Figure 6.1). The archaeological excavation at Oudenburg, where remains of a Roman settlement were found, is located approximately 10 km east from the actual North Sea coast. Of particular interest were two well preserved wooden water wells, both made of European oak. The water wells were probably constructed at the end of the 4<sup>th</sup>, beginning of the 5<sup>th</sup> century AD. In total 22 cross sections from the logs were collected for tree-ring analysis.

From several archaeological excavations in the vicinity of the medieval town of Ypres (close to the French border) tree-ring patterns from approximately 250 wood specimens were analysed. The wooden logs were used as foundations for houses and revetments along a waterway and in a harbour. Dendrochronological research proved that the main building activity took place between 1250 and 1300 AD (Haneca *et al.* 2006). In total, 111 wood samples with pith and preserved sapwood were selected for this analysis.

A restoration project provided the opportunity to collect 33 cross-sections from structural oak timbers of an impressive medieval storage house in Lissewege, ca. 10 km north of Bruges. Dendrochronological dating proved that the oaks were felled somewhere between 1365 and 1370 AD (Haneca, *unpublished data*).

### 6.2.3 Data processing

Tree-ring widths of the contemporary, archaeological and historical wood specimens were measured to the nearest 0.01 mm using a LINTAB measuring stage and the TSAP-Win acquisition and processing software (Rinn 2003). The growth patterns of the collected stem disks were highly variable due to the irregular shape of the stem at ground level. They were measured along 4-8 radii, and averaged in order to reduce intra-tree variability (Fritts 1976).

### 6.2.4 Statistical description of the ring-width series

Several statistical parameters are useful to scrutinize ring-width series with special regard to stand characteristics and forest management. *Average ring width* is supposed to provide information on a number of environmental factors, e.g. stand density, soil fertility and soil texture, water capacity, etc (Fritts 1976; Fritts and Swetnam 1989). The *standard deviation* of a ring-width series is a measure for the variability in the radial growth rate, and may among others indicate the occurrence of sudden changes in radial growth rate, like growth releases due to canopy disturbances or pollarding effects (Rozas 2005). Oaks are known to exhibit a pronounced growth or age trends. Such trends could be related to the structure of the forest and can be partly quantified by *first-order autocorrelation* which is the correlation of each value in a time series with the value of its direct predecessor. The *mean sensitivity* ( $\bar{S}$ ) is a measure of the variation in ring width from year to year (Fritts 1976), and theoretically ranges from 0 (no difference between adjacent years) to 2 (requires a ring width measurement of “zero”). Low values will represent series with more or less constant ring widths.

$$\bar{S} = \frac{1}{n-1} \sum_{i=1}^{n-1} \frac{|x_{i+1} - x_i| \times 2}{(x_{i+1} + x_i)} \quad (6.1)$$

### 6.2.5 Growth trends

Ring-width series have an annual resolution, what means that each growth ring can be assigned to a specific calendar year. Moreover, general trends in tree-ring series; e.g. the age trend, as well as the tree-ring pattern in segments of different cambial age can be considered and might be more relevant regarding forest dynamics and development. For instance, tree-rings close to the pith are supposed to bear more information on (i) the light conditions at the time of regeneration as well as (ii) the type of regeneration. It is expected that regeneration from a stool, as is the case for coppiced trees, will result in a higher radial growth rate during the first years of growth compared to regeneration from acorns, because the shoots can profit from a fully developed root system.

More commonly used in forestry is the basal area increment (BAI) instead of the ring width. The basal area is defined as the area of the cross-section of a tree stem near the base, generally measured at breast height. The BAI is then defined as the increase in basal area of a tree over a specified time period (e.g. one growing season). Ring-width series can be converted to annual basal area increments (BAI<sub>*i*</sub>) assuming that the growth rings form concentric circles. Such a conversion of ring-width series into annual BAI's helps to remove variation in radial growth attributed to an increasing circumference.

$$BAI_i = \pi \times (R_i^2 - R_{i-1}^2) \quad (6.2)$$

with, BAI<sub>*i*</sub> : basal area increment over year *i*,

R<sub>*i*</sub> : sum of all ring widths, from the pith up to the growth ring with a cambial age of *i* years, what equals the radius of the stem (without bark) at the end of the *i*-th growing season.

## 6.3 Results

### 6.3.1 Statistic descriptors of tree-ring series from contemporary forest sites

Descriptive statistics of the tree-ring series from the contemporary forest management systems are listed in Table 6.2. The youngest trees, mainly at the Eisdarbos site, are 20 years old. Although these trees were cored at breast height, the number of recorded tree rings from the pith to the bark is considered to be a good

approximation of the tree age. The oldest trees are about 135 years old and are found on the high forest sites in the Zoniën forest.

**Table 6.2:** Descriptive statistics of tree-ring series from different contemporary stands with well-known structure, with *Q. robur* (QURO) and *Q. petraea* (QUPE). AV. No. TR, AV. RW and AV. STDEV: the average number of tree rings, the average ring width and the average standard deviation of the tree-ring series. MS and AC(1): the means sensitivity and the average first-order autocorrelation of the tree-ring series. AV. RW ( $\Delta 20$ ) and AV. STDEV ( $\Delta 20$ ): the average ring width and average standard deviation of the first 20 years of growth.

| SITE   | Species | AV. No. TR<br>[years] | AV. RW<br>[mm] | AV. STDEV<br>[mm] | MS    | AC(1) | AV. RW ( $\Delta 20$ )<br>[mm] | AV. STDEV<br>( $\Delta 20$ ) [mm] |
|--|---------|-----------------------|----------------|-------------------|-------|-------|--------------------------------|-----------------------------------|
| <b>Natural regeneration of oak under canopy</b>              |         |                       |                |                   |       |       |                                |                                   |
| Mattemburg   | QURO    | 60.8                  | 1.64           | 0.98              | 0.37  | 0.69  | 2.04                           | 0.83                              |
| <b>High forest (natural regeneration) + regular thinning</b> |         |                       |                |                   |       |       |                                |                                   |
| Eisderbos  | QUPE    | 21.6                  | 2.54           | 0.80              | 0.22  | 0.62  | 2.50                           | 0.75                              |
| Kleine Homo  | QURO    | 73.0                  | 2.07           | 0.80              | 0.22  | 0.69  | 2.72                           | 0.93                              |
| <i>HF-nat. reg. (all)</i>                                    | -       | 40.2                  | 2.47           | 0.83              | -     | -     | 2.61                           | 0.84                              |
| <b>High forest (plantation) + regular thinning</b>           |         |                       |                |                   |       |       |                                |                                   |
| Buggenhout   | QUPE    | 116.3                 | 2.79           | 1.56              | 0.28  | 0.91  | 2.34                           | 1.21                              |
| Epeler   | QURO    | 88.1                  | 3.39           | 1.57              | 0.26  | 0.76  | 2.63                           | 1.28                              |
| Groenendaal  | QURO    | 83.9                  | 3.01           | 1.31              | 0.23  | 0.76  | 3.55                           | 1.26                              |
| Zevenster  | QURO    | 87.2                  | 2.42           | 1.39              | 0.26  | 0.79  | 3.12                           | 1.25                              |
| Kwekerij   | QURO    | 134.5                 | 3.22           | 1.30              | 0.28  | 0.67  | 2.53                           | 0.94                              |
| Gemeentebos 12a  | QURO    | 72.6                  | 1.89           | 0.78              | 0.23  | 0.72  | 1.59                           | 0.69                              |
| Gemeentebos 21a  | QUPE    | 73.0                  | 2.00           | 0.78              | 0.25  | 0.63  | 1.74                           | 0.74                              |
| Gemeentebos 28a  | QUPE    | 64.5                  | 2.06           | 0.89              | 0.26  | 0.71  | 2.36                           | 0.84                              |
| Pijnven  | QUPE    | 84.0                  | 1.65           | 0.84              | 0.25  | 0.73  | 2.54                           | 0.85                              |
| <i>HF-plant. (all)</i>                                       | -       | 100.3                 | 2.75           | 1.38              | -     | -     | 2.71                           | 1.15                              |
| <b>Coppice</b>   |         |                       |                |                   |       |       |                                |                                   |
| Kemmel   | QURO    | 72.1                  | 1.97           | 1.16              | 0.27  | 0.74  | 2.84                           | 1.22                              |
| Gruitrode  | QURO    | 66.0                  | 1.14           | 0.93              | 0.22  | 0.79  | 2.07                           | 1.17                              |
| Klaverberg   | QUPE    | 56.0                  | 2.33           | 0.87              | 0.21  | 0.55  | 2.59                           | 0.84                              |
| <i>Coppice (all)</i>   | -       | 65.0                  | 1.95           | 1.01              | -     | -     | 2.60                           | 1.07                              |
| <b>Standards</b>   |         |                       |                |                   |       |       |                                |                                   |
| Kemmel   | QURO    | 75.6                  | 2.61           | 1.34              | 0.226 | 0.77  | 3.64                           | 1.48                              |

The average ring width is mostly higher in the intensively managed high forest stands, compared to stands managed as coppice or naturally regenerating oak trees under a close pine canopy (Mattemburg). The five sites with the highest growth rates (Buggenhout, Epeler, Groenendaal, Zevenster and Kwekerij) are all managed as high forest and are growing on fertile loamy soils with an adequate water capacity. Other high forest sites, on more sandy soils (Gemeentebos and Pijnven), display a

more reduced growth rate. Significantly correlated with the average growth rate is the standard deviation ( $r^2 = 0.687$ ;  $p = 0.001$ ).

The highest values of the first-order autocorrelation,  $AC(1)$ , are found on the high forest plantations and coppice stands. According to these high values, these ring-width series are expected to display a conspicuous age-related trend. In general, oaks regenerated from acorns have a less pronounced age trend.

The mean sensitivity of the tree-ring series displays only little variation between the sites (Table 6.2). Only on one site, the Mattemburgh reserve, it peaks to 0.370, what expresses a higher variation in ring width compared to trees from high forest and coppice stands.

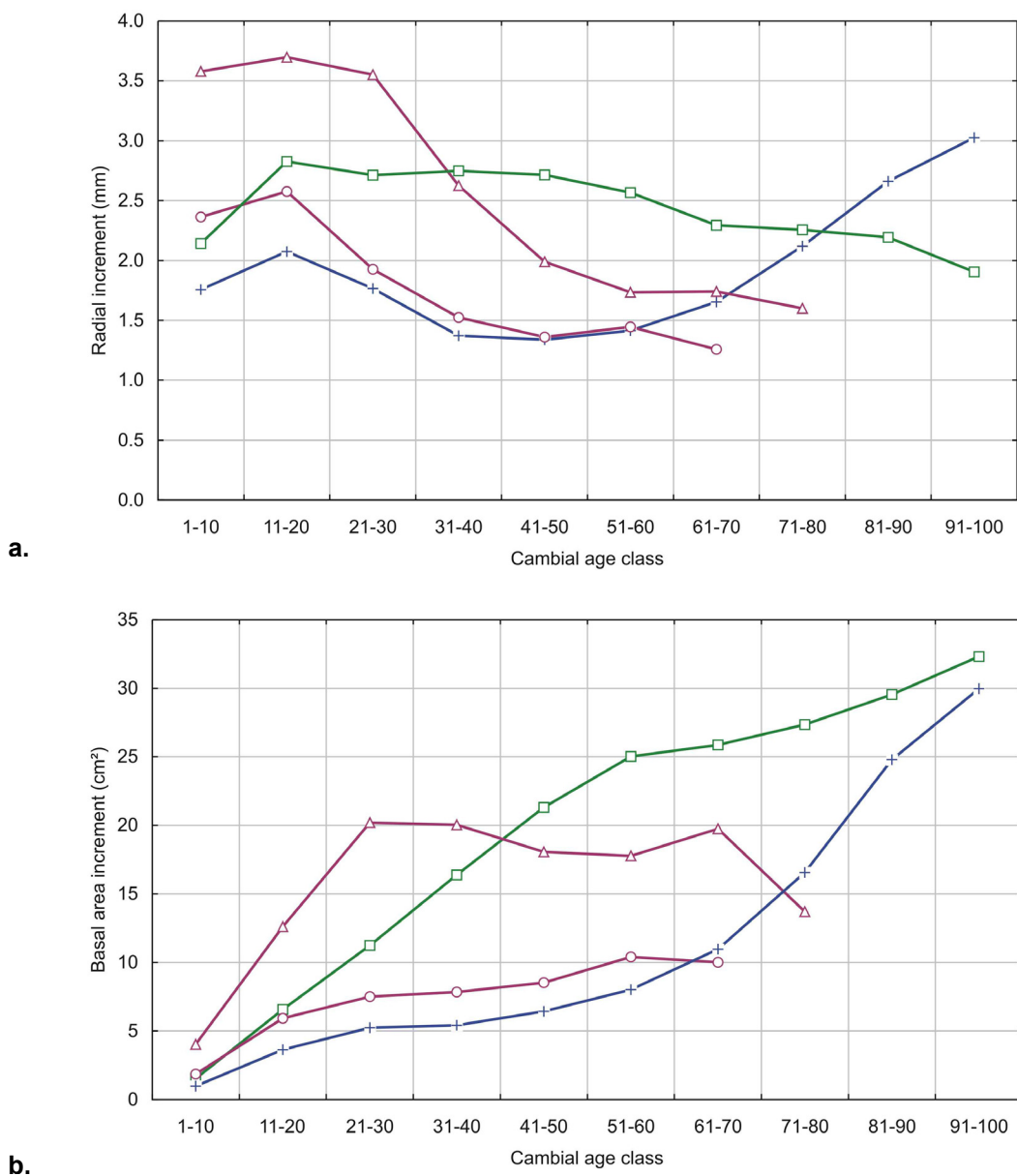
### 6.3.2 Description of the observed growth trends

In order to retrieve information on the type of regeneration – from a stool, from seed or planted from a nursery – the average radial growth rate and its standard deviation were considered for the first 20 years of growth (Table 6.2). For coppiced stands this average value is mostly higher than the overall growth rate. Stands that are managed as high forest display an opposite behaviour. Their average radial growth rate and standard deviation of the first 20 years is slightly lower than the overall growth rate.

Only when the average radial growth rate is computed for cambial age classes of 10 consecutive years, clear trends become visible. Particularly when for each management system all ring-width series with the same cambial age are averaged into one single series (Figure 6.2a). Coppiced trees, i.e. trees regenerating from a stool, display the highest radial growth rates in the first cambial age class (a cambial age of 1 to 10 years, starting from the pith). After they reached an age of ca. 20 years the growth rate rapidly decreases, and tends to stabilize at an age of 50-60 years. The widely spaced standards follow the same pattern, but the decrease in growth rate starts at least 10 years later. Oak trees in a high forest system display an increasing growth rate in the first 20-30 years, after which the growth rate steadily decreases. Naturally regenerating oak trees, which are shaded by pine trees in the Mattemburg reserve, also exhibit a rising growth rate over the first 10-20 years after germination. This trend is reversed after 20 to 30 years and starts to increase again

at an age of about 50 to 60, probably because of a less disadvantageous interference with the pines for light and nutrients.

Diverse growth trends are observed as well when BAI's are computed for the same cambial age classes (Figure 6.2b). The high forest shows a constantly increasing growth trend over the first 100 years. For the first 50-60 years of growth the increase in BAI displays a constant and positive slope, which is then followed by a more moderate growth. The oak trees that regenerated under a close pine canopy also exhibit a constantly increasing growth trend but with a more gentle slope over the first



**Figure 6.2:** Average growth rate for cambial age classes of 10 successive years, starting from the pith: **-a** radial increment (mm), **-b** basal area increment (cm<sup>2</sup>). ○ coppice; △ standards; □ high forest; + natural regeneration of oak under pine.



50-60 years compared to the high forest system. After 50-60 years the slope of the BAI-curve starts to increase, similar to the trend observed for the radial increment. The BAI of the coppice trees behave slightly different, with a rapid increase in the first 10 to 20 years of growth, after which the BAI starts to rise at a more gentle pace. This trend is even more pronounced for the more widely spaced standards from a coppice-with-standards site. For these trees the BAI increases rapidly over the first 20-30 years of growth and then levels out or even starts to decrease.

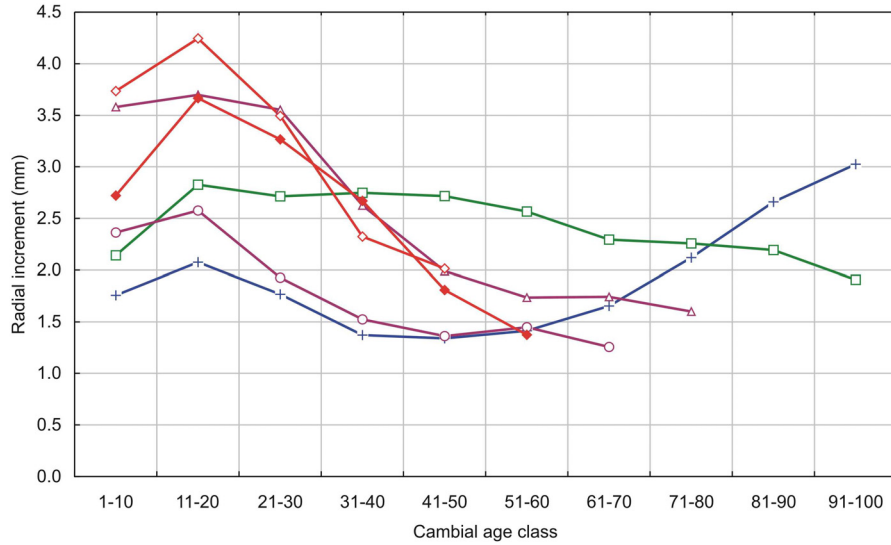
### 6.3.3 Statistic descriptors of tree-ring series from archaeological sites

A comparison of the descriptive statistics of the archaeological and historical wood specimens (Table 6.3) with the tree-ring series from modern oak trees demonstrates that all values fall within the same range. For the tree-ring series from Ypres and Lissewege a striking difference in growth rate is observed when the series are divided arbitrarily in two groups according to their total number of rings. The shorter series (with less than 50 rings) exhibit a remarkably higher growth rate compared to the group with the longer tree-ring series. This is even more pronounced when only the first 20 years of growth are considered for both groups (Table 6.3).

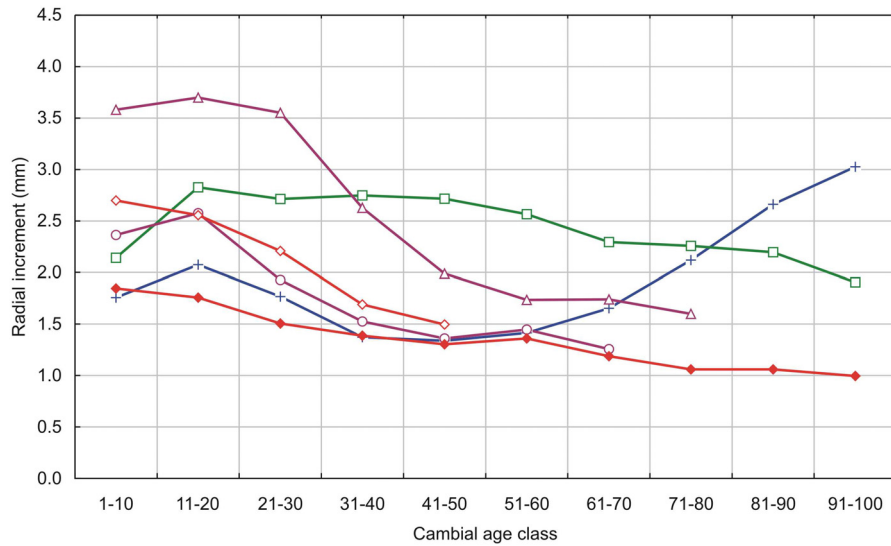
**Table 6.3:** Descriptive statistics of tree-ring series from three archaeological sites in Flanders. N: number of tree-ring series. AV. No. TR, AV. RW and AV. STDEV: the average number of tree rings, the average ring width and the average standard deviation of the tree-ring series. MS and AC(1): the means sensitivity and the average first-order autocorrelation of the tree-ring series. AV. RW ( $\Delta 20$ ) and AV. STDEV ( $\Delta 20$ ): the average ring width and average standard deviation of the first 20 years of growth.

| SITE            | N  | AV. No. TR<br>[years] | AV. RW<br>[mm] | AV. STDEV<br>[mm] | MS   | AC(1) | AV. RW<br>( $\Delta 20$ ) [mm] | AV. STDEV<br>( $\Delta 20$ ) [mm] |
|-----------------|----|-----------------------|----------------|-------------------|------|-------|--------------------------------|-----------------------------------|
| Oudenburg 1     | 8  | 38.4                  | 3.35           | 1.37              | 0.23 | 0.73  | 3.99                           | 1.31                              |
| Oudenburg 2     | 14 | 46.5                  | 2.88           | 1.13              | 0.20 | 0.80  | 3.19                           | 1.44                              |
| Ypres (<50)     | 54 | 31.6                  | 2.38           | 0.83              | 0.22 | 0.60  | 2.63                           | 1.19                              |
| Ypres (>50)     | 57 | 78.7                  | 1.41           | 0.72              | 0.23 | 0.72  | 1.80                           | 0.98                              |
| Lissewege (<50) | 21 | 38.1                  | 3.10           | 0.51              | 0.24 | 0.51  | 3.28                           | 1.83                              |
| Lissewege (>50) | 12 | 71.3                  | 2.31           | 0.66              | 0.27 | 0.66  | 2.56                           | 1.41                              |

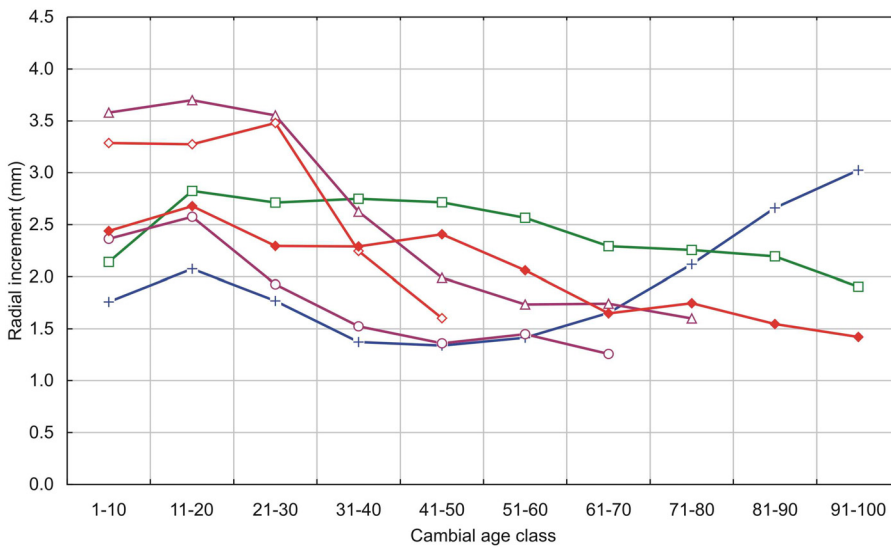
Ring-width patterns of wood specimens from the two archaeological sites and the medieval building were subjected to similar calculations as those of the contemporary trees (Figures 6.3a, c and e). For archaeological wood specimens it is difficult to convert the ring-width series to BAI's since it is not possible to locate the sample compared to breast height (1.3 m). Nevertheless a conversion of the tree-ring widths by equation 4.2 will deliver satisfying results (Figures 6.3b, d and f). They should be considered as an approximation of the actual BAI.



a.

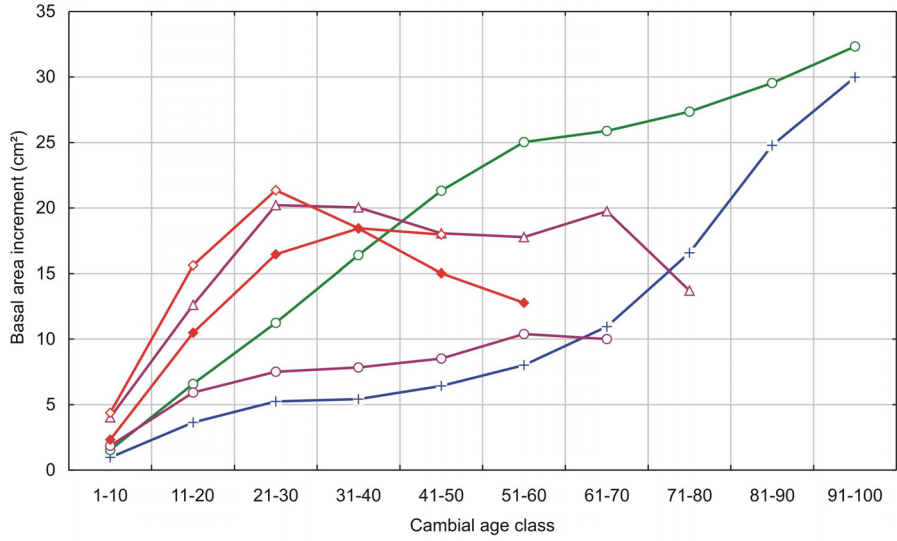


c.

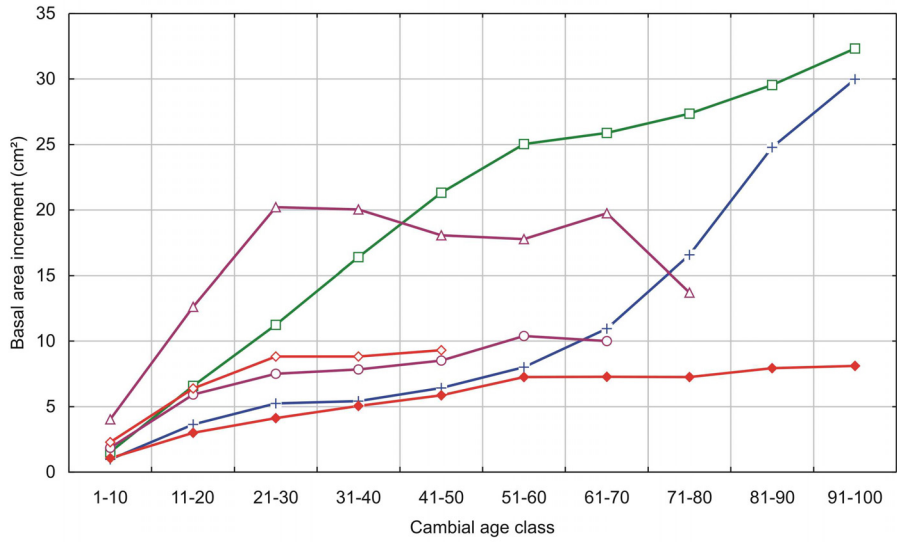


e.

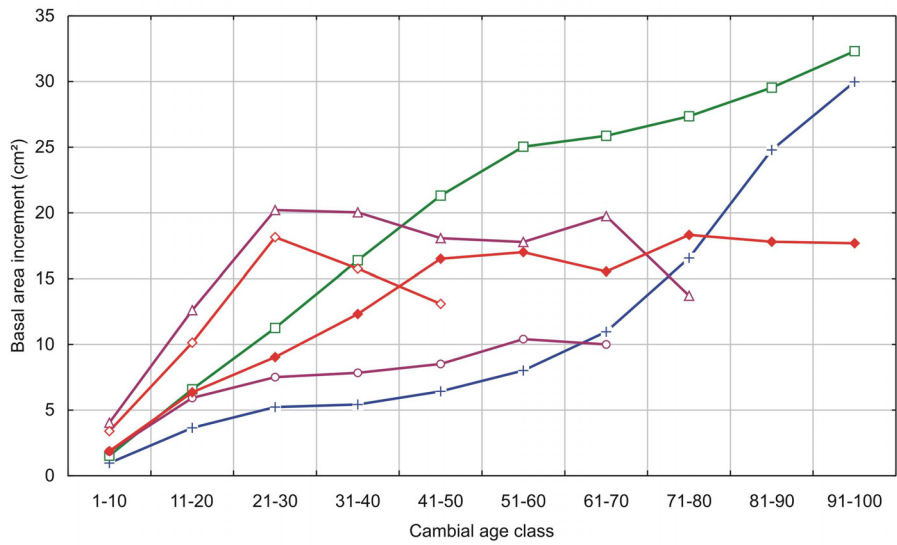
**Figure 6.3:** Growth patterns from several archaeological sites (◇ and ◆): **a-b** Roman wells from Oudenburg (ca. 350-450 AD), **c-d** revetments and foundations near Ypres (ca. 1250-1300 AD), **e-f** construction timber from a medieval storage house (1358-1370 AD) at Lissewege (○ coppice; △ standards; □ high forest; + natural regeneration of oak under pine).



b.



d.



f.

Figure 6.3: Continued.

The tree-ring series from the excavation at Oudenburg were rather short, never exceeding a length of 75 years. The radial-growth rates for the cambial age classes display a striking resemblance with the growth rates for contemporary trees from coppice stands (Figure 6.3a). The high and increasing initial growth rate over the first 10-20 years is followed by a sudden decrease. When regarding the BAI's over the same cambial age classes, a pronounced increasing and nearly linear trend is obvious over the first 30 years of growth (Figure 6.3b). This continuously rising trend is then halted and starts to decrease rapidly.

All tree-ring series from the excavations near Ypres were also aligned according to their cambial age. The radial growth rates did not display a clear trend similar to one of the contemporary forest management systems. Radial growth rates were then calculated separately for trees with less and more than 50 tree rings (Figure 6.3b). It is apparent that the short tree-ring series exhibit a significantly higher radial growth rate than the longer series. The growth rate of the short series also decreases rapidly after ca. 20 years whereas the growth rate of the longer series only displays a gradual decrease. The general trend in BAI has a gentle and positive slope for both groups (Figure 6.3c). Short series have, compared to the long series, a more rapidly increasing BAI over the first 10-20 years. Then the BAI stays nearly equal over the remaining growth period.

A similar procedure was applied to the tree-ring series from the medieval storage house at Lissewege. Again the average radial growth rates of the total data set did not show a clear agreement with one of the growth-ring patterns from the contemporary oak trees. A division into two distinct classes, with the series holding less than 50 growth rings separated from the longer ones, made the underlying differences more clear (Figure 6.3c). The longer series display, after a short increase in growth rate, a slowly decreasing growth rate. This contrasts the shorter series, which have a high and increasing growth rate over the first 40 years, followed by a drastic decrease. When converting the ring-width series to BAI, similar discrepancies between the two groups of long and short series can be observed (Figure 6.3f).

## 6.4 Discussion

Stand density, beside soil fertility, soil texture, water capacity and climate, is often considered as the most important factor to influence the general level of the radial growth rate. The average radial growth rate is therefore not suitable to provide more information on the forest structure than just stand density. Values of mean sensitivity and first-order autocorrelation are comparable to other oak stands in Europe (e.g. Lebourgeois *et al.* 2004). The highest mean sensitivity, recorded for the Mattemburg oaks, is probably induced by the more irregular nature of disturbances in an unmanaged pine stand with natural regeneration of oak. It can be concluded that the descriptive statistics mentioned have a limited potential for deducing information on stand structure and management.

The remarkable difference in growth rate between the long tree-ring series and the series with less than 50 rings suggests that the latter are not just the younger version of the former. Both groups probably experienced a different regeneration or had a completely different social status in the young developing forest.

Up to now, classification of historical and archaeological tree-ring series according to forest types is still based on assumptions. Nevertheless it is striking that confrontation of tree-ring patterns from archaeological sites with the data from contemporary oak trees reveals that highly similar and analogous growth trends are being observed. The growth rate can be expressed as ring width or as BAI. This allows further interpretation and the formulation of several hypotheses about former forest structure and management. Moreover, the method presented has the advantage that it not necessarily requires large data sets, unlike the method developed by Billamboz (1992 and 2003). The latter method, termed *dendrotypology*, classifies timber from archaeological sites using dendrological, dendrochronological and techno-morphological criteria. Single series with similar cambial age and growth trend are assembled into so-called local dendro-groups. This also leads to a more detailed insight in the age structure and dynamics of the stands where the wood was harvested.

Tree-ring series from the archaeological sites near Ypres and the medieval storage house at Lissewege exhibit a growth pattern that is more similar to oaks from a high forest stand or naturally regenerated oaks under close canopy. More specific, this statement holds for the longer tree-ring series, i.e. with more than 50 years (Figures 6.3c and 6.3e). The ring widths for the different cambial classes display a slowly decreasing trend. Moreover, the increase in BAI is nearly linear for the first 40-60 years of growth (Figures 6.3d and 6.3f). Both characteristics are similar to trees from high forest stands. On the other hand, short series from wood specimens of the Oudenburg and Ypres excavations display high similarities in growth trend with contemporary oaks from coppice stands, both in radial increment (Figures 6.3a and 6.3c) and in BAI (Figures 6.3b and 6.3d). Short series from the medieval storage house at Lissewege (Figure 6.3c) also display such a “*coppice-like*” trend. But for these wood specimens it is striking that the sudden decrease in growth rate only occurs after ca. 40 years of growth, what seems to be similar to the growth pattern from the widely spaced standards from a coppice-with-standards stand.

The overall growth rate of the Lissewege samples is also considerably high. So during the construction of the storage house (1365-1370 AD) fast-grown oaks were preferred. This also has some implications regarding the mechanical properties of the oak wood. Timber from fast-grown oaks is usually of the high-density type. For many ring-porous oak species, this type of wood often has better strength properties (Zhang 1995). So the medieval constructors might have been aware of this, and preferred to use these fast-grown oaks. Indeed, wood density is an important feature that influences the overall quality of timber. For oak, the density is mainly controlled by the cambial age and the ring width (Zhang 1995). The amount of the denser latewood will increase when the total ring width increases. According to recent research on oak trees from northern and central France, wood density hardly changes according to the type of forest management, site quality and geographic location, when cambial age and ring width are kept constant (Guilley *et al.* 2004).

The implemented silvicultural management must have altered the available wood assortments over time (Beeckman 2005). The increasing popularity of short rotation systems as coppice and coppice-with-standards during Roman times and the Middle Ages will have resulted in timber of reduced dimensions. Trees from short rotation

systems, as coppice, will usually be felled before they reach an age of 50-60 years. Such young oak trees have proportionally more juvenile wood. Also, young oak trees (less than 100 years old) have generally less sapwood rings compared to older (more than 100 years old) trees (Hillam *et al.* 1987; Hollstein 1980; Hughes *et al.* 1981). But, for the same growth rate, young trees have a relatively higher percentage of sapwood. In Flanders, a 1 m long log from a 50-year-old tree with an average growth rate of 2 mm/year has ca. 60% of sapwood where a similar log from a 150-year-old tree has only ca. 30% of sapwood. Wood from a short rotation system thus yields a reduced amount of durable heartwood.

Tree-ring patterns that are likely to come from a coppice stand have been found on sites from the late Roman period (Oudenburg). Probably this practice goes back much earlier, as observed by Billamboz (1989, 1996b and 2003) at Lake Constance/Bodensee. Similar growth trends were observed in coppiced stands in southern England and Wales (Crockford and Savill 1991), what broadens the validity of this method outside the Flemish region where the studied tree-ring series were collected. Wood found on archaeological sites is not necessarily representative for the nearest wood resources at that time. Nevertheless it is striking that so much wood specimens, used for construction purposes, seem to be related to contemporary coppice stands. This is remarkable since a primary goal for coppice management must have been the supply of firewood. This could indicate that from the remaining forests, coppice stands were the most abundant and that medieval craftsmen were dependent on those sites for the provision of timber.

The considerations regarding the physical and mechanical properties of the local timber yield additional arguments for the import of high-quality timber of oak. It is well documented that ever since the 9-10 century vast amounts of high-quality timber with Baltic origin have been imported (Houbrechts and Pieters 1996; Tossavainen 1994). This is also founded with dendrochronological evidence, especially with tree-ring series of wooden object from the 14<sup>th</sup> to 16<sup>th</sup> centuries (Bonde 1992; Bonde *et al.* 1997; Wazny 2005; Wazny and Eckstein 1987).

Past interventions in forest or woodland structure are still preserved in the growth-ring patterns of wood specimens found on archaeological sites. These growth

patterns provide a useful tool in the reconstruction of past forest structure. It also provides more information and insight in the available wood assortments in former times. Although this study has focussed on European oak, recent observations on some cross-sections of ash (*Fraxinus excelsior* L.) from a coppice stand revealed a highly similar trend in their growth pattern compared to the oak specimens (Haneca, *unpublished data*). This opens future prospects for forest and woodland reconstruction, and stimulates further characterization of growth patterns that are related to a specific stand structure or silvicultural management system.

### **Acknowledgements**

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**Part III**  
**SUBFOSSIL WOOD**





## **Part III**

# **SUBFOSSIL WOOD**

### **Preface**

The previous chapters discussed the high human impact on the original forest vegetation in Flanders during the Roman era and the Middle Ages. Therefore, it would be of interest to look at relics of undisturbed forests, preceding this high anthropogenic pressure. Consequently it is necessary to study very old material. Long-term preservation of trees or parts of stems requires permanently wet conditions. Therefore, subfossil trees are mostly found on wetland sites, along river valleys or close to abandoned branches of a river. Such subfossil oaks have contributed to the creation of millennium-long, European reference chronologies of which some are more than 10.000 years long.

Subfossil trees can be considered as remnants of past forests or woodland. An image of species composition and abundance can be obtained by analysing pollen, fruits and seeds. Nevertheless, palynology and analysis of macro-remains fail to provide more insight into local stand dynamics and development. Therefore it would

be of interest to look at the ring-width patterns of subfossil oaks in order to obtain a better understanding of past environmental conditions experienced by the trees. Growth trends and anomalies in the ring-width pattern could be related to changes in the direct growing conditions of the trees. However, since ring widths are actually integrations over the entire growing season, it could be of interest to look at intra-ring variables, i.e. particular wood anatomical features that are related to a more narrow time window. For oak it is known that the size and distribution of the earlywood vessels contains a different climatological signal compared to the width of the total ring. Hence, subtle variations in the anatomy of the wood could be of interest when studying former ecological and environmental conditions experienced by trees.

The dendrochronological frame of reference chronologies becomes sparse in prehistoric times. Therefore other dating techniques need to be consulted. Radiocarbon analysis provides a valuable alternative. Nevertheless, the precision of this dating technique does not have the same resolution as obtained by dendrochronology. Moreover, the precision is time-dependent and relies on the variations in the atmospheric radiocarbon production.

In order to enhance the precision of radiocarbon dating of wood specimens it is possible to combine tree-ring data and radiocarbon measurements into one model. This technique is referred to as *wiggle-matching*. It allows to incorporate additional information into the calibration process of radiocarbon dates, what results in a more narrow range in calendar years.

The theoretical foundation, advantages and limitations of radiocarbon dating and *wiggle-matching* are presented in **Chapter 7**, together with some simulations that illustrate the precision that can be expected from these chronometric dating techniques. The subsequent chapter of this part focuses on subfossil oaks that were discovered in Ename, along an abandoned branch of the river Scheldt (**Chapter 8**). It is evaluated whether they are able to provide more relevant information on past stand dynamics and development by scrutinizing their ring-width pattern and anatomical characteristics. In order to obtain a precise setting in time, the subfossil oaks are submitted to radiocarbon analysis, of which the theoretical background was explained in Chapter 7.

$$P(\theta|x) \propto \prod_{j=1}^n \frac{1}{\sigma_j(\theta)} \exp\left\{-\frac{(x_j - \mu(\theta))^2}{2\sigma_j^2(\theta)}\right\}$$





# Radiocarbon dating and wiggle matching

# 7

Chapter

## Summary

When dendrochronology fails to provide reliable and acceptable felling dates for trees, radiocarbon analysis can be considered as a valuable alternative. Due to variations in the atmospheric radiocarbon production ( $^{14}\text{C}$ ) radiocarbon ages need to be transformed into true calendar (solar) years. This calibration procedure will be explained and exemplified. Furthermore, due to the irregular nature of the calibration curve, it is not possible to predict the precision of radiocarbon dating. Besides the theoretical background of radiocarbon dating, figures are presented that illustrate the expected precision of radiocarbon calibration of single samples over the last 3.000 years.

Moreover, the possible interaction between tree-ring analysis and radiocarbon analysis will be presented. The latter, referred to as *wiggle matching*, relies on models based on Bayesian statistics. Probabilistic models that are used in *wiggle-matching* procedures will be explained. In addition, the expected precision of radiocarbon calibration of multiple, chronologically ordered samples will be quantified and illustrated in graphs.

## 7.1 Introduction

Soon after Willard F. Libby's (1908 - 1980) discovery of the potential of radiocarbon decay for historical and archaeological studies, serious investments were made in the optimization of the radiocarbon dating method. After the nomination of Libby for the Nobel Prize of chemistry in 1960, the Nobel Foundation acknowledged the overall influence of the radiocarbon method by stating: "... *Seldom has a single discovery in chemistry had such an impact on the thinking in so many fields of human endeavour ...*". Since then, radiocarbon dating has become a well-accepted and widely applied dating method in archaeology, geology and geophysical research.

The underlying process for radiocarbon dating is the natural production of carbon isotopes in the upper atmosphere, due to interaction of nitrogen atoms with thermal neutrons. The latter are produced as a secondary effect of the continuous cosmic ray bombardment in the upper atmosphere.



Most of the radiocarbon (ca. 60%) is formed in the stratosphere, with a maximum at approximately 12 km above sea level. Furthermore, it is documented that more  ${}^{14}\text{C}$  is produced near the poles compared to the equator. The remaining 40% is produced uniformly in the troposphere. The newly formed radiocarbon quickly oxidizes to carbon dioxide ( ${}^{14}\text{CO}_2$ ). Predominantly during spring and summer, radiocarbon is injected into the troposphere, mainly near 40 degrees of latitude on both hemispheres. The common atmospheric turbulences diffuse the oxidized radiocarbon molecules. Despite the rather uniform dispersion slight differences in radiocarbon concentration between the northern and southern hemisphere are observed (Lerman *et al.* 1970; Vogel *et al.* 1993).

The major part of the produced radiocarbon, ca. 85%, is absorbed in the oceans. Approximately 1% becomes part of the terrestrial biosphere by means of photosynthesis. The  ${}^{14}\text{CO}_2$  is integrated into organic molecules by metabolic processes. While plants are alive there is a constant exchange of carbon dioxide with the atmosphere (Figure 7.1). Once the organism stops metabolizing, the amount of radiocarbon starts to decrease due to radioactive decay. During the  $\beta$ -decay, which

occurs in  $^{14}\text{C}$ , a neutron emits an electron ( $\beta$ -particle) and becomes a proton. This results in an increase of the atomic number and transforms the carbon isotope into a nitrogen atom (Eq. 7.2).



where  $e^-$  is the emitted electron and  $\bar{\nu}$  an anti-neutrino released during the decay event. The radioactive decomposition of the  $^{14}\text{C}$  isotope obeys, as other radioisotopes, the law of radioactive decay, which is mathematically expressed as

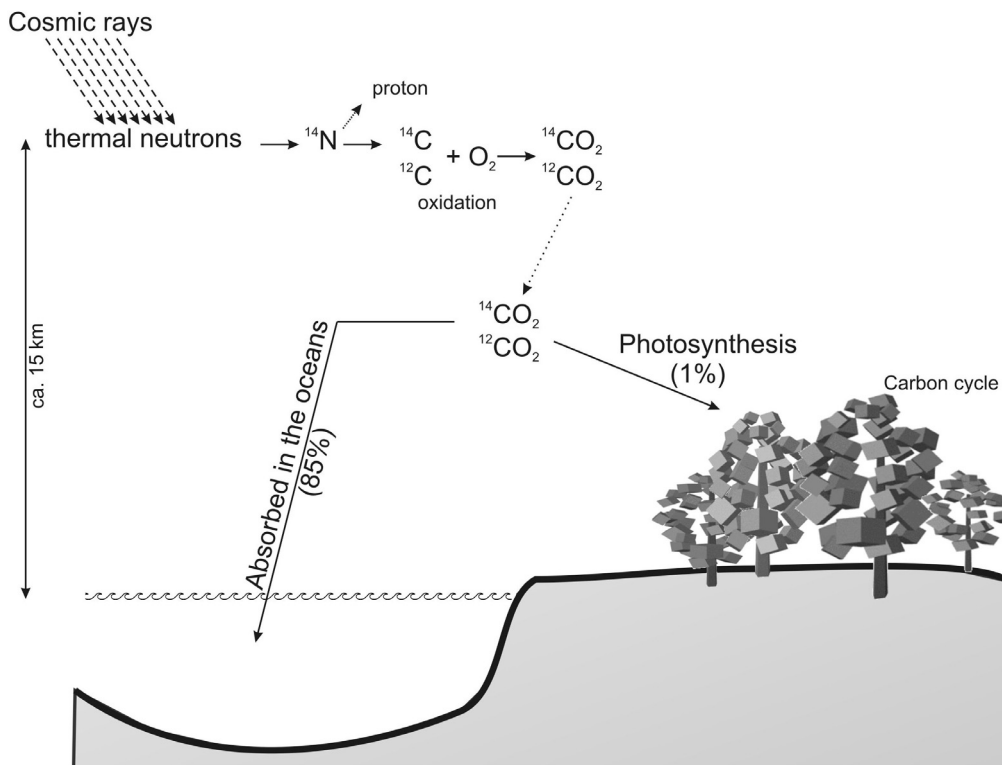
$$A = A_0 e^{-\lambda t} \quad (7.3)$$

where:

$A$  = the remaining activity (i.e. decay events per time unit) of the sample at time  $t$ ,

$A_0$  = the initial activity of the sample,

$\lambda$  = the decay rate =  $\ln 2/T$ , with  $T$  the half-life of  $^{14}\text{C}$ .



**Figure 7.1:** Schematic overview of the production and distribution of  $^{14}\text{C}$ .

The most accurate estimate of the half-life  $T$  of  $^{14}\text{C}$  isotopes is the so-called *Cambridge half-life* of 5730 ( $\pm 40$ ) years, what means that after 5730 years half of the original amount of  $^{14}\text{C}$  atoms will have disintegrated. This value for the half-life of  $^{14}\text{C}$  is higher than the half-life of 5568 ( $\pm 30$ ) years, originally determined by Libby.

Nevertheless, since many radiocarbon dates had been published before the more accurate half-life was known, it was decided to keep the original half-life of Libby for further calculations (Stuiver and Polach 1977). This implies that uncalibrated radiocarbon ages, calculated with the Libby half-life, could be improved by multiplying by the ratio of the two half-life values (i.e. 1.029). However, this is usually unnecessary since this adjustment is included in the currently available calibration curves.

In order to calculate the conventional radiocarbon age of a sample, the decay formula can be transformed into

$$t = 8033 \cdot \ln(A_0 / A) \quad (7.4)$$

where  $t$  is the radiocarbon age of the sample, and  $5568 / \ln 2 = 8033$ . This formula needs some further corrections and adaptations to compensate for isotopic fractionation. The isotopic fractionation refers to the fact that certain biochemical processes, such as photosynthesis, alter the atmospheric isotope ratios by favouring one isotope over the other (Taylor 1997). Wood for instance, tends to be depleted in heavy isotopes compared to the surrounding atmosphere. Therefore, the measured activity in wooden samples is modified by -25‰ with respect to an international reference of oxalic acid, provided by the N.I.S.T (National Institute of Standards and Technology; Gaithersburg, Maryland, USA). This reference serves as a modern standard to define a “zero”  $^{14}\text{C}$  age (Stuiver and Polach 1977).

Conventional radiocarbon ages are always reported in years before the present (BP). This trivial term refers to the number of years before the artificial *year zero* for the  $^{14}\text{C}$  age, i.e. 1950 AD (Stuiver and Polach 1977). This year was chosen since  $^{14}\text{C}$  levels in the atmosphere raised spectacularly due to the detonation of nuclear devices from the 1950s onwards.

## 7.2 Measuring procedures

Determination of the radiocarbon age relies on the measurement of the residual  $^{14}\text{C}$  content in a sample. Currently available measuring techniques can be divided in two different groups. Devices of the first group detect radioactive decay events, where

others take advantage of the differences in mass of the carbon isotopes. It should be clear that both techniques require an extremely high measuring sensitivity since the proportion of  $^{14}\text{C}/^{12}\text{C}$  is in the order of  $10^{-10}$  to  $10^{-16}$ .

The earliest attempts to measure the amount of  $^{14}\text{C}$  in a sample were conducted using a modified *Geiger* counter. Such conventional gas counters are capable to detect the  $\beta$ -particles, i.e. electrons, emitted from the  $^{14}\text{C}$  nucleus at each radioactive decay event. This technique requires large samples of up to 3 g of carbon and a measuring time of at least 1.000 – 3.000 min. This counting system was mainly replaced by Liquid Scintillator (LS) Spectrometry. During the 1950s it was discovered that certain organic compounds (scintillators) fluorescence when they are exposed to ionising radiation (e.g.  $\beta$ -particles). LS spectrometers measure the pulses of light generated from photon emissions, emitted by a scintillator in response to a radioactive decay event. The frequency of the fluorescence events is then proportional to the total number of  $^{14}\text{C}$  atoms in the sample.

A measuring device that has become widely available and highly appreciated for measuring the radiocarbon content of a sample is the Accelerated Mass Spectrometer (AMS). This complex apparatus does not count the decay events but simultaneously quantifies the different carbon isotopes in a sample, based on their difference in mass. Two of the most significant advantages of this technique are the substantial reduction in samples size (down to 30  $\mu\text{g}$  - 3 mg of carbon) and the limited measuring time of no more than ca. 15 - 120 minutes. The most critical point in this type of analysis is the possibility of micro-contamination in small samples. Contamination with modern carbon will disrupt the measuring procedure and yield erroneously young radiocarbon dates.

As all other biological samples, wood that is collected for radiocarbon dating needs a pre-treatment before it can enter the measuring procedure. The required pre-treatment predominantly depends on the applied measuring technique. At first, extreme care should be taken to eliminate all possible contamination with foreign organic or young atmospheric carbon. When wood samples are taken from buried archaeological specimens, all roots and organic soil should be removed. Samples can also be contaminated by calcium carbonate (limestone) from groundwater, and

humic acids from organic matter in the soil. Simple decontamination with HCl and/or NaOH is usually adequate to remove carbonates and humic contaminants. Wood that has been buried in anaerobic conditions, e.g. in a bog or in waterlogged soils, can exchange atmospheric CO<sub>2</sub> when excavated and exposed to the air. Therefore, it is recommended to isolate the cellulose for the radiocarbon dating. This fraction is regarded as the most stable part of the wood. However, the original amount of wood will then be reduced to more than 50%. During cellulose extraction, the wood is grinded, treated repeatedly with acidic and alkali solutions, and finally bleached, usually with H<sub>2</sub>O<sub>2</sub>. The crude cellulose or pre-treated samples are finally burned to combust the carbon into CO<sub>2</sub>. This, or conversion to methane (CH<sub>4</sub>), is required for the proportional gas counters. Further chemical conversion into benzene C<sub>6</sub>H<sub>6</sub> or toluene C<sub>6</sub>H<sub>6</sub>CH<sub>3</sub> is suitable for measurements with LS Spectrometry. For AMS the carbon dioxide is converted to graphite. The minimal amount of wood required for conventional gas counters or AMS is listed in Table 7.1.

**Table 7.1:** Required amount of wood for radiocarbon dating (after Goh 1991).

|                | Conventional counters (g) | AMS (mg) |
|----------------|---------------------------|----------|
| Wood (air dry) | 25-30                     | 12-15    |
| Wood (wet)     | 40-80                     | 20-40    |

### 7.3 Secular variation in <sup>14</sup>C production rates

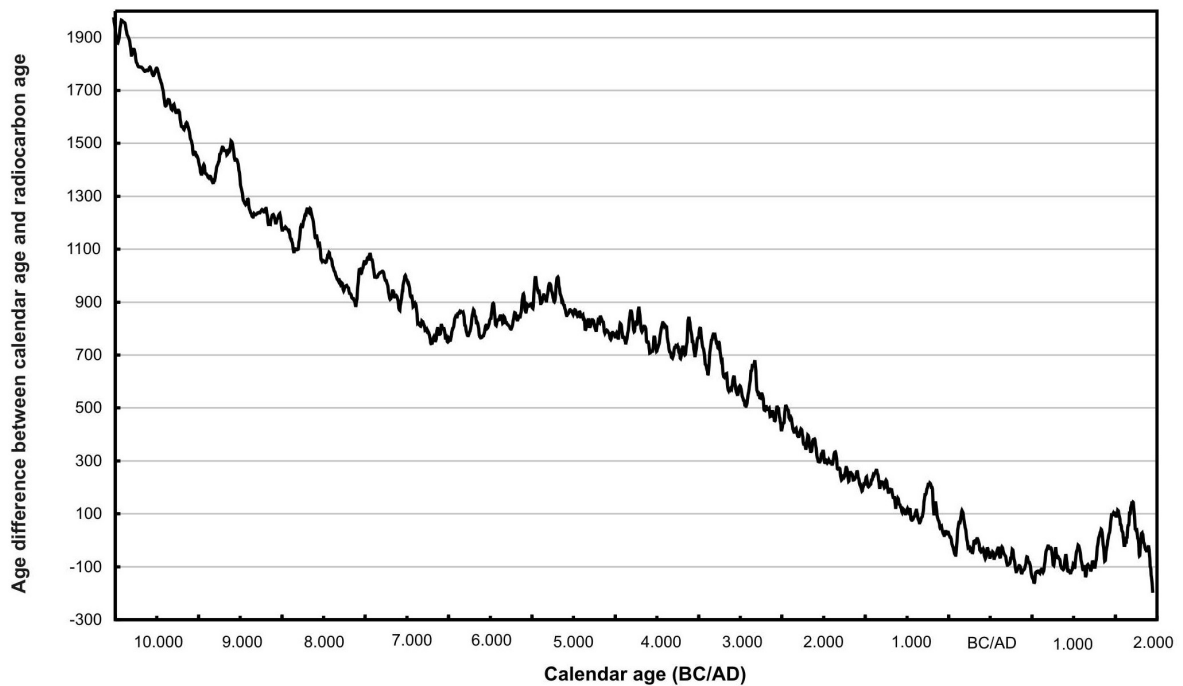
Soon after the implementation of radiocarbon dating in archaeological studies, it was recognized that one of the basic assumptions for this dating technique, i.e. that the <sup>14</sup>C production remained constant over time, was not valid. De Vries was the first to report the important and time dependent trade-off between *radiocarbon years* and *solar years* (De Vries 1958; Münnich *et al.* 1958). The rate of <sup>14</sup>C production proved to be closely related to the variations in the earth's magnetic field and the sunspot cycle (Stuiver 1961 and 1965). The term *secular variation* was introduced to denote any systematic variability in the <sup>14</sup>C time spectrum other than that caused by <sup>14</sup>C decay. Soon, attempts were made to document these variations throughout the Holocene. It was the starting point for the construction of a calibration procedure to convert radiocarbon ages into true calendar years.

It has been demonstrated that  $^{14}\text{C}$  levels in annual growth rings display the same pattern of the atmospheric data. Hence, the annual growth rings of trees can qualify as true, high-resolution calibration archives of past variations in atmospheric radiocarbon concentrations. Dendrochronologically dated wood of the giant Californian sequoias (*Sequoia gigantea* (Lindl.) Decne.), European oaks (*Quercus* spp.) from Germany and Ireland and Bristlecone pines from the White Mountains in California (*Pinus aristata* Engelm.), was used for the construction of high-precision calibration curves. High-precision calibration refers to the careful determination of counting uncertainties, which are on the  $1\sigma$  level smaller than 20 years. An internationally accepted high-precision calibration curve was first published in 1986 (Stuiver and Becker 1986). At that time the calibration curve was based on radiocarbon measurements from bidecadal (20 year long) tree-ring segments. This calibration curve was further enhanced and corrected by interlaboratory comparison and resulted in the IntCal93 calibration curve, with a bidecadal resolution running back to 9.840 years BP, based on dendrochronologically dated wood (Stuiver and Becker 1993). IntCal98 was the first calibration curve with a decadal tree-ring part back to 9.668 BC (Stuiver *et al.* 1998b). The complete IntCal98 calibration curve goes back to 22.050 BC, where the oldest part is based on samples from corals and laminated lake sediments (Stuiver *et al.* 1998a).

The most recent high-resolution calibration curve for Northern Hemisphere terrestrial samples, IntCal04, presents radiocarbon dates for 5 year intervals, back to 12.400 BP, 10 year intervals from 12.400 up to 15.000 BP and 20 year segments for the 15.000 to 26.000 BP interval (Reimer *et al.* 2005). The youngest part of the IntCal04 calibration curve, back to 12.400 BP, was calculated with radiocarbon measurements of dendrochronologically dated wood specimens. Figure 7.2 illustrates the age difference between radiocarbon and calendar years for the tree-ring part of the IntCal04 calibration curve (0 - 12.400 BP), which ranges from -199 up to +1966 years. For the entire IntCal04 calibration curve, the manifest difference between radiocarbon ages and the true calendar age ranges from -199 up to 4.659 years, over the last 26.000 years BP.

Besides the high-resolution calibration curves for 5 to 20 year segments, a calibration curve based on single-year wood samples from Washington State and Kodiak Island

in Alaska has been published (Stuiver et al 1998b). This calibration curve covers the 1510 AD - 1954 AD interval.



**Figure 7.2:** Age difference between the radiocarbon age and the true calendar date, based on the IntCal04 calibration curve.

Two types of periodicity can be observed when regarding the radiocarbon calibration curve. At first, a general declining trend which is mathematically comparable to a decay function can be distinguished. This general trend is superimposed by a series of high-frequency components, with a strong variation in periodicity and duration. These variations are referred to as *wiggles*.

The detonation of nuclear weapons during the 1960s induced a dramatic increase in atmospheric  $^{14}\text{C}$  levels. The most spectacular rise occurred in the years 1962 to 1963 AD when the concentration of  $^{14}\text{C}$  isotopes in the northern troposphere nearly doubled, compared to the pre-nuclear era (Hua *et al.* 1999). After the Nuclear Test Ban Treaty of 1963,  $^{14}\text{C}$  levels gradually started to decrease. The magnitude of the atmospheric  $^{14}\text{C}$  levels and the year in which the highest values are encountered (i.e. the *bomb-peak*) depends on the latitudinal position on the globe. Post-nuclear  $^{14}\text{C}$  values decrease from north to south. On the northern hemisphere the atmospheric  $^{14}\text{C}$  concentration peaks in 1964. Southern hemispheric values are lower and peak with a delay of 1-2 years (Hua *et al.* 1999). In wood, the highest  $^{14}\text{C}$  concentrations



are found in the growth ring that corresponds to the year in which the *bomb-peak* occurred in the atmospheric data (e.g. Fichtler *et al.* 2003, Worbes 1995, Worbes and Junk 1989).

#### 7.4 Calibration of a single radiocarbon measurement

After measuring the  $^{14}\text{C}$  content of a sample, the calculated radiocarbon age needs to be converted into the true calendar date using the calibration curve. This process often results in a considerable loss of precision, due to the fact that the shape and the associated uncertainty on the calibration curve are time dependent. Mathematically the calibration curve, which represents the relationship of  $^{14}\text{C}$  dates versus calendar dates, can be described according to the formula:

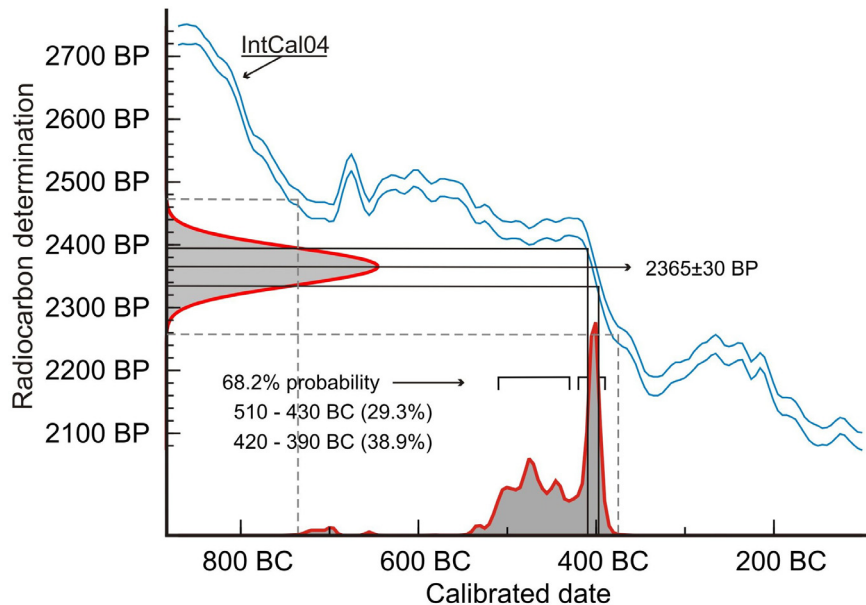
$$r = \mu(\theta) \pm \sigma(\theta) \quad (7.5)$$

where  $\sigma(\theta)$  is the uncertainty on the calibration curve itself. Due to its irregular character, there is no simple mathematical function that can be used to describe the calibration curve. For the IntCal04 high-resolution calibration curve, the uncertainty on the curve itself is approximately 14 years at the  $1\sigma$  level over the past 10.000 years. This uncertainty can rise up to 25 years, and can be as low as 6 years. Radiocarbon ages are reported as the estimated age  $x_i$  with the corresponding standard deviation  $\sigma_i$ .

##### 7.4.1 Intercept approach

A first, and simple, approach is to transfer the confidence intervals of the radiocarbon age determination directly to the calibration curve and bring these intercepts directly to the actual time axis. This procedure is illustrated in Figure 7.3 and immediately illustrates why this intercept approach does not yield reliable results (Telford *et al.* 2004). In some cases, due to the irregular character of the calibration curve, this intercept method delivers calendar age ranges that are considerably smaller than the range of radiocarbon ages derived from the  $^{14}\text{C}$  measurement. Furthermore it is possible that the confidence limits of the radiocarbon age determination intersect with the calibration curve at several positions, due to the wiggly nature of this curve. Therefore it is not recommended to use the confidence intervals of the radiocarbon

time scale and transfer them to the solar time scale by using the intercepts with the calibration curve.



**Figure 7.3:** Calibration of the  $^{14}\text{C}$  age  $2365 \pm 30$  BP into a range of calendar dates using the IntCal04 calibration curve (blue). The black lines illustrate the intercept approach, the shaded areas the Bayesian approach.

### 7.4.2 Bayesian statistics

An alternative method to convert radiocarbon dates into calendar ages is the development of a probabilistic model. This approach is based on the theory of Thomas Bayes (1702° - 1761<sup>†</sup>) and referred to as Bayesian statistics (Bayes 1763). The Bayes' theorem is a mathematical expression that allows to calculate conditional probabilities. It can be viewed as a means of incorporating information, e.g. from an additional observation or preceding event, to produce a modified or updated probability distribution. It provides the conditional probability distribution of a random variable  $A$  given some observation (evidence)  $B$  by relating it to the conditional probability distribution of variable  $B$  given that  $A$  is observed and the marginal probability distribution (referred to as the *prior probability distributon*) of  $A$  alone. In a mathematical format, Bayes' theorem in its simplest form is written as

$$p(A|B) = \frac{p(B|A).p(A)}{p(B)} \tag{7.6}$$

where:

$p(A|B)$  = conditional probability that  $A$  occurs given that  $B$  has occurred already  
 = *posterior probability distribution*

$p(A)$  = probability that  $A$  occurs = *prior probability*

$p(B)$  = probability that  $B$  occurs

$p(B|A)$  = conditional probability that  $B$  occurs given that  $A$  has occurred already

The term  $p(B|A)$ , for a specific value of  $B$ , is called the *likelihood function* for  $A$  given  $B$  and can also be written as  $l(A|B)$ . With this terminology, the theorem may be paraphrased as

$$\text{posterior} = \frac{\text{likelihood} \times \text{prior}}{\text{normalizing const.}} \quad (7.7)$$

### 7.4.3 Calibration for one single sample

The main goal of a calibration is to derive the true calendar age  $\theta$  from the  $^{14}\text{C}$  age  $x_i$ . Each  $x_i$  is a realization of the random variable  $X_i$

$$X_i \sim N(\mu(\theta_i), \sigma_i^2 + \sigma^2(\theta)) \quad (7.8)$$

where  $\mu(\theta)$  represents the high-precision calibration curve and,  $\sigma^2(\theta)$  the uncertainty in the calibration curve itself. When  $\sigma_i^2$ , i.e. the uncertainty on the measurements, is much higher than  $\sigma^2(\theta)$ , the latter can be removed from the further calculations. Recent developments in radiocarbon measurement have reduced the value of  $\sigma_i^2$  considerably. Values of less than 30  $^{14}\text{C}$  years are now common. In such cases  $\sigma^2(\theta)$  can not be ignored (Christen and Litton 1995). For ease of notation one uncertainty term is introduced:

$$\omega_i^2(\theta_i) = \sigma_i^2 + \sigma^2(\theta_i) \quad (7.9)$$

Implementation of Bayes' theorem allows to convert a radiocarbon age into a calendar date in a probabilistic sense (Steel 2001; Steier and Rom 2000; Steier *et al.* 2001). The Bayes' theorem allows to derive the *posterior probability*  $p(\theta_i | x_i)$  from the *likelihood* and the *prior*.

$$p(\theta_i | x_i) \propto p(x_i | \theta_i) \cdot p(\theta_i) \quad (7.10)$$

How likely an assumed calendar age  $\theta_i$  for the sample of interest is going to yield the data  $x_i$  observed in the actual measurement is called the *likelihood function*  $p(x_i | \theta_i)$ . For a single  $^{14}\text{C}$  date this is

$$p(x_i | \theta_i) = \frac{1}{U} \frac{1}{\omega_i(\theta_i) \sqrt{2\pi}} e^{-\frac{(x_i - \mu(\theta_i))^2}{2\omega_i^2(\theta_i)}} \quad (7.11)$$

where  $U$  is a normalization constant to achieve  $\int_{-\infty}^{+\infty} p(x_i|\theta_i) dt = 1$ .

Since the calibration curve and its associated uncertainty are highly variable, the likelihood function is not Gaussian in shape. This would only be possible with a strictly linear calibration curve that has a constant uncertainty term.

The *prior density function*  $p(\theta_i)$  can be described as the probability distribution of the true calendar age of the sample prior to the radiocarbon measurement. However, the crucial assumption that is necessary to implement the Bayes' theorem is that all calendar dates are equally probable and differ from zero. In other words, no *a priori* information about the age of the samples should be available. The prior  $p(\theta_i)$  then becomes

$$p(\theta_i) \propto \begin{cases} 1 & 0 < \theta_i < \infty \\ 0 & \text{otherwise} \end{cases} \quad (7.12)$$

This reduces the previous equation of the posterior probability to

$$p(\theta_i|x_i) \propto p(x_i|\theta_i) \quad (7.13)$$

since  $p(\theta_i)$  is a constant (= 1). The posterior probability equals the likelihood function in this case.

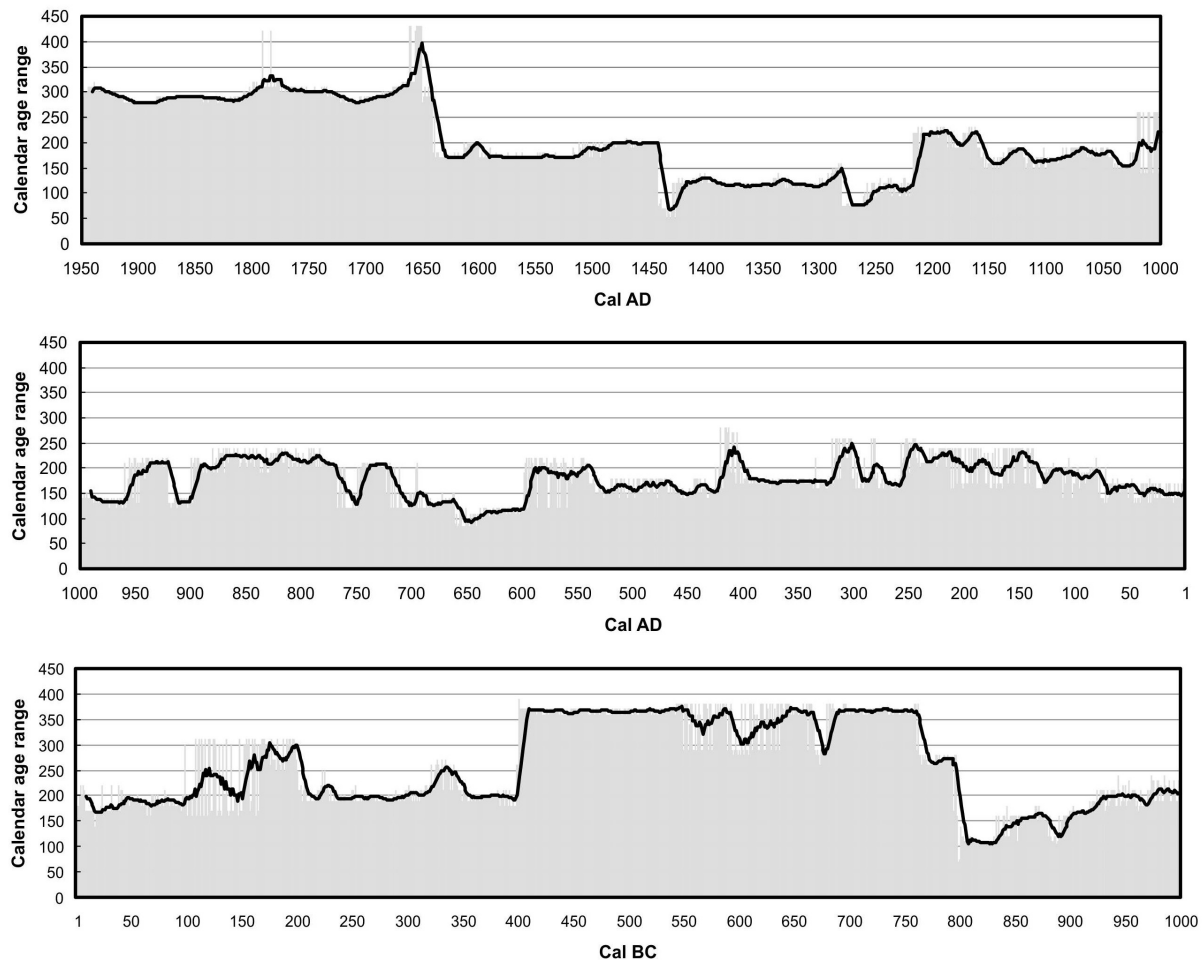
This Bayesian approach is implemented into several software routines (e.g. OxCal, BWigg, Calib, BCal, Cal25 and CalPal). Figure 7.3 visualizes the posterior probability function after Bayesian calibration of a radiocarbon age ( $2365 \pm 30$  BP). Each intersection of the radiocarbon age distribution with the calibration curve, results in a proportional probability in the calibrated age distribution. It is clear that a radiocarbon date may correspond to several calendar dates, what then results in a local probability maximum along the range of possible calendar dates. It should be clear that the shaded areas in Figure 7.3 are proportional. The calculated probabilities for each calendar year are then accumulated until the total probability reaches a threshold level, often 95.4% ( $2\sigma$ ) or 68.2% ( $1\sigma$ ).

#### 7.4.4 Precision of radiocarbon dating

Due to the irregular nature of the calibration curve it is not possible to predict the precision of a radiocarbon dating procedure on an unknown sample, where the precision is defined as the range of possible calendar dates. The latter will be

influenced by the standard error on the initial radiocarbon measurement, the shape of the calibration curve and the uncertainty on the calibration curve.

The program OxCal 3.10 (Bronk Ramsey 1995 and 2001) includes a function (R\_Simulate) to simulate a radiocarbon age given the exact calendar age and the expected error term on the radiocarbon measurement. This involves some randomization and will not yield the same radiocarbon age for each simulation. In order to average the variability involved in the simulations, this procedure was repeated 10 times for each calendar date from 1950 AD to 1000 BC, with an assumed measurement error on the radiocarbon age of 30 years. The ten simulated radiocarbon ages for each calendar year were finally averaged. The obtained *average* radiocarbon age was then calibrated yielding a range of calendar dates. The difference between the upper and lower limit of the 95.4% confidence interval defines the precision in calendar years for each calibration and is plotted in Figure 7.4 for each calendar year. It is noticed that for samples of less than 350 years old a very low precision is obtained (Figure 7.4). On average the 95.4% probability interval is more than 250 years wide up to 1650 AD. For older samples, that have metabolized atmospheric carbon dioxide before 1650 AD, the width of the probability interval drops down to ca. 170 years for the rest of the AD section. A remarkable plateau in precision is observed in the Hallstatt period (ca. 750 - 400 BC). There the calibration curve is extremely flat over a long period what results in a very low precision for radiocarbon dating. Samples from that 350 year long period will all fall within the same range of calendar dates. This clearly demonstrates the varying degrees of temporal resolution that can be obtained from  $^{14}\text{C}$  data.



**Figure 7.4:** Expected precision of a standard calibration of single samples, from 1950 AD – 1000 BC, based on the IntCal04 calibration curve. The black line is the 10-year running mean.

## 7.5 Wiggle-matching

Besides the radiocarbon dates, often more relevant archaeological information is available, e.g. from typology, stratigraphy or dendrochronology. Often, this extra information is available as logical statements with a non-probabilistic nature. Of particular interest for radiocarbon dating is the chronological order of the samples. This is for instance known for tree-ring sequences or annually laminated lake sediments. In such cases it is possible to say that event *A* (e.g. the year in which a tree-ring was formed) happened before event *B* (a tree ring formed in a subsequent year). In order to narrow the range of possible calendar dates from a  $^{14}\text{C}$  age it is useful to take multiple samples, at distinct intervals. This provides extra data (i.e. the known interval between the sampling points) for the calibration process. It is acceptable to assume that the inclusion of the radiocarbon ages and their

chronological order in the calibration process will yield a more accurate setting in time than can be achieved by calibrating the individual radiocarbon ages separately (e.g. Buck *et al.* 1996).

This technique of dating material with known age separation is often referred to as *wiggle-matching*. Two appropriate methods were developed for *wiggle-matching*. The first is basically a curve-fitting technique where the other calibration procedure involves Bayesian statistics. In general these techniques can be applied to any dataset where the relationship between the individual samples is described in terms of sequences.

### 7.5.1 Curve fitting

Radiocarbon dates ( $x_i$ ) with known age separation can be considered as an approximation of the actual calibration curve. The  $^{14}\text{C}$ -dates of individual, chronologically ordered samples can be fitted to the calibration curve. This technique was described in detail by Pearson (1986). The quality of the fit can be expressed by the mean-square difference between the  $^{14}\text{C}$  ages of the samples and the interpolated ages  $y_i$  derived from the calibration curve. It has been demonstrated that the sum of the squared differences,  $SS$ , reaches a minimum at the position of the best fit with the calibration curve (Pearson 1986). The calendar date with the lowest  $SS$  value is then regarded as the most probable calendar date  $\theta_s$  for the whole sequence.

$$SS = \sum_{i=1}^n (x_i - y_i)^2 \quad (7.14)$$

where  $n$  is the total number of samples.

Discussing the uncertainty involved, Pearson (1986) noted that at the position of the best fit, the  $SS/2\omega^2(\theta)$  has a  $\chi^2$ -distribution.

$$\sum_{i=1}^n \left[ \frac{x_i - y_i}{\sqrt{2\omega(\theta)}} \right]^2 = \frac{SS}{2\omega^2(\theta)} \sim \chi_n^2 \quad (7.15)$$

From  $\chi^2$ -tables it is possible to lookup the critical  $\chi^2$ -value,  $\chi_{\text{crit}}^2$ , for any degree of confidence, and to use this value for the delineation of confidence intervals. Nevertheless there is one serious drawback to this method since it has the

characteristic that the larger the scatter on the measurements, the narrower the uncertainty limits become (Bronk Ramsey *et al.* 2001; Goslar and Madry 1998). Therefore, this technique should be avoided since it can lead to erroneous results when trying to derive a probability distribution for  $\theta_s$ .

### 7.5.2 Implementation of Bayesian statistics for wiggle matching

In order to use additional information, presented as logical statements, in a statistical analysis, the data need to be transformed into probability distributions. This contrasts the classical statistical analyses that rely solely on the observed data and measurements. A Bayesian approach has led to the development of new models for radiocarbon dating that are able to incorporate such *prior* (chronological) information (Bronk Ramsey *et al.* 2001; Buck *et al.* 1996; Christen and Litton 1995; Goslar and Madry 1998; Steier and Rom 2000; Steier *et al.* 2001).

In the case of a wood specimen with distinct growth rings, it is possible to take samples for radiocarbon dating from different growth rings. The samples then have a chronological order since the interval between two sampling points (in calendar years) equals the number of annual rings between the successive sampling points. Assume a sequence of  $n$  samples from one wood specimen, with associated calendar dates represented by  $\theta_i$  ( $\theta_1, \theta_2 \dots \theta_n$ ). For each sample  $i$  (with  $i = 1, 2 \dots n$ ) a radiocarbon age  $x_i$  with associated standard deviation  $\sigma_i$  is available. Suppose  $\phi_j$  to be the interval in calendar years between the samples  $j$  and  $j-1$ . Then  $\theta_j - \theta_{j-1} = \phi_j$ , where  $j = 2, 3, \dots n$  and  $\phi_1 = 0$ . This implies that when  $\theta_1$  is accurately known, the other dates can be calculated using the  $\phi_j$  values.

Similar to the calibration of a single sample, the crucial assumption for a Bayesian approach is that every calendar date is *a priori* equally possible and differs from zero. This results in the following prior  $p(\theta_1)$ :

$$p(\theta_1) \propto \begin{cases} 1 & 0 < \theta_1 < \infty \\ 0 & \text{otherwise} \end{cases} \quad (7.16)$$

For all  $n$  radiocarbon measurements, assuming that they are all independent, the *likelihood*  $p(x|\theta_1)$  becomes



$$p(x|\theta_1) = \prod_{j=1}^n p(x_j|\theta_j) \quad (7.17)$$

where

$$x = (x_1, x_2 \dots x_n),$$

$$p(x_j|\theta_j) = \frac{1}{\omega_j(\theta_j)} \exp\left\{-\frac{(x_j - \mu(\theta_j))^2}{2\omega_j^2(\theta_j)}\right\},$$

$$\theta_j = \theta_1 + \sum_{i=1}^j \phi_i \text{ with } \phi_1 = 0,$$

$$\text{and } \omega_j^2(\theta_j) = \sigma_j^2 + \sigma^2(\theta_j).$$

Furthermore, the *posterior* density function  $p(\theta|x)$  can be calculated by implementing Bayes' Theorem and yields

$$p(\theta_1|x) \propto p(x|\theta_1).p(\theta_1) \quad (7.18)$$

with  $p(\theta_1)$  as the *prior* density of  $\theta_1$  and  $p(\theta_1|x)$  the *posterior* density of  $\theta_1$ . The *prior* is known to be a constant (see 7.16) and can be removed from the previous equation. Hence, the posterior probability distribution for wiggle-matching  $n$  radiocarbon dates becomes:

$$p(\theta_1|x) \propto \prod_{j=1}^n \frac{1}{\omega_j(\theta_j)} \exp\left\{-\frac{(x_j - \mu(\theta_j))^2}{2\omega_j^2(\theta_j)}\right\} \text{ for } 0 < \theta_1 < \infty \quad (7.19)$$

Again, due to the nature of the high-precision calibration curve  $\mu(\theta_j)$  there is no simple analytical form for the posterior density. Consequently, it has to be computed numerically. Such routines are implemented in calibration software like OxCal 3.10 (Bronk Ramsey 1998; Bronk Ramsey *et al.* 2001) and Bwigg (Christen 2002).

### 7.5.3 Precision obtained by wiggle matching

Chronologically ordered samples that are involved in a *wiggle-matching* procedure are expected to yield a more narrow range in calendar dates compared to the calibration results of their individual  $^{14}\text{C}$  ages. In radiocarbon dating, the acquired precision depends on the shape of the calibration curve, the spacing between the subsequent samples, the precision of the individual  $^{14}\text{C}$ -measurements and the number of samples involved (Bronk Ramsey *et al.* 2001; Galimberti *et al.* 2004). The influence of the number of radiocarbon measurements involved is illustrated in Figure 7.5 from 1950 AD to 1000 BC. It is immediately clear that when the number of samples is low, i.e. 4 to 6, the range in calendar years is not noticeably reduced

compared to the calibration of the individual radiocarbon ages. When 8 or more samples are included, the precision significantly increases. When no serious *wiggles* occur in the calibration curve, e.g. like the Hallstatt plateau, the range in calendar years can be as low as 25 years at the  $2\sigma$  confidence level when 8 to 10 subsequent samples are analysed. Involving more chronologically ordered samples in the calibration process do not considerably enhance the precision.

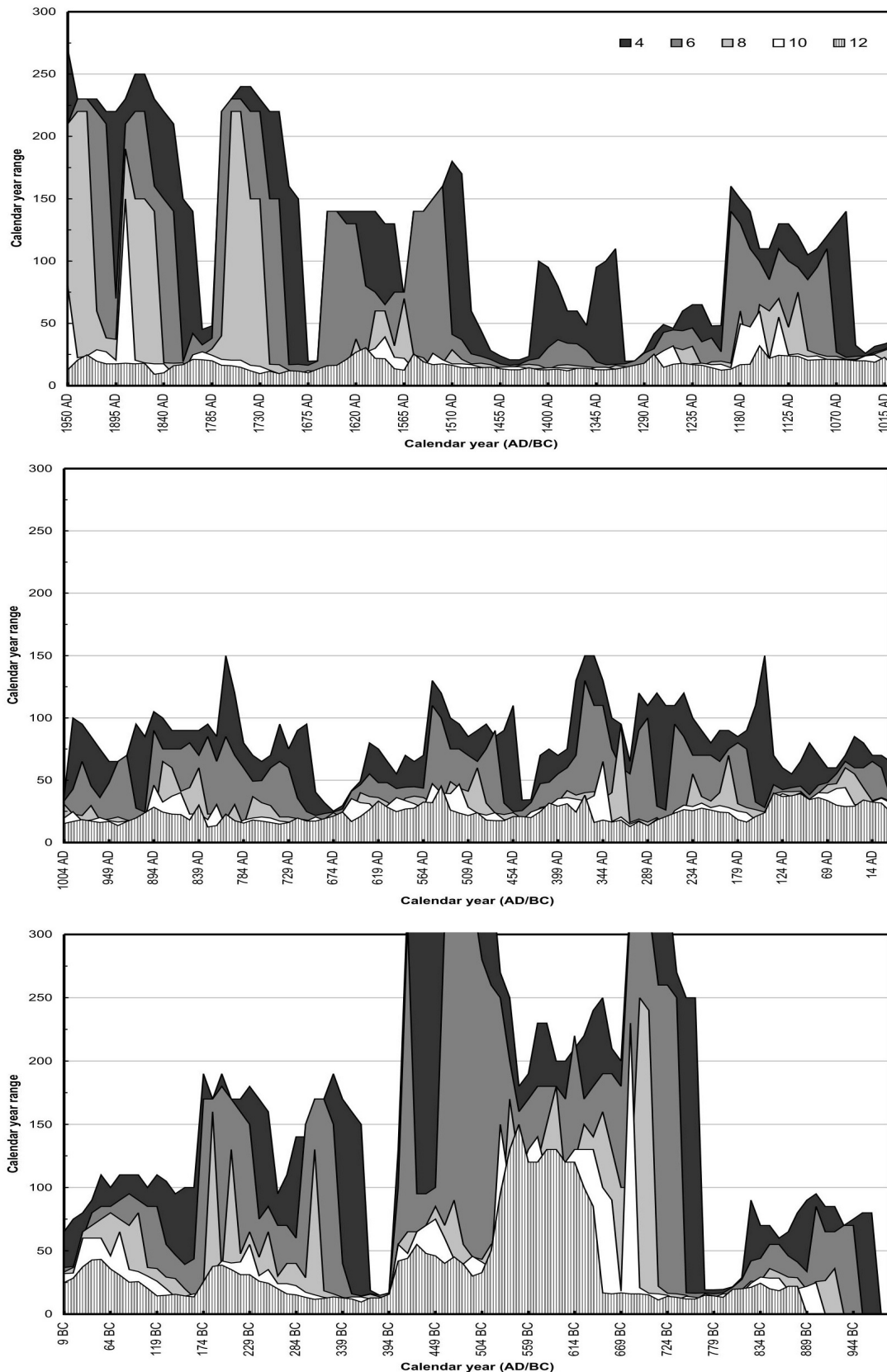
Galimberti *et al.* (2004) demonstrated from simulated calibration results that a 95% confidence range of less than 25 years can be obtained by including 5 to 10 chronologically ordered measurements with a 10 year spacing and 25 - 30  $^{14}\text{C}$  year precision in a Bayesian wiggle-matching procedure.

## 7.6 Conclusions

Radiocarbon dating can be considered as a valuable chronometric dating tool in archaeological and palaeontological research, especially for wood specimens. However, it should be clear that the precision obtained, expressed as a range in calendar years, is not even close to the accuracy of tree-ring dating. Dating results from the latter technique have an annual precision, although some uncertainty regarding missing sapwood must often be taken into account.

Combination of tree-ring data and radiocarbon measurements (i.e. *wiggle matching*) can yield a higher level of precision compared to the calibration of individual radiocarbon ages. It should be clear however that it is generally necessary to include 8 to 10 chronologically ordered samples in order to narrow the range of calendar dates significantly. In such cases, wood specimens can be dated with a precision of up to 25 years at the  $2\sigma$  uncertainty level. Including more than 12 samples in a *wiggle-matching* procedure will usually not result in further reduction of the precision. Moreover, the costs involved for the radiocarbon analysis also rise considerably when multiple samples are involved.

For trees that grew during the 1960s, the detection of the *bomb-peak* in the growth rings can be used to date wood specimens to the year and can help to confirm whether the growth layers have an annual character or not (Worbes and Junk 1989).



**Figure 7.5:** Expected precision of *wiggle-matching* for different numbers of chronologically ordered samples with a time spacing of 10 years, from 1950 AD to 1000 BC, based on the IntCal04 calibration curve. The single radiocarbon dates were simulated with OxCal 3.10 and are also presented in Figure 7.4. The different shadings correspond to the number of samples involved. Maximum precision is obtained for 10 to 12 chronologically ordered samples.



# Subfossil oak trunks as *ecological archives* of forest dynamics along the river Scheldt

# 8

Chapter

## Summary

Subfossil trees are considered as archives of past forest and woodland dynamics. In NW Europe, cross-sections of more than 9.000 subfossil oaks have been collected and analyzed, mainly from wetland sites in Germany, England, Ireland and The Netherlands. The majority of those subfossil oaks were preserved in bogs, river gravels or marine sediments. During an archaeological inspection in spring 2002, subfossil oak trees were discovered along a former branch of the river Scheldt (Ename, Belgium). This provided the opportunity to study the growing conditions and site dynamics of a riparian forest, at the beginning of the Atlantic period, by scrutinizing the ring-width pattern and wood anatomical structure of the subfossil oaks.

Ring widths of the subfossil oaks proved to be extremely narrow with conspicuous small earlywood vessels in the smallest growth rings, compared to contemporary trees. This clearly indicates that the subfossil oaks experienced limiting growing conditions. Most probably local hydrology affected and regulated tree growth. Due to those specific growing conditions that control the growth-ring pattern, it is not possible to establish a dendrochronological connection with other European absolutely dated reference chronologies.

The results presented clearly demonstrate that a detailed analysis of the growth pattern and the size of the earlywood vessels from subfossil oaks can provide more information and insight into local hydrology and stand dynamics of riparian forests throughout the Holocene.

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### *In preparation:*

K. Haneca, K. Deforce, J. Bastiaens, J. Van Acker and H. Beeckman (2005). Subfossil oak trunks as *ecological archives* of forest dynamics along the river Scheldt (Belgium).

## 8.1 Introduction

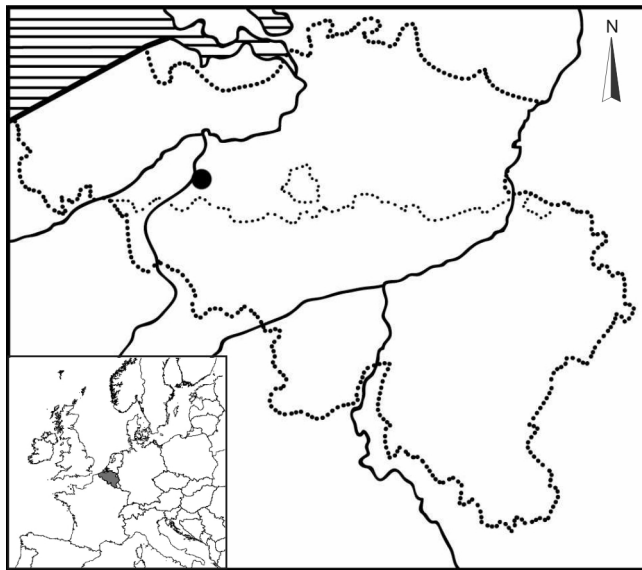
Subfossil trees are considered as archives of past forest and woodland dynamics (Heyworth 1978; Leuschner and Sass-Klaassen 2003; Leuschner *et al.* 2002a; Leuschner *et al.* 2000; Sass-Klaassen and Hanraets 2005). In NW Europe, cross-sections of more than 9.000 subfossil oaks have been collected and analyzed, mainly from Germany, England, Ireland and The Netherlands. The majority of the subfossil oaks were preserved in bogs, river gravels or marine sediments. Ring-width series of those subfossil oaks (*Quercus* spp.) have been used to compile millennia-long chronologies (Friedrich *et al.* 2004; Jansma 1995; Leuschner 1992; Pilcher *et al.* 1984; Spurk *et al.* 1998). Currently, the absolutely dated ring-width chronologies of subfossil oaks run back to 8480 BC (Friedrich *et al.* 2004), and are used for tree-ring dating (dendrochronology). The wood of the dated oak specimens is also the basic material for the development of the radiocarbon calibration curve and is studied with special regard to past climatological and ecological conditions.

Two major groups can be distinguished when regarding subfossil oaks from wetland sites: bog oaks and riverine oaks (Leuschner 1992). The first group comprises trees that grew in or at the margins of peat bogs. Subfossil riverine oaks on the other hand are considered as remnants of riparian forests, standing on mineral soils. Local hydrology must have affected tree growth and stand dynamics on both types of sites. Rapid desiccation of the peat or excess of floodwater from nearby rivers must both have induced, at least occasionally, marginal ecological growing conditions for the trees.

The growth ring profile of subfossil oaks is often characterized by prolonged growth depressions that are synchronous within one site (Leuschner 1992). Such remarkable reductions in ring-width can last up to 30 years and start or end abruptly. It has been observed that there had been synchronous phases of germination and dying-off, demonstrating a synchronicity between distant sites across NW Europe (Leuschner *et al.* 2002b; Leuschner *et al.* 2000). These phenomena have been linked to variations in the local hydrology or changes in past climate. Therefore, it has been hypothesized repeatedly that ring-width chronologies of subfossil oaks can be used

as proxies to reconstruct former tree population dynamics and climate (Spurk *et al.* 2002).

During an archaeological inspection in spring 2002, subfossil oak trees (*Quercus* spp.) were discovered in a clay extraction pit at Ename (province of East-Flanders, Belgium). Ename is situated along the upper river Scheldt (Figure 1). The subfossil oaks provide evidence of a forest on the former banks of the river Scheldt, some thousands of years ago. The trees were particularly well preserved in the peaty clay



**Figure 8.1:** Location of Ename along the river Scheldt.

deposits. Loamy and clayey sediments covered the trees that were submerged in the peat, creating ideal waterlogged and anoxic preservation conditions.

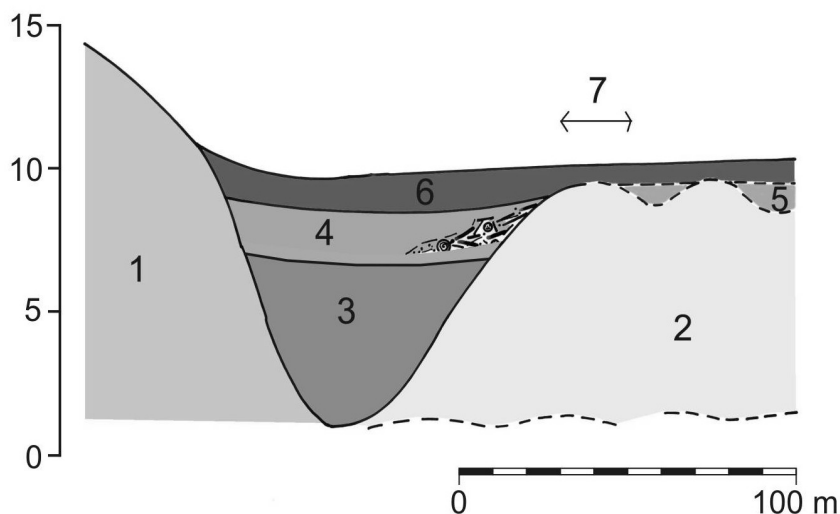
The wood of the subfossil oaks provides the unique opportunity to study the growth patterns and site conditions experienced by trees along the river Scheldt at the beginning of the Holocene.

Fluctuations in growing conditions and stand development must have been archived in the ring-width pattern and other specific wood anatomical features. Especially the size and distribution of the earlywood vessels of the subfossil oaks are quantified and confronted with similar analyses on wood from contemporary oaks, in order to gain more insight into past ecological conditions along the river Scheldt. It will be evaluated how the study of the growth patterns and wood anatomical particularities of the recovered wood specimens can contribute to palaeoecological studies. Moreover, it will be examined whether it is possible to establish the first dendrochronological reference chronology for the Scheldt region with the ring-width series of the subfossil trees. It is hypothesized that subfossil oak logs from the Scheldt can be crossdated with one of the long European oak chronologies. A successful crossdate could then be held up as evidence that the Scheldt oaks contain a common signal that is likely to be related to climate conditions in northwestern Europe.

## 8.2 Methods

### 8.2.1 Site description

Ename is situated along the upper river Scheldt, which is now channelized but used to be a meandering river. The subfossil oaks were excavated on the former banks of an oxbow lake, formed by a cut-off branch of the river. These riverbanks are described as *point bars* and are associated with a huge meandering river. Once the river branch was cut off, it was filled up, first with gyttja, later with peaty clay (Figure 2). Palynological and geomorphological research (K. Deforce and J. Bastiaens, *unpublished data*) revealed that the sedimentation in the abandoned river channel started during the Late Glacial (ca. 12.000 - 10.000 BP\*), when the landscape was characterized by an open tundra-like vegetation with *Betula*, *Pinus*, *Juniperus* and *Artemisia* spp., and continued until the end of the Atlantic period (ca. 5.000 BP) when the vegetation was dominated by *Tilia*, *Quercus* and *Ulmus* on the drier parts of the landscape and *Alnus*, *Quercus* and *Fraxinus* in the lower and more humid parts.



**Figure 8.2:** Geological transect of the site, with (1) pleistocene sand and loess, (2) point bars, (3) gyttja, (4) peaty clay with subfossil trees, (5) peaty clay, (6) late Holocene alluvial clay and (7) the alluvial plain.

When the abandoned river channel was filled up, clay and loamy clay was deposited in the whole river valley, probably as a consequence of Neolithic land reclamation and deforestation (Ameels *et al.* 2003).

A sample from the peaty clay, in which the oaks were preserved, yielded seeds from plants typical for (open) water and lakeside/marshland vegetation. This is a reflection of the local situation. The palynological analysis on the other hand provides an image of the regional vegetation as well, i.e. woodlands dominated by *Quercus*, *Corylus*, *Tilia* and *Alnus* (Table 1).

\* BP refers to uncalibrated radiocarbon ( $^{14}\text{C}$ ) years, which are not equal to calendar years due to the inherent variations in the atmospheric  $^{14}\text{C}$  production.



**Table 8.1:** Pollen spectrum of the peaty clay layer in which the subfossil oaks were preserved. (K. Deforce, unpublished data). The pollen percentages based on the sum of trees, shrubs and dryland herbs only.

| <b>Trees and shrubs</b>              | <b>%</b>   |
|--------------------------------------|------------|
| <i>Alnus</i>                         | 28.3       |
| <i>Betula</i>                        | 1.6        |
| <i>Corylus avellana</i>              | 15.2       |
| <i>Fraxinus excelsior</i>            | 1.1        |
| <i>Pinus</i>                         | 5.6        |
| <i>Quercus</i>                       | 18.2       |
| <i>Salix</i>                         | 2.1        |
| <i>Sambucus</i>                      | 0.3        |
| <i>Tilia</i>                         | 8.8        |
| <i>Ulmus</i>                         | 1.6        |
| <b>Herbs</b>                         |            |
| Apiaceae                             | 2.4        |
| Aster type                           | 0.3        |
| Brassicaceae                         | 0.8        |
| Caryophyllaceae                      | 0.5        |
| Chenopodiaceae                       | 0.3        |
| Compositae liguliflorae              | 0.8        |
| Cyperaceae                           | 4.5        |
| Galium type                          | 0.8        |
| <i>Plantago major</i>                | 0.3        |
| Poaceae                              | 4.8        |
| <i>Polygonum aviculare</i> type      | 0.3        |
| <i>Polygonum persicaria</i> type     | 0.8        |
| <i>Ranunculus</i> type               | 0.3        |
| <i>Trifolium</i> type                | 0.3        |
| <b>∑P</b>                            | <b>374</b> |
| <b>Aquatics</b>                      |            |
| <i>Alisma plantago-aquatica</i> type | 4          |
| <i>Sparganium emersum</i> type       | 1.3        |
| <i>Sparganium erectum</i> type       | 11.2       |
| <b>Ferns and mosses</b>              |            |
| Polypodiaceae                        | 0.3        |
| <i>Polypodium vulgare</i>            | 2.1        |
| <i>Sphagnum</i>                      | 0.3        |
| <b>Total pollen and spores</b>       | <b>446</b> |

### 8.2.2 Wood anatomy and dendrochronology

Preceding to the dendrochronological and wood anatomical survey, the position of all wood macrofossils was recorded following the methodology of Lageard *et al.* (1995). Cross-sections of 5 to 7 cm thick were collected from each single subfossil tree specimen. Such samples allow to identify the species and can be used for tree-ring and radiocarbon analyses. All collected cross-sections were sealed in plastic bags in

order to avoid desiccation. This would result in serious deformation of the cross-sections and create favourable conditions for fungal growth and biological deterioration (Eckstein *et al.* 1984).

Besides wood identification, a detailed analysis of the wood anatomy can provide more information on the ecology of early Holocene forests along the river Scheldt. Since all wood specimens were preserved under anaerobic and wet conditions, the microscopic structure of the wood proved to be intact. All wood anatomical structures and cell-types became clearly visible after planing the cross-sections with a sharp razor blade. Calibrated, high resolution images (1280 x 1024 pixels) were then obtained with a digital camera (ColorView 8) mounted on a stereomicroscope (Olympus SZX12) with reflected light. Vessel characteristics, as tangential diameter and vessel frequency, were measured using the software package AnalySIS<sup>®</sup> 3.2.

Ring-width series were recorded to the nearest 0.01 mm using a measuring stage (Lintab) connected to a PC with acquisition and processing software (TSAP-Win 0.53, Rinn 2003). The ring-width series entered a standard crossdating procedure (Fritts 1976; Eckstein *et al.* 1984; Schweingruber 1983), i.e. series that display a high correlation in the year-to-year variability of their growth patterns are averaged into a chronology. This was evaluated by calculating correlation measures as *t*-values (Baillie and Pilcher 1973) and coefficients of parallel variation (*Gleichläufigkeit*, *GLK*) (Eckstein and Bauch 1969), followed by a final visual verification. The obtained chronologies were then compared to long, absolutely dated European reference chronologies.

### **8.2.3 Radiocarbon and wiggle matching**

In order to determine the time frame in which the subfossil trees had been growing, radiocarbon measurements were performed. Samples for radiocarbon analyses, consisting of minimum 2 g of wood each, were taken from single growth rings using a hypodermic needle (type 18G; 1.2 mm diameter). When the growth rings proved to be too narrow to obtain the required amount, wood from two or more successive growth rings was collected.

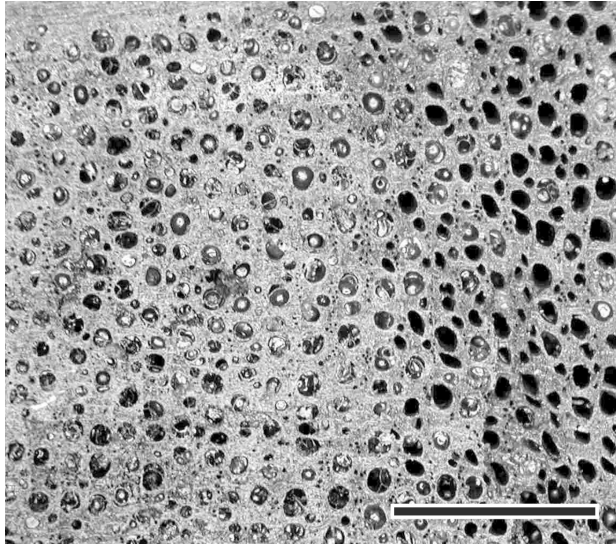
Due to variations in the atmospheric  $^{14}\text{C}$ -production, radiocarbon ages need to be calibrated and transformed into true calendar years. This is executed with the OxCal 3.10 software package (Bronk Ramsey 1995; Bronk Ramsey 2001) using the IntCal98 calibration curve (Stuiver *et al.* 1998). In order to enhance the precision of the dating procedure, radiocarbon measurements were combined with the tree-ring analysis. This technique, referred to as *wiggle matching*, is able to increase the precision of the dating results obtained from the individual radiocarbon measurements (Buck *et al.* 1996). Again, this procedure can be performed using the OxCal 3.10 software which implements models, based on Bayesian statistics, that allow to incorporate *prior* information (Bronk Ramsey *et al.* 2001).

This *prior* information refers to the exactly known chronological separation between different radiocarbon samples; i.e. the number of annual growth rings between two sampling points (Christen and Litton 1995; Goslar and Madry 1998). This can be easily determined when several samples are taken from one particular cross-section. On the other hand, when samples for radiocarbon analysis are taken from cross-sections of different trees it is only possible to quantify the exact time interval between sampling points when the ring-width patterns of all trees involved crossdate. Hence, the interval between different sampling points can be easily quantified since the chronological arrangement of all series is accurately known.

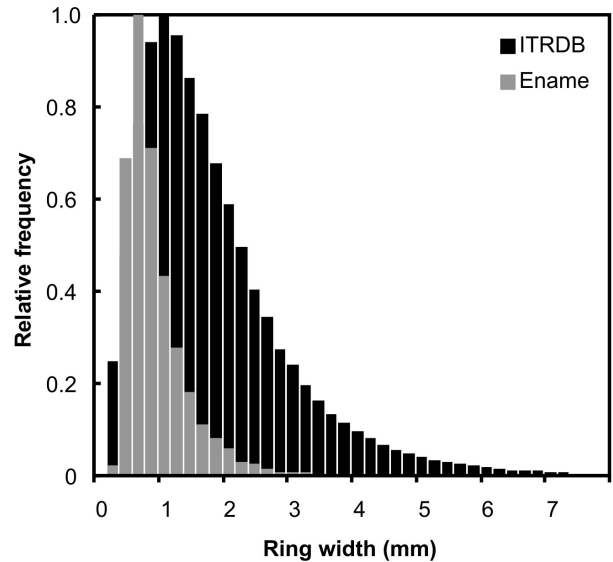
### 8.3 Results

In total 67 cross-sections were collected. Wood anatomical observations showed that nearly all preserved trees were oak (*Quercus* spp.). A few badly preserved wood specimens of *Alnus* were found as well. The majority of the collected cross-sections are characterised by bands with extremely narrow growth rings (Figure 3). The average ring width for all samples, disregarding their cambial age, is 785  $\mu\text{m}$ . Compared to ring-width series of European oaks, submitted to the International Tree-Ring Data Bank (<http://www.ncdc.noaa.gov/paleo/treering.html>; Grissino-Mayer and Fritts 1997), this is a low value (Figure 4). In order to be able to discriminate between the two most common *Quercus* species in Europe, i.e. *Q. robur* L. and *Q. petraea* (Matt.) Liebl., it is necessary to study at least four growth rings per specimen that are approximately 2 mm wide and more than 60 growth rings away from the pith (Feuillat

*et al.* 1997). Due to the narrow growth ring patterns, this is only possible for four samples of all collected cross-sections (ENCA-A2, -B13, -C10 and -E3). However, the measurements were inconclusive to discriminate between the two species.

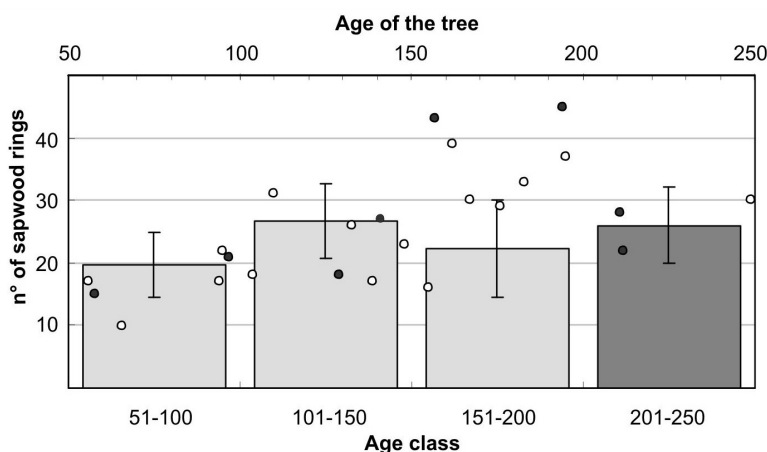


**Figure 8.3:** Extremely narrow growth rings with small earlywood vessels, resulting in a diffuse porous appearance (ENCA-C1). Scale bar represents 2 mm.



**Figure 8.4:** Distribution of ring-width measurements on the subfossil oaks from Ename ( $n = 6.992$ ) compared to ring-width series of European oak, submitted to the International Tree-Ring Data Bank (ITRDB) ( $n' = 224.628$ ).

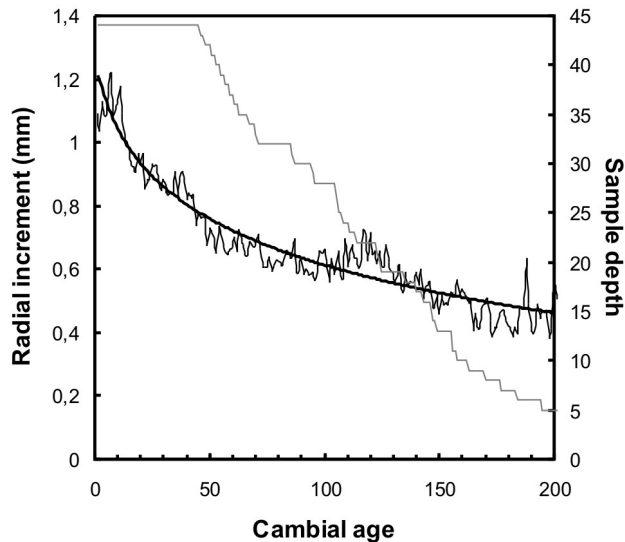
In a few cases at least part of the sapwood was preserved as well. Only eight of the collected cross-sections still had bark attached. Often it proved to be very difficult to distinguish the growth ring boundaries in the sapwood. First of all, the growth rates



**Figure 8.5:** The number of sapwood rings versus the age of the tree. Dots (•) and circles (◦) represent cross-sections of the subfossil oaks with complete (bark) and incomplete sapwood respectively. Bars represent sapwood estimates for oaks from Flanders (grey bars, Haneca *et al.* 2006) and Germany for the oldest age class (dark grey, Hollstein 1980).

are very low in the sapwood; i.e. on average 440  $\mu\text{m}$  wide (st.dev. 174  $\mu\text{m}$ ). Secondly, the sapwood is mostly not as well preserved compared to the more durable heartwood. The number of sapwood rings displays a certain dependency on the age of the tree (Figure 5). Older trees of 180 - 250 years can have up to 45 sapwood

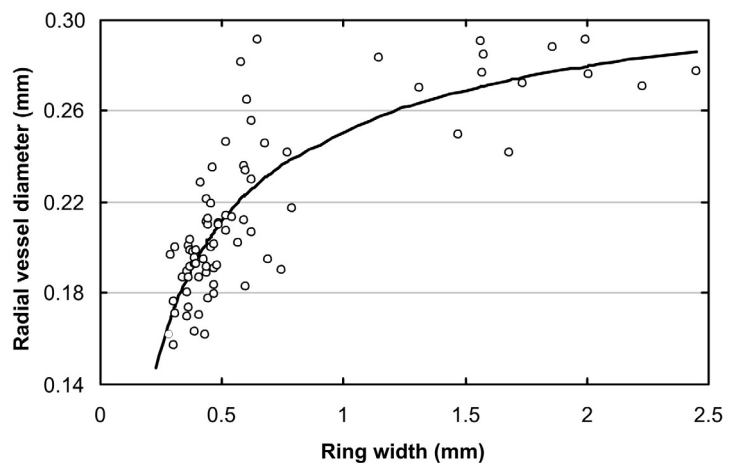
rings, whilst younger trees of 50 - 100 years have 15 to 25 sapwood rings. On average, disregarding the age, 27 sapwood rings are observed on the subfossil oak specimens from Ename. This number corresponds to the average number of sapwood rings from contemporary oaks. Nevertheless, it is observed that trees of 150 up to 200 years tend to have a considerably higher number of sapwood rings compared to the contemporary oaks from high forest sites (Figure 5).



**Figure 8.6:** Growth trend of all collected wood specimens where the pith was preserved.

When the ring widths drop below 300  $\mu\text{m}$  the oak wood tends to display a diffuse porous appearance, due to the fact that the latewood section of the growth rings becomes extremely small or even absent at all. As a consequence, growth-ring boundaries become very hard to discern since succeeding earlywood vessel rows are not longer clearly separated by the latewood (e.g. Figure 3).

The radial diameter of the earlywood vessels seem to be related to the ring width. Narrow growth rings are mostly characterized by smaller earlywood vessels (Figure 7). This is reflected in small radial diameters of 115 to 220  $\mu\text{m}$  for the earlywood vessels. Growth

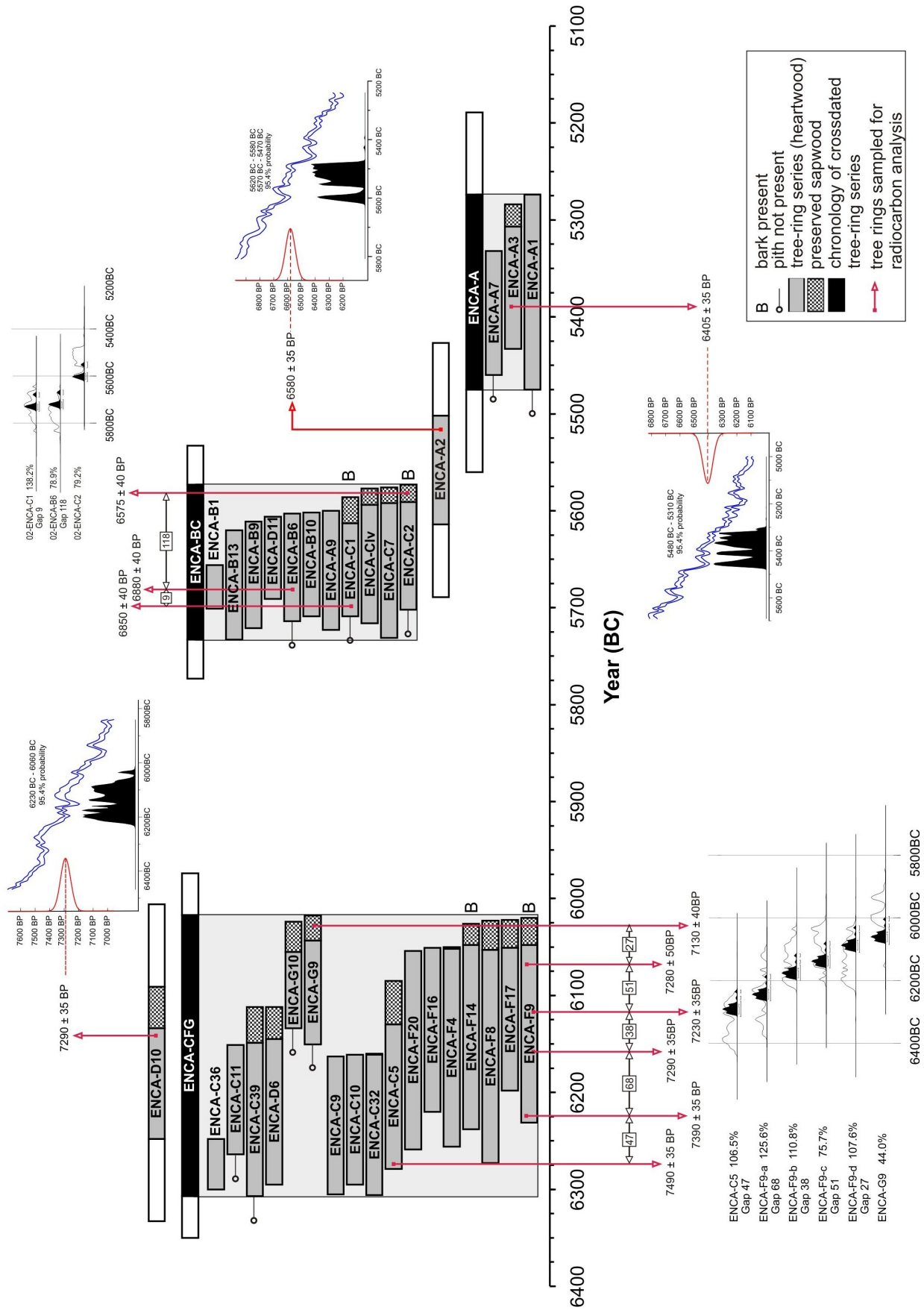


**Figure 8.7:** Vessel diameters versus ring width of the subfossil oak trees. On average 20 vessels per growth ring were measured ( $N = 77$ ; trend line  $y = a + b \cdot x^{-0.5}$ ).

rings of more than 1 mm wide usually contain larger earlywood vessels with a radial diameter of more than 250  $\mu\text{m}$ . The latter is in accordance to the average diameter range (150  $\mu\text{m}$  up to 350  $\mu\text{m}$ ) of the earlywood vessels from contemporary *Quercus robur* and *Q. petraea* specimens (Wagenführ and Scheiber 1989).

The recorded ring-width sequences were crossdated and joined into chronologies when the correlation, both visual and statistical, was sufficiently high. Three groups of synchronized ring-width series can be distinguished (Figure 8). The mean chronologies from those groups, ENCA-A, ENCA-BC and ENCA-CFG, are 201, 160 and 290 years long respectively. The unsynchronised series were then compared to the floating chronologies and four more series were added to the group that founds the ENCA-CFG chronology and one more to the ENCA-BC group. In total 31 of the recorded ring-width series now belong to one of three floating chronologies, whereas the 36 remaining series could not be crossdated. None of the floating chronologies displays any significant correlation among each other. Bar graphs of the crossdated series, in their correct chronological arrangement, are presented in Figure 8.

Comparison of the Ename (ENCA-) chronologies with absolutely dated reference chronologies of subfossil European oaks from bogs and river gravels did not result in an absolute dating of the sequences. Such reference chronologies, like the Hohenheim-chronology (Friedrich *et al.* 2004), can be up to 10.429 years long. This means that they go back as far as the arrival of the first oak populations in Central Europe after the last glacial period. Several possible positions along reference chronologies from Germany and Ireland were found, all with low statistical significance (M. Friedrich & M.G.L. Baillie, *pers. comm.*). In order to demarcate a narrow range of calendar years for the subfossil trees, radiocarbon measurements ( $^{14}\text{C}$ ) were performed. Based on the tree-ring analysis, nine cross-sections were selected of which wood was collected from 1 to 3 successive growth rings. In total, 12 wood samples were prepared for radiocarbon analysis (Figure 8). Since most of the selected cross-sections for radiocarbon analysis synchronise with other series, the result of one radiocarbon analysis can be extrapolated to the other crossdating series.



**Figure 8.8:** Bar graphs representing the crossdated ring-width series, with respect to the radiocarbon dating and wiggle matching results.

The radiocarbon ages range from  $7.490 \pm 35$  BP to  $6.405 \pm 35$  BP. Calibration of those radiocarbon ages yielded true calendar ages from 6430 BC to 5310 BC. This demonstrates that the oak trees were growing at the beginning of the Atlantic period, 7.000 to more than 8.000 years ago. Each of the calibrated radiocarbon dates has a 95.4% confidence interval along the time axis of 150 up to 290 calendar years wide.

Wood of four different growth-rings was collected from cross-section ENCA-F9 in order to obtain more accurate dating results from the radiocarbon analyses. This specimen was selected for this intensive sampling strategy since its ring-width pattern crossdates with 16 other series of the ENCA-CFG chronology, for its considerable length (211 years) and the presence of preserved bark. As a consequence it is possible to determine the year in which the tree died when this series can be dated. From the same group of synchronised series, wood of two other cross-sections was collected for radiocarbon analysis. Furthermore, two cross-sections of the ENCA-BC group were sampled. Additionally, wood was collected from three cross-sections (ENCA-D10, -A2 and -A3) that could not be crossdated to any of the other ring-width series (Figure 8).

In the 95.4% confidence interval, the range of calendar years is reduced to 85 years when 6 successive radiocarbon measurements, from the ENCA-CFG group, are incorporated into one Bayesian model. The same precision was obtained for the ENCA-BC group where only three radiocarbon measurements were combined. This is due to the slope of the calibration curve which is remarkably steeper between 5500 BC and 5700 BC compared to the part between 6000 BC and 6300 BC that displays a more *wiggly* nature. The most recent tree-ring measured on the Ename-specimens was formed between 5359 BC and 5189 BC, and was observed on sample ENCA-A1 from the ENCA-A group. The oldest ring on the other hand is part of cross-section ENCA-C39 from the ENCA-CFG group, and was created between 6350 BC and 6265 BC. In between, the cross-sections from the ENCA-BC group grew between 5773 BC - 5693 BC and 5613 BC - 5533 BC, when regarding the 95.4% confidence intervals. According to these dating results, an overlap is expected between the tree-ring series from the ENCA-CFG group and sample ENCA-D10 (Figure 8). Nevertheless, crossdating values were unable to point out a position where both series display a high and significant correlation. Likewise, the tree-ring series of



sample ENCA-A2 could display an overlap with the series of the ENCA-BC group or the ENCA-A group. But for none of the possible positions a significant correlation was found between both ring-width series. These dating results of the combined radiocarbon/tree-ring analysis are at some points confirmed by the stratigraphy of the excavated subfossil oaks. Older wood specimens are mostly superimposed by the younger ones.

#### 8.4 Discussion and conclusions

The excavated subfossil trees along the river Scheldt are almost exclusively oak (*Q. robur* or *Q. petraea*). Analysis of pollen revealed that other species must have been present as well, mainly hazel (*Corylus avellana* L.) and lime (*Tilia* spp.). Alder (*Alnus* spp.) is dominant in the pollen spectrum, but is known to be an abundant pollen producer. Its distribution is usually restricted to wet habitats in the alluvial plain. The observed pollen spectrum is typical for the Atlantic period (ca. 6000 BC – 3000 BC). However, only large amounts of oak wood have been discovered. This suggests that the taphonomic conditions favoured the preservation of the oak stems. Although only the heartwood of oak is highly durable, sapwood was preserved as well. Nevertheless, stems of other woody specimens were not preserved.

The subfossil trees must originate from a forest or woodland with a mixed age structure. A maximum age of 250 years was found for sample ENCA-F8. Most trees were only 50 - 100 years old. Contemporary oak trees can easily reach the observed maximum age of the subfossil trees. In undisturbed oak stands, trees are expected to reach ages of 400 to 500 years. On other locations where subfossil trees were found, it was also observed that the maximum age was considerably lower compared to old contemporary oak trees. It is suggested that this is the result of the suboptimal conditions in which the trees were growing (Leuschner *et al.* 2002b), what is expressed in the low growth rates. Despite the limiting growth conditions it is observed that in the first 10 to 20 years after germination the young trees were able to grow well, with ring-widths of ca. 1 mm (Figure 6).

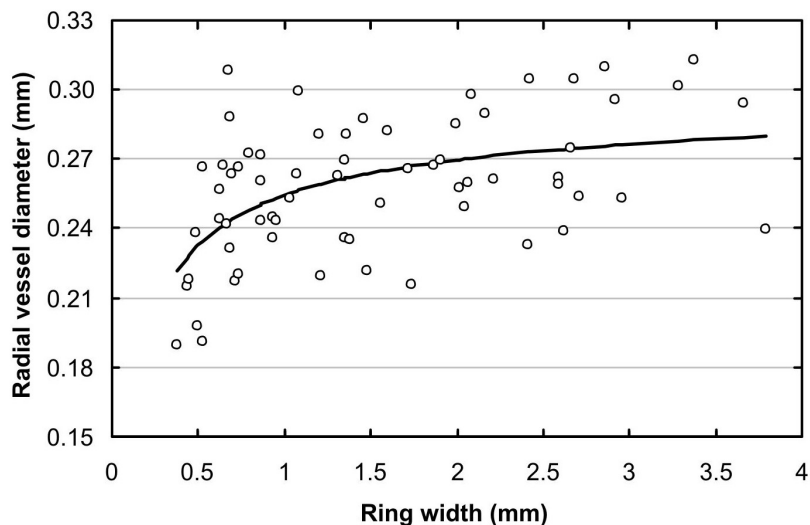
From all the pieces of wood that have been examined, none could be identified as part of a root system. The wood of *Quercus*-roots is usually characterized by wide

vessels (up to 400  $\mu\text{m}$ ), sometimes arranged in loose oblique lines, with indistinct growth-ring boundaries (Cutler *et al.* 1987). Although the growth rings sometimes display a diffuse-porous and indistinct appearance (Figure 3), they are not considered to originate from roots since the earlywood vessels have narrow diameters. Therefore it is suggested that when the trees fell, the trunks were rapidly submerged and covered into the peaty clay. The root systems on the other hand must have remained uncovered and deteriorated by fungi and insects.

It is now well documented that during the Late Glacial period, the genus *Quercus* was restricted to areas, termed refugia, with advantageous micro-climates (Petit *et al.* 2002). Three principal refugial areas can be distinguished: the south of the Iberian and Italian peninsula, and the southern Balkans. When climatic conditions improved during the late glacial interstadial, oak tree populations spread north, up to the Pyrenees on the Iberian Peninsula and reached the southern border of the Alps in present-day Italy (Petit *et al.* 2002). Little changed in the distribution of European oak trees between 11000 BC and 9600 BC (the Younger Dryas). At the beginning of the Holocene, ca. 10.000 years ago, temperatures rose and were accompanied by an increased moisture availability. Along the Atlantic coast, oak trees rapidly dispersed, reaching southern Ireland and England by ca. 9000 BC - 8200 BC, at that time still connected to the European mainland. In Central Europe, the dispersal of oak was delayed by the physical barrier of the Alps. When these mountains were finally passed, oak rapidly reached its current range in Europe around 5000 - 4500 years BC (Brewer *et al.* 2002). Autochthonous oak populations in Belgium are known to be mainly of the Iberian chloroplast haplotypes. Only in northeastern part (province of Limburg), chloroplast haplotypes of the Italian Peninsula are encountered (Anonymous 2001). As a consequence, the subfossil oak trees from Ename are probably genetically related to the late-glacial oaks from the Iberian refugia that spread rapidly into Western Europe at the beginning of the Holocene.

In order to retrieve more information regarding the growing conditions experienced by the subfossil oaks ca. 8.000 years ago, detailed wood anatomical observations were made. It is clear from the ring-width series that the radial growth rate of the trees is very low. Measurements of the diameter of the earlywood vessels reveal a relationship between the total ring-width and the average radial vessel diameter

(Figure 8). Narrow rings of 0.5 mm and less often occur in sequences and are seen as significant growth reductions in the ring-width pattern. This suggests that recurrent events hampered *normal* growth. Shading by other trees is unlikely to cause the growth depressions since the transition to the narrow rings is abrupt. Moreover, the striking growth depressions in the subfossil oaks are associated with significantly smaller earlywood vessels. This is not observed on Xylarium\* samples, of contemporary trees from the “Zevenster” stand in the Soignes forest near Brussels that have been gradually shaded by beech (Figure 9). Although earlywood vessel



**Figure 8.9:** Average radial vessel diameter plotted against the total ring width of contemporary oak trees that have been gradually shaded by beech trees ( $N = 65$ ; trend line  $y = a + b \cdot x^{-0.5}$ ).

diameters are slightly reduced in narrow rings, this trend is not as pronounced for the contemporary trees ( $r^2_{adj} = 0.682$ ) compared to the subfossil oaks ( $r^2_{adj} = 0.243$ ). To date, in mixed deciduous forests in Western Europe, oak is often dominated and shaded by beech. However, this species

was not even present at that time (Verbruggen *et al.* 1996). Furthermore, vessel diameters of less than 20  $\mu\text{m}$  rarely observed on the contemporary specimens in contrast to the subfossil specimens. The narrow ring widths, in combination with small earlywood vessels of the examined subfossil wood clearly indicate that the oak trees experienced limiting growth conditions.

Several hypotheses can be formulated to explain the observed wood anatomical peculiarities in vessel size. Small earlywood vessels in ring-porous species have been associated with (1) frost events in winter and early spring (Fletcher 1975; Leuschner and Schweingruber 1996; Tapper *et al.* 1978), (2) increased salinity (Eckstein *et al.* 1976), (3) the year following severe defoliation by insects (Asshof *et*

\* The examined cross-sections (Tw53417, -427, -435, -439, -460, -467, -468, -472, -474 and -478) are part of the Xylarium of the Royal Museum for Central Africa (Tervuren, Belgium).

*al.* 1999), (4) prolonged inundation during spring and early summer (Astrade and Begin 1997; St. George and Nielsen 2003; St. George *et al.* 2002) and (5) the years following pollarding (Rozas 2005). It is clear that changes in vessel diameter and frequency are an adaptive response of plants to their environment.

Especially hypothesis (1) and (4) could be acceptable to explain the small earlywood vessel diameters of the subfossil oaks from Ename. Vessel development starts almost simultaneously throughout the cambium of the stem in ring-porous species. According to Aloni (Aloni 2001; Aloni 2004), differentiation of vascular tissues is regulated by plant hormones. Especially the differentiation, expansion and density of vessels are controlled by the concentration of auxin in the cambial zone. High auxin concentrations induce rapid vessel differentiation what considerably reduces time for cell expansion before the deposition of the secondary wall. Low concentrations on the other hand cause slow vessel differentiation, what results in large vessels. This plant hormone is mainly synthesized in the leaf primordia and later in the lobes of expanding, newly formed leaves. Earlywood formation is known to start up to six weeks before the onset of leaf expansion, when low auxin concentrations are encountered throughout the cambial zone (Zimmermann and Brown 1971). Bud burst is accompanied by the production of high auxin concentrations, and hence reduces the size of water conducting vessels. A frost event during late winter or early spring can interfere with the production of plant hormones by damaging the swelling buds or young leaf primordia. The subfossil oak trees from Ename are expected to be the early generation of oaks that rapidly spread from the Iberian Peninsula at the beginning of the Holocene. It could be possible that the rapid spread of oak trees was too fast to ensure sufficient adaptation to the local environment in present-day Flanders. Early swelling of the buds and sprouting of the young leaves increases sensitivity to frosts during early spring. This can be expected from trees that are (genetically) adapted to southern, and hence warmer, provenances (Deans and Harvey 1995). Trees affected by frost events will not develop large earlywood vessels. However, the Atlantic period is considered the climatic optimum of the Holocene with prevailing mild temperatures (Negendank 2002). Hence, recurrent frost events, at the beginning of the growing season could dramatically affect tree growth, and result in an inferior water conducting system.

Another explanation for the occurrence of small earlywood vessels could come from considerable variations in the local hydrology. The water balance of riparian forests is essentially controlled by ground- and floodwater. Precipitation is of secondary importance. Small earlywood vessels have been associated repeatedly with inundations during spring and early summer, that last for several days or weeks (Astrade and Begin 1997; St. George and Nielsen 2003; St. George *et al.* 2002). When roots of flood-intolerant species are inundated, root growth is usually more inhibited compared to stem growth, combined with a reduction in leaf formation and expansion and a rapid decrease in the rate of photosynthesis (Kozłowski 1997). Hence, prolonged soil inundations could explain the occurrence of the narrow growth rings, with nearly absent latewood, associated with the small earlywood vessels.

The subfossil trees standing on the banks of a meandering river, some 8.000 years ago, were most probably subjected to recurrent flooding in spring or early summer. This could be the reason why it is not possible to establish a dendrochronological connection with absolutely dated, long oak chronologies for Central Europe. A common, driving climatological factor seems to be lacking or in any case not strong enough, to modulate Western and Central European tree-ring series in a corresponding way. The climatological signal in the ring-width series of the subfossil trees at Ename is most probably *blurred* by the local site dynamics, and more specific by variations in the hydrological conditions.

This clearly demonstrates that a detailed analysis of the growth pattern and anatomy of the wood from subfossil oaks can provide more information and insight in local site conditions and stand dynamics of riparian forests throughout the Holocene.

### **Acknowledgements**

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## **UTILISATION POTENTIAL and PERSPECTIVES**





## Utilisation potential and perspectives

# 9

### Chapter

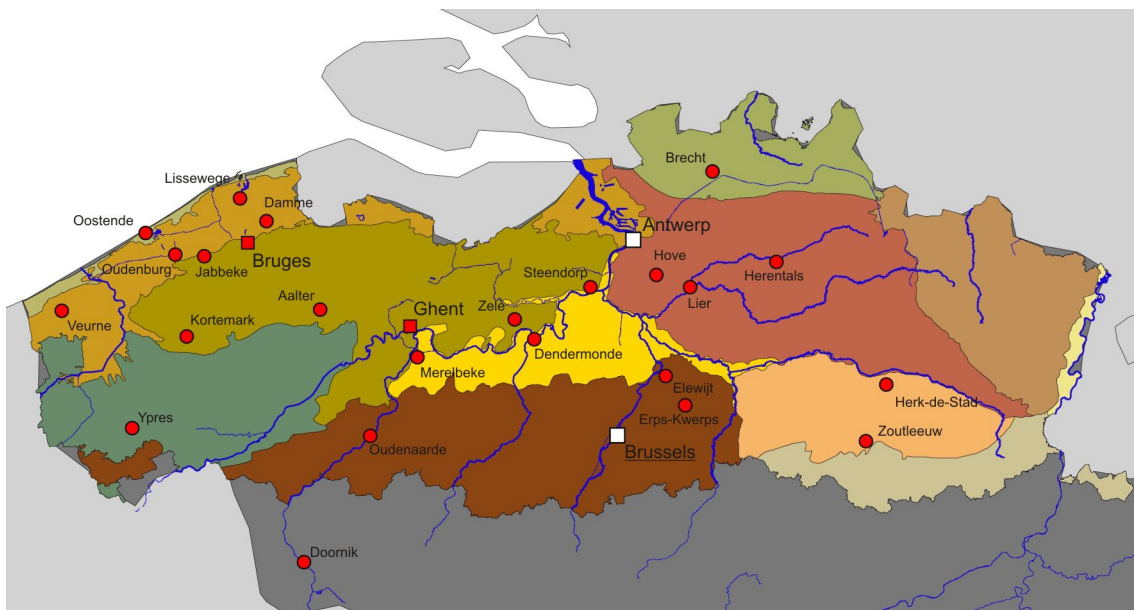
#### 9.1 Introduction

Tree-ring analysis has become a standard chronometric dating tool, highly appreciated by archaeologists, art-historians, restorers, palaeobotanists and many more. Exact dating of wood specimens with a high temporal (annual) resolution has not been encompassed by any other dating technique. However, despite the large number of successful applications of tree-ring dating, a rigid and strict standard methodology that is valid under all circumstances is not available. Indeed, dendrochronology as a dating tool displays some plasticity in its methodology. The ideal situation, where large amounts of well preserved wood with long and climate sensitive tree-ring series are found has proved, in actual practise, to be seldom encountered. Especially in regions with a high human impact on the original vegetation cover, dendrochronology as a dating tool becomes a tentative task. In Europe, for instance, where many regions have been densely populated ever since the Roman Era and the Middle Ages, archaeological timber with short ring-width

series are often the most common type of wooden remains. It is clear that such basic material can hamper the successful implementation of dendrochronology for dating purposes and source of information on past vegetation and environmental dynamics. Therefore it is of the uttermost importance to continuously enhance and adapt the methodology involved.

## 9.2 Towards a Flemish reference chronology?

To date, no well replicated Flemish reference chronology exists. Here the question arises “*Do we need one?*”. Former attempts to date tree-ring series from archaeological wood in Flanders that were successful (Figure 9.1), although low in number, have relied on reference chronologies from southern Belgium, Germany or the Netherlands (e.g. Jansma *et al.* 2004). Nevertheless, correlation measures (*t*-values, *GLK*, etc.) often remain low and are inconclusive. Comparison with multiple reference chronologies that represent different regions can enhance the reliability of the dating results. Therefore an extensive database of absolutely dated reference chronologies from surrounding regions should be available to the dendrochronologist working with local material from Flanders. Especially references that cover the original timber source of the examined wood are expected to maximise the chances on finding a correct visual and statistical match. For Flanders only few site



**Figure 9.1:** Locations in Flanders where local wood from archaeological sites and/or historical buildings was subjected to a dendrochronological analysis. Data compiled from unpublished data (Haneca), Hoffsummer (2002) and the database of the RING foundation (the Netherlands). The colours on the map represent the eco-districts in Flanders (Sevenant *et al.* 2002).

chronologies, mostly composed out of a small number of individual series, are currently available, each covering relatively short periods (Figure 9.2). Moreover, it remains unclear if site chronologies of oak from Flanders tend to crossdate. Site chronologies from Roman water wells in Merelbeke (province of East Flanders) and Elewijt (province of Flemish Brabant), ca. 65 km apart, display a good visual and statistical correlation. Correlations with a site chronology from a water-well in Donk (province of Limburg) on the other hand are low and inconclusive (see Table 9.1).

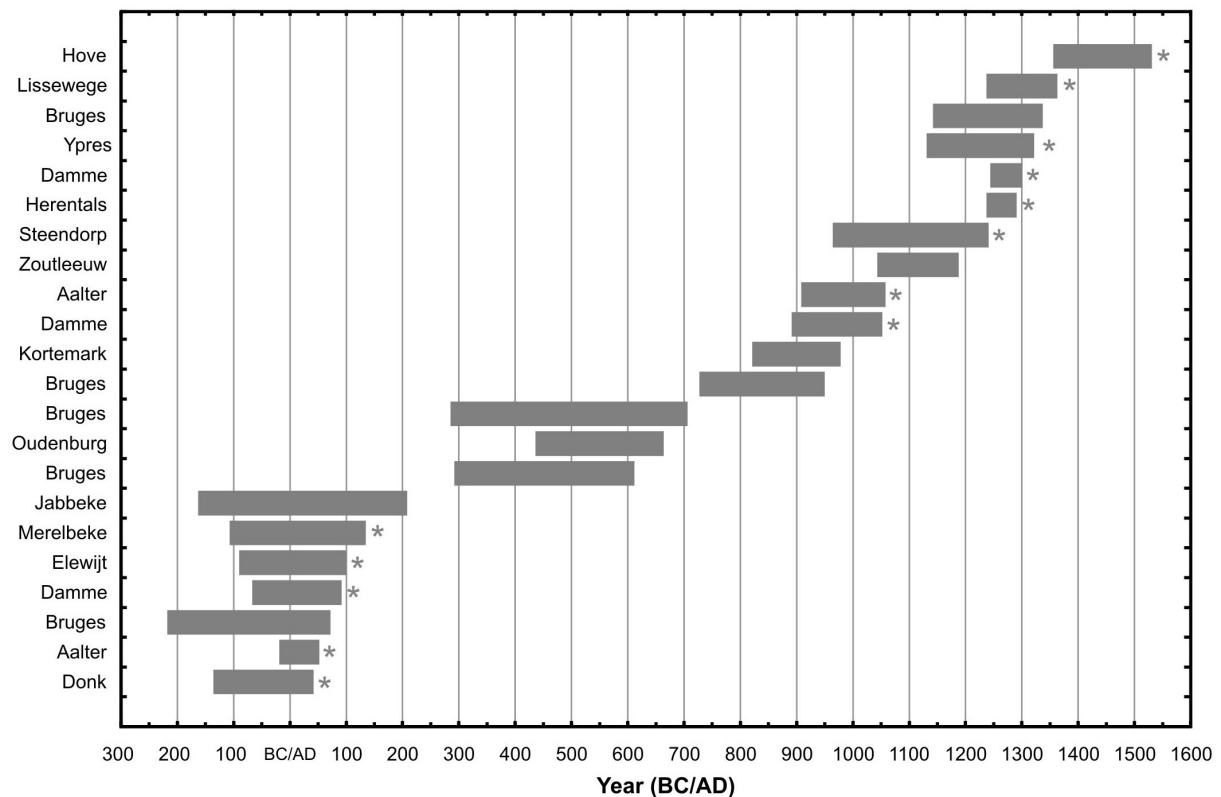
**Table 9.1:** Correlation values, *Gleichläufigkeit* and *t*-values according to Baillie and Pilcher (1973), between overlapping tree-ring chronologies of three archaeological sites from Flanders

| $t_{BP} \backslash GLK$     | Merelbeke | Elewijt  | Donk |
|-----------------------------|-----------|----------|------|
| Merelbeke (107 BC – 135 AD) | -         | 64.6 *** | 55.1 |
| Elewijt (90 BC – 100 AD)    | 5.6       | -        | 54.2 |
| Donk (136 BC – 42 AD)       | 1.9       | 0.1      | -    |

Due to the high human impact on forests in Flanders, to date and in the past, the clear differences in soil texture, water availability etc., ring-width series do not contain a strong regional climatic signal but mostly reflect the experienced local growing conditions. Therefore it might be more appropriate to develop separate chronologies according to the phyto-geographical and phyto-sociological division of Flanders into ecodistricts (see Figure 9.1). In the coming years, the development of an exhaustive database of site chronologies from Flanders should be strived for. This could certainly enhance the potential of dendrochronology as a dating tool in Flanders. Moreover, such a database could be used to assess the legitimacy of a single reference chronology for Flanders.

In Flanders often only short ring-width series are available for crossdating. However, it should be clear that long and short ring-width series can be joined into one single site chronology. This has been demonstrated in Chapter 5 where ring-width series of medieval oak were analysed. A site chronology, computed from short series only proved to display a very high resemblance with the site chronology build exclusively with longer series (see Section 5.4). Therefore no distinction should be made between short ring-width series and longer ones when chronology building is the goal. Despite this potential of the short series for chronology building, it remains a tentative task to date such series against a reference chronology. Comparison with

several reference chronologies in order to observe whether the same positions along the time axis are returned with high visual and statistical agreement is a must to provide a reliable dating report.



**Figure 9.2:** Bar graph representing the time periods covered by a selection of site chronologies from Flanders, compiled from the database of the RING Foundation (the Netherlands) and unpublished date of the author (the latter are indicated with \*).

### 9.3 The historical timber trade

Chapter 4 is focussed on assessing how accurate the original timber source of imported *Baltic timber* can be determined. The necessity to analyse extensive databases with regional and site chronologies was clearly demonstrated. Such chronologies are expected to reflect regional or local growing conditions. Therefore, in order to maximise the potential of dendro-provenancing, it is of the uttermost importance to have access to a widespread network of site chronologies. Although reference chronologies are indispensable for dating purposes, it would be of interest to re-assemble the existing chronologies again into site chronologies, representing more restricted areas. Characteristic information with a high spatial resolution, enclosed in the tree-ring series would be preserved, instead of blending all site chronologies into one reference chronology of, for instance, the *Baltic region*.

Nevertheless, it should be clear that simply the highest correlation values not necessarily indicate the location of the original timber source (Bonde 2004). The original timber source might be located in a region that is not covered by any of the local or site chronologies. Hypothetically, higher correlation values might be found when the proper regional or site chronology becomes available. Therefore, dendrochronological research should be stimulated in regions that are known to have taken part in the historical timber trade. For instance, the Baltic States currently have only a limited number of site chronologies for oak (Pukiené 2002), but are known to have exported vast amounts of (oak) timber towards Western Europe.

#### 9.4 Sampling strategy

It is clear that when investments (costs, labour, etc.) involved with dendrochronological analysis need to be minimised, only timbers with large cross-sections and narrow growth rings should be sampled in order to obtain long ring-width series. Such long ring-width series have the highest chance to be successfully dated (see Figures 5.2a and 5.2b). Nevertheless, it has been demonstrated that when a maximum number of wooden remains from the same context enter the dendrochronological analysis, a maximal return in information can be obtained. When such a maximal sampling strategy is pursued the total amount of information obtained will go beyond the analysis of the individual specimens. This observation is relevant disregarding the context of the analysis. For instance, in the art-historical part of this dissertation it was demonstrated that by studying the complete set of available growth-ring patterns from a maximum number of sculptures of one collection or altarpiece, this not only provides an estimate of the construction date, but yields additional information on the creative process and medieval timber use (Section 3.4).

When constructing site chronologies or absolutely dated reference chronologies for a wide region, it is hard to estimate when a chronology is sufficiently replicated and contains a robust signal. The *Expressed Population Signal* (EPS) is a valuable parameter to assess the robustness of a chronology. Running EPS values (see also Section 5.4 and Figure 5.3), where consecutive sections of the chronology are considered, can highlight parts of a chronology where the EPS values are

conspicuously low. Such parts are often computed from a limited number of individual tree-ring series that do not display a high mutual correlation. To enhance the common signal more individual tree-ring series that cover the appropriate time window should be added in order to increase the quality of the chronology. Moreover, EPS values directly yield some guidelines for archaeologists and dendrochronologists when sampling wooden remains for tree-ring analysis. This was illustrated in Section 5.4 where the required EPS value was arbitrarily set to 0.85, according to the Wigley *et al.* (1984) publication. It is then possible to determine the minimal number of series that are necessary to compute a sufficiently replicated chronology. In future publications chronologies should be presented together with their associated running EPS values. This would demonstrate the quality of the chronology and indicate where the chronology needs further improvements. Once a chronology is available for a particular site that has high EPS values, sampling strategies can be altered. Instead of sampling all well preserved wood specimens for dating purposes and chronology building, fewer samples with large cross-sections and many growth rings can be taken for tree-ring dating.

Another point of interest is the sampling strategy to be applied for radiocarbon analysis on wooden remains. When the growth-ring boundaries can be clearly distinguished, they can help to enhance the precision of radiocarbon dating (see Section 7.5). Therefore it is recommended not to pool wood from several growth rings into one sample for radiocarbon dating. It is better to make sure that each sample for radiocarbon analysis represents wood from one single growth ring, or when the tree-rings are extremely narrow (see Section 8.3) few neighbouring rings. Consequently it becomes possible to document the chronological separation between different sampling points. This is possible within one cross-section, but also between crossdating specimens. Moreover, this technique (i.e. wiggle-matching) can be of importance when site chronologies are compared to one another. Since site chronologies often only cover a limited time frame it is possible that when crossdating chronologies from the same region, e.g. Flanders, they only have a limited overlap. Then, correlation measures will become unreliable and inconclusive to verify correct dating. When several radiocarbon determinations have been executed on crossdating samples from both sites, wiggle-matching all available radiocarbon dates can help to identify anomalous dating of the chronologies and/or single tree-ring

series. Therefore, when radiocarbon analyses are executed on archaeological wood specimens, it should also be archived from which tree ring wood was collected for the analysis. When the examined series can be crossdated with other series of the same site or cross-matched with a reference chronology, the related radiocarbon measurements can be joined into one Bayesian model for wiggle-matching (see Section 7.5.2), and help to support the dendrochronological dating results.

## 9.5 Preferences and techniques of medieval woodworkers

Scrutinizing ring-width patterns of archaeological and art historical wood specimens or wood from historical buildings yields more insights into the preferences of woodworkers towards the raw, basic material they used. For instance, it was illustrated that the medieval guild prescriptions (see Section 3.4) still have a strong influence on today's dendrochronological research. By imposing the use of valuable oak wood, medieval wood carvers were almost forced to use the imported high-quality oak. Especially the assortment described as *wainscot* was highly appreciated. Due to the sawing pattern applied to the logs in order to obtain wainscot boards, often many growth rings can be observed on the lower end of the statues. The requested removal of the sapwood, on the other hand, necessitates accurate estimates on the average number of sapwood rings that are expected for oak trees of all ages. It also implies that it often becomes a tentative task to provide a good estimate of the felling date of the tree.

It is also observed that the timber used for construction purposes displays a completely different nature in its ring-width pattern compared to the oak wood preferred by the medieval wood carvers. Fast-grown oak timbers, similar to the wood collected from the roof of a medieval storage house at Lissewege (see Section 6.2.2), have better strength properties compared to slow-grown variants. Moreover, when ring-porous species develop wide rings the wood tends to become denser (Zhang 1995). Furthermore, high-density oak timber will shrink more when dried from green wood to oven dry (rad. 4.6%; tang. 9.6%) compared to the low-density oak timber (rad. 3.4%, tang. 7.7%) (Rijsdijk and Laming 1994), and has a higher risk in developing cracks and splits. This makes wood from fast-grown oaks less suitable for woodcarving and the construction of barrels that both require stable and high quality

timber. Nevertheless, oak trees with wide rings, and hence excellent strength properties, were used during the Middle Ages for construction purposes. This illustrates that medieval craftsmen had already built up extensive technical knowledge and expertise about wood and wood processing (Beeckman 2005). Moreover, they were highly capable in grading timber with respect to the intrinsic properties of the wood, in the light of their final end-use.

## **9.6 Past forest dynamics, structure and management**

(Pre-)historical wood specimens are considered as relics of former forests or woodlands. Hence, scrutinizing the anatomy and growth pattern of subfossil and archaeological wood is highly relevant when one wants to gain more insights in past forest dynamics and structure. It has been demonstrated that the characterisation of the growth patterns, recorded on archaeological timbers, often display comparable trends with the growth patterns of contemporary trees from stands with a well-know management and structure (see Section 6.3 and Figures 6.3a-f). This opens new perspectives for tree-ring studies. More information about former stand structure and management practices can be extracted from the general trend in the growth patterns. Striking is the recurrent discrepancy between the observed growth trends of historical timbers from young (less than 50 years) and older trees. Where the former are related to coppiced trees and the latter usually resemble more to trees from high forests stands or the widely spaced standards from a coppice-with-standards stand.

More detailed observations regarding the anatomical structure of the wood provides an image of the local environment (see Section 8.3) and sometimes even management practices (see Section 2.7.2) experienced by the trees. Especially the size of the earlywood vessels has proved to be a rewarding feature when studying past environmental conditions.

## **9.7 Xylo-chronologies**

Some ring-width series, even if they span more than 100 years, are not characteristic enough to establish a significant correlation with a reference curve. Therefore it



would be of interest to assess the potential of other wood anatomical features with an annual resolution for the construction of absolutely dated time series. Some of those variables that display a high year-to-year variability could be integrated into chronologies describing the annual ring on a higher level of detail. This idea has already been raised and applied by Polge and Keller (1969). They introduced the term *xylo-chronology*, as a means to describe time series of growth rings in a mathematical way. Polge (1971) combined minimum and maximum density together with the ring width into a single time series. Both density measurements reflect the influence of an environmental variable on the radial growth of trees in a specific time window. This contrasts the total ring width, which can be considered as an integration over an entire growing season (Sass 1993).

Recent studies have shown the potential of other wood anatomical descriptors for ecological studies. For instance, vessel size (diameter, surface, etc.) has proven to contain a different climatological signal compared to total ring width series. Moreover, vessel area time series of oak do not display a pronounced growth trend, in contrast to ring width series. The first-order autocorrelation of such time series is also remarkably lower. This reflects that the vessel area is less dependent on the growing conditions of the previous growing season (Fonti and García-González 2004; García-González and Eckstein 2003; Woodcock 1989). The application of these vessel time series in dating and chronology building has not been tested and validated yet.

It should be clear however that when chronologies are being built with measurements of more detailed anatomical features, it is not feasible to mix *Q. robur* and *Q. petraea* into one single chronology. The proportion of their anatomical features differs significantly (Feuillat *et al.* 1997) and a mixture of measurements on both species would yield an incorrect reference chronology. Further development of so-called *xylo-chronologies* will only be possible when a fast methodology (e.g. Vansteenkiste 2002) is available to quantify wood anatomical features (Eckstein 2004).

## **9.8 Outlook for the future**

Tree-ring analysis will remain the most precise dating tool available for archaeologists and art historians. With a continuously growing database of local and

regional reference chronologies, tree-ring dating has the potential to become even more successful. Moreover, the tracking of the original timber source of wooden objects will become more detailed when local and site chronologies are separately stored in a database before merging them into a reference chronology.

Recent advances in image analysis (e.g. García-González and Eckstein 2003; Vansteenkiste 2002) and high-resolution scanning techniques (see Section 2.4.1) open new possibilities to investigate large datasets of wood specimens within an acceptable time frame. Moreover, this would allow to incorporate more detailed information about the anatomical structure of the wood into time series containing more than ring width alone.

In Flanders, archaeologists and historians have more and more become aware about the potential of dendrochronology. This will stimulate archaeologists to preserve and collect the wood that is found and examined during field campaigns for tree-ring analysis. Ultimately this could lead to the development of a true Flemish reference chronology or at least a well replicated database of site chronologies covering different regions in Flanders. Moreover, when large datasets of tree-ring series can be examined and analysed, more detailed information on the dynamics, structure and management of former woodlands and forests will become available. However, the historical fact that vast amounts of timber were imported into Flanders necessitates close cooperation and exchange of data with dendrochronologists from all over Europe.

It is clear that historical research of wooden artefacts benefits from close collaboration with wood scientists. By scrutinizing growth patterns and anatomical particularities, relevant information and insights regarding the original timber source, wood processing activities and the creative or constructive process are unravelled from the wood. Hence it is highly valid to approach Flanders' precious cultural heritage, created out of wood, from a multidisciplinary point-of-view, where wood technology and biology should play an important and valuable role.

14 November 2005.





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## Curriculum vitae

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### Opleiding

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1988-1994: St.-Lievenscollege (Zilverenberg 1, 9000 Gent)  
*Humaniora, Wetenschappelijke A*

1995-1999: Universiteit Gent, Faculteit Landbouwkundige en Toegepaste Biologische Wetenschappen  
(Coupure Links 653, 9000 Gent)  
*Bio-ir. in het Land- en Bosbeheer, optie Bodem- en Waterbeheer*

Afstudeerwerk: Dendrochronologische evaluatie van het El Niño-effect te Oost-Afrika;  
Gevalstudie: *Brachystegia spiciformis* Benth.  
(gewaardeerd met de *Prijs van de Staatssecretaris voor Ontwikkelingssamenwerking* 1999).

2001-2004: *Doctoraatsopleiding* aan de Faculteit Bio-ingenieurswetenschappen

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### Werkervaring

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1999-2000: Wetenschappelijk medewerker aan het Laboratorium voor Houtbiologie & Xylarium, Koninklijk Museum voor Midden-Afrika te Tervuren.  
- Onderzoek naar de geschiktheid van houtsoorten voor buitenschrijnwerk in opdracht van het Wetenschappelijk en Technologisch Centrum voor het Bouwbedrijf (WTCB)

2001-2004: Doctoraatsbursaal aan het Laboratorium voor Houttechnologie van de FBW, Universiteit Gent.  
- FWO-onderzoeksproject: Methodisch en interdisciplinair onderzoek naar kenmerken, evolutie en maatschappelijk-culturele betekenis van de Brabantse gesneden retabels, 15<sup>de</sup>-16<sup>de</sup> eeuw.

2005-2006: Wetenschappelijk medewerker aan het Laboratorium voor Houttechnologie van de FBW, Universiteit Gent.  
- BOF-onderzoeksproject: Ecologie en exploitatie van het Holoceen bos. Optimalisatie van dendrochronologie als dateringsmethode en archeologische informatiebron binnen Vlaanderen.

## Publicaties

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- A1: - Trouet V., Haneca K., Coppin P. & Beeckman H. 2001. Tree ring analysis of *Brachystegia spiciformis* and *Isobertinia tomentosa*: Evaluation of the ENSO-signal in the Miombo woodland of Eastern Africa, *IAWA Journal* 22(4): 385-399.
- Haneca K., Wazny T., Van Acker J. & Beeckman H. 2005. Provenancing Baltic timber from art historical objects: success and limitations, *Journal of Archaeological Science* 32(2): 261-271.
- Haneca K., De Boodt R., Herremans V., De Pauw H., Van Acker J., Van de Velde C. & Beeckman H. 2005. Late Gothic altarpieces as sources of information on medieval wood use: a dendrochronological and art historical survey, *IAWA Journal* 26(3): 273-298.
- Haneca K., Van Acker J. & Beeckman H. 2005. Growth trend reveal the forest structure during Roman and Medieval times in Western Europe: a comparison between archaeological and actual oak ring series (*Quercus robur* & *Quercus petraea*), *Annals of Forest Science* 62(8): *in press*.
- Haneca K., Boeren I., Van Acker J. & Beeckman H. 2005. Dendrochronology in suboptimal conditions: tree rings from medieval oak from Flanders (Belgium) as dating tools and archives of past forest management, *Vegetation History and Archaeobotany*: *in press*.
- Haneca K., Deforce K., Bastiaens J., Van Acker J. & Beeckman H. *in preparation*. Subfossil oak trunks as ecological archives of forest dynamics along the river Scheldt (Belgium).
- Goris R., Kint V., Haneca K., Geudens G., Verheyen K. & Beeckman H. *in preparation*. Gap dynamics in an unmanaged conifer plantation with spontaneous ingrowth of broadleaves: a dendro-chronological reconstruction.
- A3: - Ameels V., Bastiaens J., Bats M., Crombé P., Deforce K., Haneca K., Parent J.-P. & Van Strydonck M. 2003. Recent Steentijdonderzoek in de regio Oudenaarde (Oost-Vlaanderen, België), *Notae Praehistoricae* 23: 61-65.
- De Clercq W., Bastiaens J., Deforce K., Desender K., Eryvynck A., Gelorini V., Haneca K., Langohr R. & Van Petegem A. 2002. Waarderend en preventief archeologisch onderzoek op de Axxes-locatie te Merelbeke (prov. Oost-Vlaanderen): een grafheuvel uit de Bronstijd en een nederzetting uit de Romeinse periode, *Archeologie in Vlaanderen VIII*: 123-164.
- C1: - De Boodt R., Haneca K. & Cuvelier H. 2005. Reconstruction and Deconstruction. Interdisciplinary research on the altarpieces of Bassine, Pailhe and Gaasbeek, *in*: Van de Velde C., Beeckman H., Van Acker J. and Verhaeghe F. (Eds.), *Constructing Wooden Images: proceedings of the symposium on the organization of labour and working practices of late Gothic carved altarpieces in the Low Countries, Brussels 25-26 October 2002*. VUB Press, Brussels, 147-180.
- Overige: - Haneca K. & Deforce K. 2002. Kalenders van hout. *Ename 974*, nr. 20: 6-7.
- Haneca K. 2003. Dendrochronologisch onderzoek op retabelfragmenten uit het Vleeshuis. *Behoud en beheer berichten*, december 2003: 6-8.

## Congressen, studiedagen en stages

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- Congressen: - 6th International Conference on Dendrochronology. Dendrochronology, environmental change and human history. 22-27 augustus 2002, Québec City, Canada.  
Voordracht: Dendrochronological research on Brabantine altarpieces from 15th-16th century.
- Constructing Wooden Images. A symposium on the organization of labour and working practices of late Gothic carved altarpieces in the Low Countries, 25-26 oktober 2002, Brussel.  
Voordracht: Reconstruction and deconstruction. Interdisciplinary research on the altarpieces of Pailhe, Bassine and Gaasbeek.
- EuroDendro 2003, 10-14 september, Obergurgl, Tirol, Oostenrijk.  
Voordracht: Provenance of Baltic timber used for carving Brabantine altarpieces during 15<sup>th</sup>-16<sup>th</sup> century.
- EuroDendro 2004, 15-19 september, Rendsburg, Duitsland.  
Voordracht: Tree rings and quality of oak timber: growth patterns from roman, medieval and modern trees.



- EuroDendro 2001, 6-10 juni 2001, Ljubljana, Slovenië.  
Poster presentatie: Dendrochronological research on two Brabantine altarpieces (K. Haneca, H. Beeckman, R. De Boodt, H. De Pauw, J. Van Acker, M. Stevens & C. Van de Velde).
  - International Conference on Past Climate Variability Through Europe and Africa, 27 - 31 Augustus 2001, Aix-en-Provence, France.  
Poster presentatie: The value of growth ring series of the miombo wood-land in southern and eastern Africa as proxy data for climate reconstruction (V. Trouet, K. Haneca, P. Coppin & H. Beeckman).
  - Tree-Rings and People, 22-26 september 2001, Davos, Zwitserland.  
Poster presentatie: Dendroclimatology of Miombo woodland species in Southern and Eastern Africa (V. Trouet, K. Haneca, P. Coppin & H. Beeckman).
  - IUFRO-Symposium. History and forest biodiversity, challenges for conservation, 13-15 januari 2003, Leuven.  
Poster presentatie: Early to Middle-Holocene forests on the banks of the river Scheldt: the drowned forest at Ename, eastern Flanders, Belgium (K. Haneca, V. Ameels, J. Bastiaens, K. Deforce & H. Beeckman).
  - TRACE 2003, Tree Rings in Archaeology, Climatology and Ecology, 1-3 mei 2003, Utrecht, Nederland.  
Poster presentatie: Early Holocene forests on the banks of the river Scheldt: the drowned forest at Ename, Eastern Flanders, Belgium (K. Haneca, V. Ameels, J. Bastiaens, K. Deforce, M. Van Strydonck & H. Beeckman).
  - IAWA Symposium, International symposium on wood science, 24-29 oktober 2004, Montpellier, Frankrijk.  
Poster presentatie: A dendrochronological and wood anatomical survey on carved wooden altarpieces from 15<sup>th</sup>-16<sup>th</sup> century (K. Haneca, R. De Boodt, J. Van Acker & H. Beeckman).  
Poster presentatie: Oak trees from ca. 8.000 BP: Interdisciplinary research on subfossil wood specimens from a submerged forest along the river Scheldt (Ename, Belgium). (K. Haneca, V. Ameels, J. Bastiaens, K. Deforce, M. Van Strydonck & H. Beeckman).
- Studiedagen: - 2000, Hout en Bast Club, Nationaal Herbarium te Leiden (NL).  
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- 2002, 42<sup>ste</sup> Nederlands – Belgische Palynologendagen, Kruikeke (B).  
- 2003, Microscopy automation – Olympus (B)  
- 2004, Anwendungen der 3D-Computertomographie in Archäologie, Restaurierung und Kunstgeschichte, Aalen (D)  
- 2005, Starters in Bosonderzoek, Brussel (B)
- Stage: - 2001, 16th Dendroecological Fieldweek, Zwitserland.
- Overige: - Lid van wetenschappelijk en organiserend comité van het symposium *Constructing Wooden Images: a symposium on the organization of labour and working practices of late Gothic carved altarpieces in the Low Countries*, georganiseerd te Brussel op 25 en 26 oktober 2002.  
Lid van wetenschappelijk en organiserend comité van het congres *Tree Rings in Archaeology, Climatology and Ecology* (TRACE), dat zal georganiseerd worden in het Koninklijk Museum voor Midden-Afrika in Tervuren van 20 tot 22 april 2006.  
- Reviewer voor het *IAWA Journal* en *Journal of Archaeological Science*.