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ORIGINAL ARTICLE

Sapwood estimates of pedunculate oak (*Quercus robur* L.) in eastern Baltic

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ABSTRACT

Pedunculate oak (*Quercus robur* L.) is one of the widely used and dendrochronologically investigated species in Europe. Still, it is a problematical dating object if its outermost section is missing partly or totally. Thus, we need sapwood estimation of living trees. As sapwood amount varies geographically, numbers of sapwood rings have been published for different regions in Europe but no such estimation has been done for the Baltic States yet. Therefore, this paper deals with the estimation of pedunculate oak sapwood growing in the eastern Baltic region, i.e. in Finland, Estonia, Latvia, and Lithuania.

In total, 668 oak core samples of living trees from 43 stands were investigated. Ring widths were measured and the number of sapwood rings was determined according to two criteria: difference of colour and absence of tyloses in earlywood vessels. The samples were divided into two sets, according to the t_H-values between site chronologies and the major geobotanical sub-provinces. Thus, the nine Finnish and western Estonian sites were attributed to the western region and the 34 eastern Estonian, Latvian and Lithuanian sites to the eastern region.

As the result of a statistical analysis, we explain that the number of oak sapwood rings ranges from 4.09 to 20.85 and 6.45 to 18.02 within 95% confidence limits in the western and eastern regions, respectively. For the three Baltic countries and southern Finland in general, we recommend to consider a sapwood estimate of 6.18–18.71 rings. Regarding earlier studies, the general European trend of decreasing sapwood ring number towards the east was confirmed. A geographical pattern of eastward decrease of the median sapwood ring number was noticed in the Baltics as well. The chronology based upon 668 samples of living oak trees from all sites covered the period of 1631–2008.

Introduction

Pedunculate oak (*Quercus robur* L.), distributed up to 60° northern latitudes in Europe, is one of the dendrochronologically most investigated species in Europe. However, often the dendrochronological date of an oak item does not show the felling date of the tree. This occurs because a part or the whole sapwood is missing due to woodworking techniques or decay in archaeological samples. The number of sapwood rings is necessary to establish for precise dating as the last sapwood ring points to the felling date.

Therefore, the number of sapwood rings in living trees and historic timber needs to be examined to estimate the number of missing sapwood rings in the dating objects. Sapwood number in oaks has been widely investigated and statistics for different regions of Europe have been published (e.g. Hughes et al., 1981; Hillam et al., 1987; Wazny and Eckstein, 1991; Miles, 1997; Rybníček et al., 2006). A comprehensive summary is available in Haneca et al. (2009). Usually minimum and maximum number of sapwood rings within 95% confidence limits is presented. In general, the frequency distribution of the number of sapwood rings is positively skewed. The number can vary greatly both within and between individual trees at one site (Hughes et al., 1981). The amount of sapwood within a trunk increases with the sampling height. Significant variation can occur around the cross-section of the tree trunk as well. Sapwood also increases with the ageing of a tree (e.g. Hillam et al., 1987). It is assumed that the sapwood amount has remained constant for the oak populations throughout the history, although some archaeological oak artefacts have shown considerably greater or smaller sapwood numbers than in the modern timber (Grynaeus, 2003; Randsborg and Christensen, 2006). The total of all sapwood estimates reveals a tendency towards decreasing sapwood number moving from west to east within Europe. This is a potential problem in the interpretation of tree-ring dates of imported timbers (Baillie et al., 1985). There may also be a north–south trend based on material of British Isles (Hillam et al., 1987).

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Hence, the amount of sapwood in different regions is relevant in the context of historical timber trade. Basing on historic data and dendroprovenancing research the oak timber export from the Baltic ports to Western Europe from the 13th century up to the mid-19th century has been established (e.g. Baillie et al., 1985; Eckstein et al., 1986; Wazny and Eckstein, 1987; Bonde et al., 1997; Zunde, 1998–1999; Wazny, 2002, 2005; Haneca et al., 2005). Dendrochronological analysis of structural timbers from Scotland has shown that the timber was imported from eastern Denmark and/or southern Sweden throughout the 16th century (Crone and Fawcett, 1998). To Western Europe in general, a large quantity of oak was transported via the eastern Baltic ports of Danzig (Gdańsk), Königsberg (Kaliningrad), Memel (Klaipeda), Libau (Liepāja), and Riga (Bonde et al., 1997; Zunde, 1998–1999; Kremser, 1998). Its original sources were mainly the catchments of the Vistula, Neman and Daugava rivers as well as the Dnieper basin, now parts of Poland, Ukraine, Belarus, Russia, Lithuania, and Latvia. The largest quantity of timber was exported through Danzig until the end of the 16th century when the Baltic timber trade shifted towards the Couronian ports and Riga in the north (Zunde, 1998–1999; Wazny, 2005). The centre of timber trade from the Russian territory close to Lake Peipus was Narva in Estonia, which peaked in the second half of the 17th century (Soom, 1940; Kremser, 1998) and was lively at least until the second half of the 18th century (Hupel, 1777; Eckstein and Wrobel, 2007).

Oak forests in the Baltic countries have declined because of natural and anthropogenic factors during the centuries. The most devastating factor for oak forests in Estonia has been the felling of timber for the shipbuilding industry for the Russian Empire during the 18th century (Daniel, 1929). Nowadays, oak is the dominant tree species only in 0.3% of forest stands area in Estonia (Metsakaitse- ja Metsauuenduskeskus, 2009) and correspondingly in 2.0% in Lithuania (State Forest Survey Service, 2009).

No estimation of oak sapwood rings for the Baltic States exists yet. So far, the sapwood estimate from Poland (e.g. Wazny and Eckstein, 1991) are used to specify felling dates for historical oak timbers in Lithuania (Pukienė and Ožalas, 2007). Therefore, the objectives of this study were to describe and standardise the variability of the number of sapwood rings of growing oaks in the eastern Baltic Sea region, i.e. in Estonia, Latvia, Lithuania, and Finland, and to present the average oak growth series of living trees to characterise this region.

Material and methods

Altogether, a data set of 668 sample cores of pedunculate oak (*Q. robur* L.) from 43 sites was compiled (Fig. 1). The sampled subset represents the geographical distribution of the whole population, as most of the oaks in the region grow in Lithuania. The southern Finnish cores were sampled from the oaks growing in the semi-natural parks of Annala and Tammisto near Helsinki, characterised by outcrops of Precambrian bedrock. The average thickness of organic soil layer was less than 50 cm there. In both parks, ten trees were sampled during 2007–2008. These oaks represent the northernmost distributional limit of *Quercus* in the world (Axelrod, 1983). The fieldwork in Estonia was carried out in 2000–2008, sampling 128 oak cores from 11 sites. These were fresh boreo-nemoral forests or semi-natural parks (*Quercetum aegopodiosum* type in Saue, Lehmja, Lasva, Päinurme, Rava) and dry and moist boreo-nemoral wooded grasslands (in Mäetaguse, Loode, Keskranna, Mullutu, Tammiku). The cores of the Ruhnu Island were sampled from the single trees in the village. From Latvia, 81 oak cores were sampled from seven sites in 2007. These represented mostly the *Quercetum aegopodiosum* fresh boreo-nemoral type (Moricsala, Limbaži, Seldži Āraiši, Barkava, Pededze, Piļori-Pahatnieki). The oak samples from Lithuania were borrowed from the database of the Group of Dendroclimatology and Radiometrics of the Vytautas Magnus University (sampled between 1969 and 1997). A total of 439 Lithuanian cores from 23 sites were used. On the soil moisture scale from wetter to dryer, these were distributed from the *Quercetum filipendulosum* rich paludified type (Troškūnai, Žalioji), *Quercetum aegopodiosum* fresh boreo-nemoral type (Vėžaičiai, Biržai, Kurtuvėnai, Kaltinėnai, Spirakiai, Anykščiai, Utena, Kėdainiai, Gelvonai, Naujoji Ūta, Stakliškės, Bukta, and Alytus), *Quercetum myrtillo-oxalidosum* (Naukaimis), to *Quercetum oxalidosum* (Plateliai, Pagėgiai, Viduklė, Babtai, Dūkštas, Aukštadvaris, and Subartonys) fresh boreal forests (Kairaitis, 1978).

The cores from Finland, Estonia and Latvia were sampled at the height of 100–130 cm and mostly from the northern side of the trunk. A 40 or 50 cm long increment borer was used to core samples of 5 mm in diameter. The aim was to core radially towards the pith. However, owing to the great diameter of the trees, not all core samples had near-pith rings. The same aim was targeted in sampling the Lithuanian cores, although the authors did not participate in the sampling during 1969–1997. Only cores with complete sapwood were used in this work.

Tree-ring widths were measured with a 1/100 mm precision on a Lintab™ measuring table equipped with a Leica S4E light microscope. The measured values were recorded and graphs were displayed using the TSAP-Win™ software by RINNTECH. The quality control of the measurements was performed visually from graphs and with the COFECHA software from the Dendrochronology Program Library (DPL) (Holmes, 1983; Grissino-Mayer, 2001). The series were standardised into site chronologies by CRONOL software (DPL, routine CRN).

In order to compare the study area with adjacent regions, Polish reference oak chronologies from Goldap ($n=22$) and Gdańsk ($n=45$) were used, made available by T. Wazny in the International Tree-Ring Data Bank (ITRDB, http://www.ncdc.noaa.gov/paleo/treering.html) and the chronology from Białowieża ($n=13$; M. Koprowski and M. Murawska, unpublished).

As the index of similarity between site chronologies, Hollstein's *t*-values (t_H) (Hollstein, 1980) were calculated with the TSAP-Win™ software as:

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

where r is the correlation coefficient between chronologies and n is the number of overlapping years between chronologies.

Several clustering techniques were used and a principal component analysis was carried out with the site chronologies in order to establish chronology groups. As the resulting clusters had no geographical meaning, the sites were grouped arbitrarily according to the t_H-values between site chronologies and regarding the geobotanical zones (Fig. 1). The Baltic geobotanical province is divided into western and eastern sub-provinces. The first of them encompasses southern Sweden, southwestern Finland, coast of the Gulf of Finland, western Estonia and coast of Latvia and Lithuania. The characteristic feature of the sub-region is the occurrence of Atlantic elements in the flora. The eastern Baltic sub-province covers eastern Estonia and the continental Latvia and Lithuania, featuring no Atlantic elements. The western Baltic sub-province is considered part of the sub-Atlantic region of the northern mixed broadleaf-coniferous forest zone. The corresponding eastern Baltic sub-province is called the sub-continental region of the zone. Southern Lithuania belongs to the sub-continental region of the southern mixed broadleaf-coniferous forest zone already (Sochava et al., 1960; Laasimer, 1965).

Fig. 1. Study area with 43 oak sites in the Baltic countries and southern Finland. The dotted line indicates the schematic border of geobotanical sub-provinces (Sochava et al., 1960; Laasimer, 1965).

Boundaries between sapwood and heartwood were determined and recorded in the core samples and the number of sapwood rings counted under the microscope. In order to do that, two different sapwood criteria were used – lighter colour and absence of tyloses in the earlywood vessels. The few sample cores that had no visible features usable for the detection of the limit of sapwood were left out of the analysis.

The sapwood and mean ring width data as well as the distribution of site median sapwood number were tested for normality with the Shapiro–Wilk's *W*-test, calculated with the STATISTICA^{TM} 7 software package. In order to test the asymmetry of the data series, skewness (A) was calculated and standardised as:

$$\frac{A}{S_A}$$

where A is skewness and S_A is the standard deviation of skewness calculated as:

$$S_A = \sqrt{\frac{6}{n}}$$

where n is sample size.

In cases where standardised skewness was above $|2|$, the data were transformed towards symmetry.

Further statistical analysis was modelled along the precedent investigations of sapwood parameter estimations, which present 95% confidence intervals of the number of sapwood rings (e.g. Hughes et al., 1981; Hillam et al., 1987; Miles, 1997; Haneca et al., 2009). A mean, median, minimum, maximum and the 95% (more accurately 95.44%) interval of expected values (mean ± 2 standard deviations) were calculated for the normally distributed series.

In three additional analyses, only sapwood data by colour criterion were performed. A regression model was used to study the relationship between sapwood number and mean ring width. The median sapwood values of individual sites were divided into three classes and plotted on a map, in order to describe the geographical variation in sapwood. The middle class was defined as the median of the total of medians ± 1 ring. The relationships between the sapwood ring number and the longitude and latitude were described by linear regression models.

Results

Site chronologies

The geographical grouping of sites showed that the region with the most homogenous increment pattern was Lithuania, as expressed by the t_H-values (Table 1). Thus, the Lithuanian site chronology was built to compare it with other site chronologies. The Finnish, Estonian, and Latvian oak sites showed an unclear similarity pattern to each other. However, it can be stated that

Table 1
Hollstein's t-values for 23 Lithuanian oak chronologies in 1862–1969. Values ≥3.5 are marked in bold.

Site	Plateliai	Vėžaičiai	Pagėgiai	Biržai	Kurtuvėnai	Kaltinėnai	Viduklė	Naukaimis	Spirakiai	Troškūnai	Anykščiai	Utena	Kedainiai	Babtai	Gelvonai	Dūkštas	Žalioji	Naujoji Ūta	Aukštadvaris	Stakliškės	Bukta	Alytus	Subartonys
Plateliai	-																						
Vėžaičiai	**6.2**	-																					
Pagėgiai	**5.2**	**6.7**	-																				
Biržai	**4.4**	**4.2**	**7.3**	-																			
Kurtuvėnai	**7.2**	**6.1**	**9.2**	**8.7**	-																		
Kaltinėnai	**5.9**	**7.6**	**7.5**	**6.2**	**8.0**	-																	
Viduklė	**7.6**	**6.7**	**9.2**	**6.2**	**8.5**	**9.8**	-																
Naukaimis	2.7	**3.7**	**4.3**	**4.7**	**5.1**	**5.0**	**6.8**	-															
Spirakiai	2.5	**4.2**	**4.9**	**5.7**	**5.4**	**3.8**	3.4	**5.0**	-														
Troškūnai	**6.0**	**5.1**	**6.9**	**7.2**	**9.1**	**5.5**	**5.8**	**5.8**	**7.2**	-													
Anykščiai	**4.8**	**5.0**	**7.6**	**7.1**	**7.0**	**6.5**	**6.4**	**6.7**	**6.5**	**8.7**	-												
Utena	2.6	**4.6**	3.4	**3.9**	**3.5**	**4.0**	2.6	**4.0**	**3.6**	**5.0**	**7.3**	-											
Kedainiai	**4.0**	**3.9**	**6.9**	**6.3**	**7.7**	**4.8**	**5.0**	**6.9**	**7.6**	**8.3**	**7.3**	**4.3**	-										
Babtai	2.3	**4.2**	**6.2**	**5.9**	**6.1**	**5.2**	**5.0**	**8.6**	**6.5**	**6.8**	**8.1**	**6.5**	**7.8**	-									
Gelvonai	**4.4**	**5.5**	**7.7**	**6.0**	**6.6**	**7.6**	**8.5**	**7.4**	**6.5**	**7.6**	**11.1**	**4.1**	**7.9**	**8.6**	-								
Dūkštas	**4.7**	**4.2**	**4.7**	**4.9**	**4.5**	**4.7**	**5.8**	**6.6**	**6.2**	**6.7**	**8.7**	**4.8**	**5.1**	**6.8**	**7.1**	-							
Žalioji	2.4	**5.2**	**5.8**	3.3	**3.5**	3.1	2.8	**4.2**	3.4	3.0	**4.2**	**3.7**	**4.9**	**5.1**	**4.8**	**4.5**	-						
Naujoji Ūta	**5.2**	**3.7**	**7.0**	**6.5**	**4.9**	**5.0**	**4.7**	**4.1**	**4.6**	**7.4**	**7.7**	**3.8**	**5.2**	**6.0**	**6.3**	**6.2**	**4.4**	-					
Aukštadvaris	**6.4**	**5.7**	**8.4**	**6.6**	**7.4**	**7.1**	**8.0**	**5.1**	**6.5**	**7.7**	**9.1**	**4.9**	**6.2**	**6.6**	**7.7**	**8.0**	**3.5**	**8.3**	-				
Stakliškės	**4.0**	**5.4**	**4.6**	**4.0**	**3.9**	**4.8**	**4.9**	**4.2**	**6.1**	**5.1**	**6.5**	**4.0**	**3.5**	**4.8**	**5.4**	**7.8**	**3.8**	**5.3**	**6.8**	-			
Bukta	2.8	**4.5**	**4.3**	**4.8**	**3.9**	3.1	**4.6**	**4.7**	**3.9**	**4.1**	**4.6**	2.7	**4.3**	**6.3**	**4.9**	**5.4**	**6.0**	**5.3**	**4.3**	**3.8**	-		
Alytus	**4.2**	**3.8**	**4.7**	**3.7**	**3.9**	**4.3**	**5.2**	**3.6**	3.4	**3.8**	**4.7**	2.2	3.3	**4.4**	**4.1**	**5.6**	2.6	**6.5**	**5.9**	**5.4**	**5.1**	-	
Subartonys	**5.0**	**3.8**	**5.5**	**5.4**	**5.1**	**4.7**	**4.9**	2.6	**3.6**	**5.5**	**5.3**	**3.7**	**4.3**	**5.2**	**4.8**	**4.2**	**3.6**	**6.4**	**6.1**	**5.4**	**4.1**	2.3	-

the oak stands in western Estonia were similar to each other. The oaks in Latvia were more similar to each other and to those of Lithuania than to the Estonian sites (Table 2). Hence, the sites were divided into two sets so that the nine Finnish and western Estonian sites were attributed to one group, and the 34 eastern Estonian, Latvian, and Lithuanian sites to the other group. The chronologies of these two groups overlapped within 281 years (1728–2008). The t_H-value between those was 7.0. The chronology based upon 668 samples from all sites covered 1631–2008 (Fig. 2).

The comparison of the eastern Estonian, Latvian, and Lithuanian chronology with the Polish sites gave the greatest similarity to Białowieża ($t_H = 7.5$; common interval 1773–2007), slightly smaller to Gdańsk ($t_H = 6.7$; common interval 1762–1985), and to Goldap ($t_H = 5.7$; common interval 1871–1986). The accordance between the Polish chronologies and the Finnish and western Estonian chronology was much lower ($t_H < 4.0$).

Sapwood estimates

Sapwood boundaries were determined in 660 cores by the colour criterion and in 630 cores by the tyloses criterion. Thirty samples showed tyloses in the latest rings just beneath the bark (Fig. 3a). These cores were removed from the sapwood analysis by the tylosis criterion. The two criteria coincided in 414 samples (63%).

It can be stated that all investigated oak cores were taken from mature trees since the ring count was 81–193 in 90% of samples (median 131) while 82% of the samples belonged to the 100–200 year age class. The samples that had fewer rings were likely to have

Table 2
Hollstein's t-values for 2 Finnish, 11 Estonian, 7 Latvian, and average Lithuanian oak chronologies in 1907–1997. Values ≥3.5 are marked in bold.

Site	Annala	Tammisto	Saue	Lehmja	Loode	Keskranna	Mullutu	Tammiku	Ruhnu	Mäetaguse	Rava	Päinurme	Lasva	Moricsala	Limbaži	Āraiši	Pededze	Seldži	Barkava	Piļori-Pahatieki	Lithuania
Annala	-																				
Tammisto	**7.5**	-																			
Saue	2.2	**4.4**	-																		
Lehmja	**4.7**	**6.0**	**8.1**	-																	
Loode	2.1	2.4	**3.9**	**4.3**	-																
Keskranna	1.8	2.4	2.5	2.7	**6.9**	-															
Mullutu	1.3	2.8	**4.8**	2.4	**7.1**	**4.1**	-														
Tammiku	1.9	2.2	**5.2**	**4.3**	**9.2**	**7.5**	**6.9**	-													
Ruhnu	1.1	0.4	1.0	1.8	**5.2**	**6.2**	1.6	**3.8**	-												
Mäetaguse	2.1	1.6	1.7	2.9	1.1	3.0	0.2	2.2	2.5	-											
Rava	2.9	2.1	2.7	**3.9**	**4.4**	**5.1**	2.0	**4.8**	3.4	**4.8**	-										
Päinurme	1.9	1.1	1.7	2.0	3.1	3.3	1.1	2.9	1.4	0.6	3.2	-									
Lasva	2.3	3.3	**3.5**	**4.7**	2.5	2.5	0.8	2.2	1.2	**3.5**	2.2	0.7	-								
Moricsala	2.4	2.5	1.6	2.7	1.4	3.4	1.1	2.2	2.4	0.1	2.3	1.2	2.1	-							
Limbaži	1.1	1.4	2.3	**3.6**	2.4	2.9	1.5	**3.5**	2.7	**7.5**	**4.2**	1.4	**4.4**	2.7	-						
Āraiši	0.2	0.6	3.0	2.2	3.0	**3.7**	1.6	3.0	**3.8**	**3.7**	**3.5**	2.7	**4.5**	2.4	**5.9**	-					
Pededze	3.0	2.8	0.9	2.1	2.2	2.6	1.8	2.1	1.2	2.9	3.0	0.7	**4.5**	3.1	**4.6**	**4.6**	-				
Seldži	0.9	0.4	0.1	1.5	2.0	2.3	1.4	1.5	1.3	2.8	2.6	0.8	2.0	2.4	**4.5**	2.6	**6.0**	-			
Barkava	0.3	0.6	0.3	0.6	1.3	1.6	0.6	0.6	1.3	2.6	1.4	2.4	1.6	0.1	2.8	1.6	2.0	**4.2**	-		
Piļori-Pahatieki	1.4	1.9	1.9	2.7	2.9	1.9	2.8	2.2	0.7	3.2	**3.9**	1.7	2.4	**4.1**	**5.2**	2.5	3.2	**5.1**	3.0	-	
Lithuania	2.4	2.1	2.7	**3.8**	**3.9**	**4.6**	2.6	**4.5**	**4.0**	**3.9**	**6.0**	1.3	**3.9**	**4.5**	**5.4**	**3.8**	**3.6**	2.0	2.3	**4.1**	-

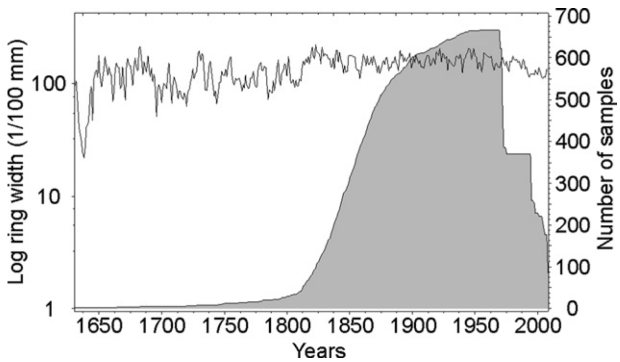

Fig. 2. The average oak chronology of the eastern Baltic region in 1631–2008 and sample depth ($n = 668$).

higher actual cambial age because of the recorded natural damages to the core samples and the missing part of the core near the pith.

The sapwood ring number in the southern Finnish and western Estonian group was normally distributed by both colour (Shapiro–Wilk's $W = 0.979$; $p > 0.05$; Fig. 4a) and tyloses criterion (Shapiro–Wilk's $W = 0.976$; $p > 0.05$; Fig. 4c). Hence, the variance parameters apply for the southern Finnish and western Estonian oak population. The distribution of sapwood amount in the eastern Estonian, Latvian, and Lithuanian group differed significantly from normality by the colour criterion (Shapiro–Wilk's $W = 0.970$; $p < 0.05$; Fig. 4b). The number of rings had positive asymmetry initially (standardised skewness 5.46). After square root transformation, the data became symmetric (standardised skewness −0.15). The same kind of normalisation was performed with the total data set ($n = 660$). The distribution of sapwood amount in the eastern Estonian, Latvian and Lithuanian group differed significantly from normality by the tyloses criterion as well (Shapiro–Wilk's $W = 0.966$; $p < 0.05$; Fig. 4d). The distribution had slight negative asymmetry initially (standardised skewness −3.55). A power transformation was applied to reduce this (amended standardised skewness 0.15). The same procedure was performed with the total data set ($n = 630$).

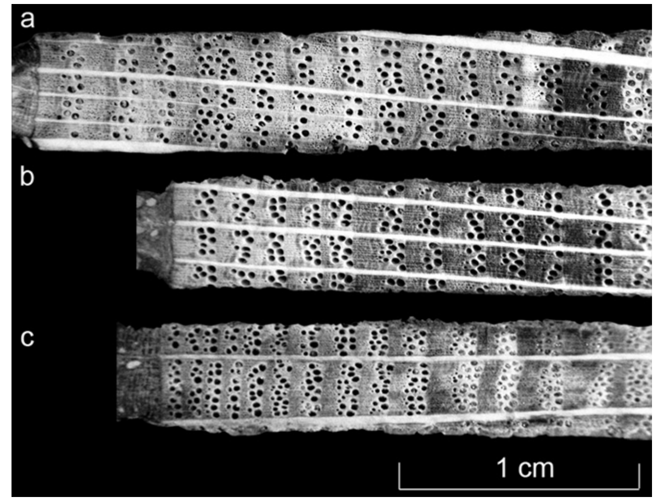

Fig. 3. Examples of heartwood–sapwood boundaries in the cores: (a) 13 lighter rings and rings filled with tyloses beneath the bark; (b) 5 lighter rings and 11 rings without tyloses; (c) a coincidence of 10 lighter rings and the rings without tyloses.

Table 3 presents detransformed sapwood parameters. The median sapwood ring count by the colour criterion in the three Baltic countries and Finland is 12. Within 95% confidence limits the sapwood number varies from 6.18 to 18.71 rings. In more detail, the same parameter varies from 4.09 to 20.85 and 6.45 to 18.02 in the southern Finnish and western Estonian group and in the

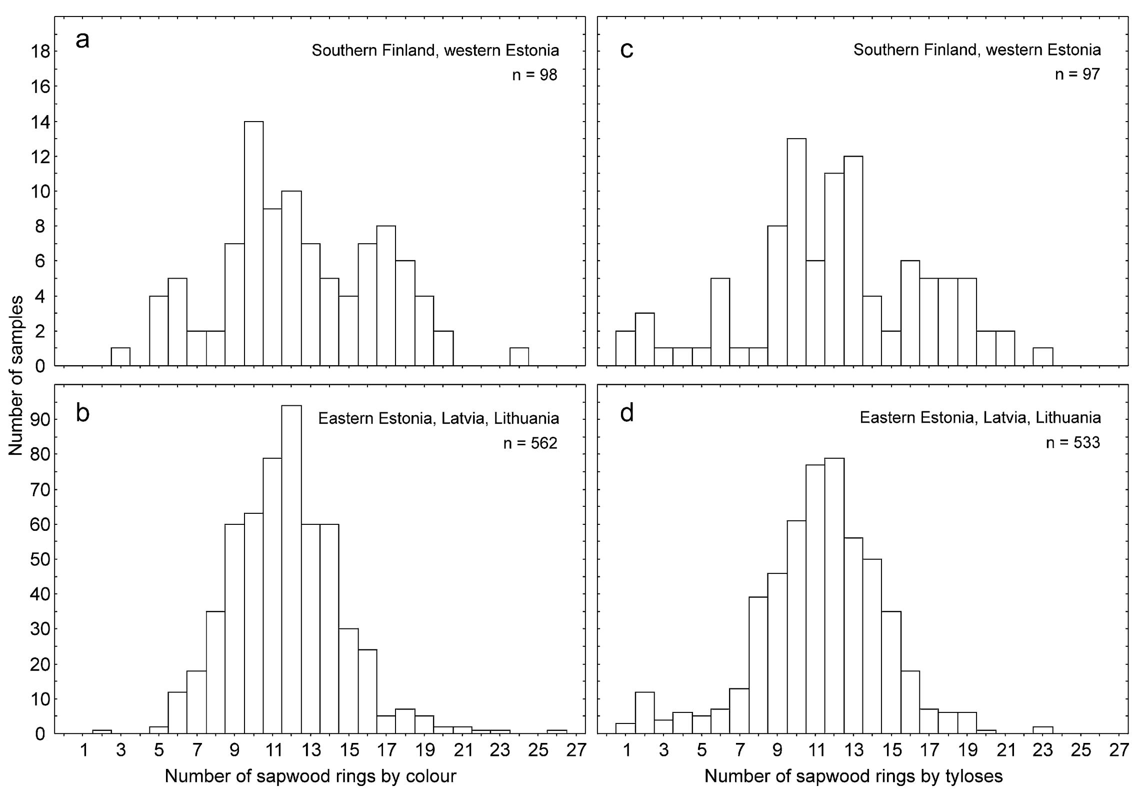

Fig. 4. Frequency histograms of sapwood data, determined by colour (a and b) and by tyloses (c and d). The sapwood number by both criteria is normally distributed in southern Finland and western Estonia, and is slightly skewed in eastern Estonia, Latvia, and Lithuania.

Table 3
Regional sapwood characteristics of oaks.

Region	Number of samples	Arithmetic/detransformed* mean	Median	Absolute range	95% confidence interval
By colour					
Southern Finland, western Estonia	98	12.5	12	3–24	4.09–20.85
Eastern Estonia, Latvia, Lithuania	562	11.5*	12	2–26	6.45–18.02
Eastern Baltic	**660**	**11.6***	**12**	**2–26**	**6.18–18.71**
By tyloses					
Southern Finland, western Estonia	97	12.1	12	1–23	2.60–21.69
Eastern Estonia, Latvia, Lithuania	533	11.4*	11	1–23	4.17–17.55
Eastern Baltic	**630**	**11.5***	**11.5**	**1–23**	**3.64–18.19**

* Detransformed

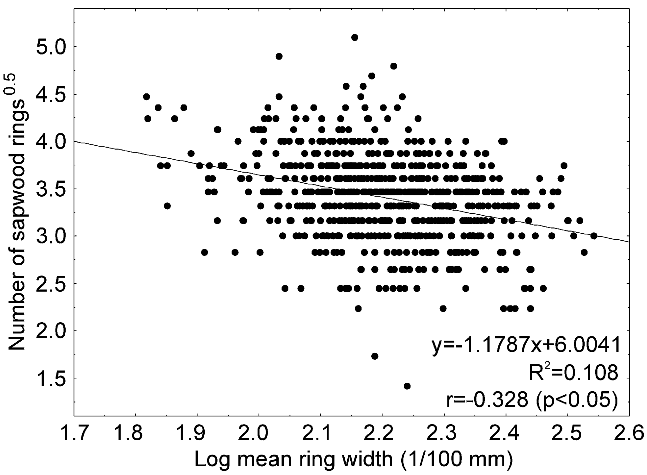

Fig. 5. Relationship between sapwood number and mean ring width; the variables are respectively square root and $\log_{10}$ transformed ($n = 660$).

eastern Estonian, Latvian and Lithuanian group, respectively. For comparison, the results by tyloses criterion show a slightly wider range, giving a 95% range of 3.64–18.19 in the eastern Baltic region, 2.60–21.69 in the southern Finnish and western Estonian group, and 4.17–17.55 in the eastern Estonian, Latvian and Lithuanian group.

The mean ring width distribution across the samples differed significantly from normality. Initially it had positive asymmetry (standardised skewness 7.65). The data set was normalised by $\log_{10}$ transformation (standardised skewness −1.38). It is noticeable that the slowly growing trees have slightly more sapwood rings than the ones with fast growth. The correlation of mean ring width and sapwood number in the series was low but significant ($r = -0.328$; $p < 0.05$; Fig. 5).

The site median sapwood number did not differ significantly from normality and varied between 8 and 15 rings. Most commonly, the medians lay within 10–12 rings. However, the linear regression model showed a weak but significant relationship between the site median sapwood number and the longitude ($r = -0.462$; $p < 0.05$; Fig. 6). According to the determination coefficient ($R^2 = 0.213$) the model described approximately 20% of the total dispersion only. The regression model between sapwood and latitude had even a lower predictive value – ca. 10% ($r = -0.352$; $p < 0.05$).

Discussion

Generally, oak sapwood is distinguished from the heartwood by lighter colour and the absence of tyloses in earlywood vessels. In cases of uncertainty, Hughes et al. (1981) used the tyloses criterion rather than colour difference. However, Savill et al. (1993) determined heartwood–sapwood boundary as the first line of earlywood vessels at which tyloses were presented in >75% of the vessels within the region of colour change in the wood. In our study, we determined sapwood separately by both the colour and the tyloses criterion. Altogether in 37% cores of the set, we detected a mismatch between these two criteria. For example, there were cores where discolouration had started earlier than the formation of tyloses (Fig. 3b) and vice versa. There were even more problematical samples. For instance, a total of 30 cores from living trees had the vessels in the latest rings filled with tyloses either partly or completely (Fig. 3a). Such samples we excluded from the tyloses analysis. We also registered cores where few filled rings were present in the middle of lighter sapwood and empty vessels. In such cases we still marked the heartwood–sapwood boundary by the latest ring with tyloses. That is why the records show so few sapwood rings according to the tyloses criterion in some cases (Fig. 4 and Table 3). We do not know when these 'irregular' tyloses have formed but it is known that tyloses can form in the sapwood after the felling as well (Murmanis, 1975). Also it is appropriate to remind that we studied only core samples from one side of each trunk and it is unknown how the tyloses have developed in the other sides. Due to these 'irregular' tyloses we suggest to use the sapwood results based on the colour criterion. However, precise determination of the heartwood–sapwood boundary based on colour is also somewhat subjective because the change is not clearly discernible in every case.

As the result of the statistical analysis, we explain that the oak sapwood ring number by colour and by tyloses ranges from 6 to 19 (median 12) and 4 to 18 (median 11.5), respectively, within 95% confidence limits in the whole eastern Baltic region (Table 3). The main difference between these two data sets is the lower value of the range, which is probably caused by the 'irregular' tyloses mentioned above.

Earlier studies in southwestern Finland show oak sapwood values of 7–24 (mean 13.9; Baillie et al., 1985) and of 8.32–21.80 within the 95% confidence interval (Briffa, unpublished cit. Haneca et al., 2009). The main difference between that and our southern Finnish and western Estonian data (Table 3) lies in the minimal number of sapwood, and therefore, the mean as well. This may be due to site-specific causes as well as to different sample size. The Finnish sites (Annala and Tammisto) were represented only by 20 cores, among the 98-sample set of the western group. This was considerably less than the 60 cores from 49 trees in the reference data set from Ruissalo and Solböle, located in the Archipelago Sea (Baillie et al., 1985). Our sample sites from Finland are located in the Helsinki region more eastwards along the coast.

Comparing the results with earlier studies, the general trend of decreasing sapwood ring number of oaks towards the east in Europe was confirmed (Baillie et al., 1985; Hillam et al., 1987). For example, the building timber data from England and Wales show the following estimates within the 95% confidence limits: 12–45 sapwood rings for the North and Midlands, 11–41 for Wales and the

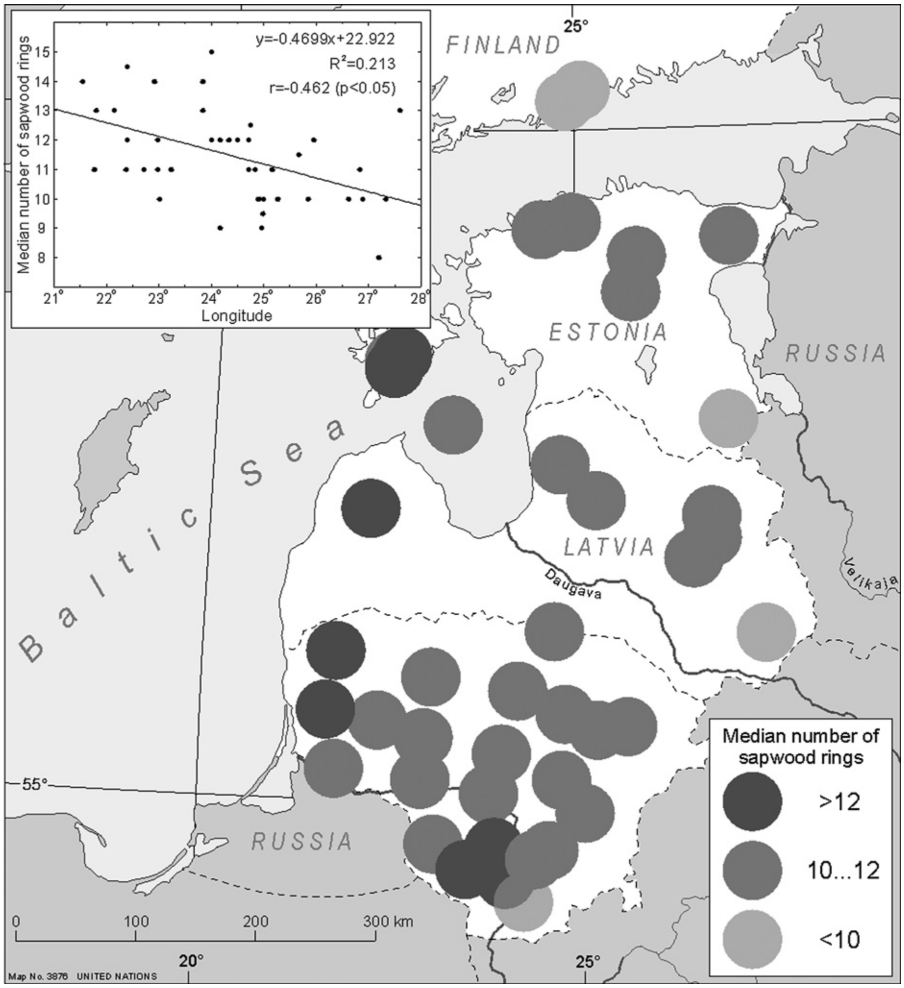

Fig. 6. Distribution of site median sapwood ring numbers in the eastern Baltic region and their relationship with longitude (inset).

Border Countries, 9–41 for the South (Miles, 1997); the living trees from northwest England and North Wales show 13.7–44.6 of sapwood (Hughes et al., 1981). At the same time, the historical timbers from Poland give sapwood estimate of 9–23 rings within 90% confidence limits (Wazny and Eckstein, 1991). The ranges presented in this study derive only from living trees but the tendency towards a decreasing sapwood number is still obvious. Whether this is related to the length of vegetation period, other climatic characteristics or something else, should be analysed in further research. Currently we can observe a slight eastward decrease in the median sapwood number in the Baltic States (Fig. 6), probably following the shift from subatlantic to continental climate. At the same time, the trend along the north–south gradient does not emerge, or in other words, the length of daylight and the growing season are not essential in such a small area. As mentioned, the greatest number of samples used in this work originates from Lithuania according to the natural distribution of the oak population. The historical Baltic timber has proved to originate from even further eastwards, particularly in modern Belarus, Ukraine and Russia (Zunde, 1998–1999). Thus, further investigations are necessary to explain more precisely the variability in the oak sapwood amount in the region.

In addition to geographical variation, it is commonly known that sapwood amount varies depending on age and the intensity of radial growth of the tree as well. As the examined trees have little variance in age, this was not analysed here. Although our data showed a slight decreasing trend in sapwood numbers along the mean ring width increase, the model had a low predictive value (Fig. 5). A similar relationship has been reported before (e.g. Hughes et al., 1981; Wrobel and Eckstein, 1993) but the model is more descriptive for younger oaks (Hillam et al., 1987).

Although the Lithuanian database featured vegetation site types, there were no particular soil or water regime parameters available to compare. Therefore, it was impossible to cluster the sites according to ecological conditions. Actually, this was irrelevant for this work, as site conditions are usually unknown for dating objects. Hence, only general sapwood estimates are presented in this paper.

Nevertheless, the explained oak sapwood estimate of 6–19 rings for the eastern Baltic, based upon the mainly 100–120 years old trees, will give us benchmarks in order to evaluate missing sapwood and thereby increase the dating precision for artefacts made of Baltic oak. So far, the sapwood estimate from Poland, 9–23 rings within 90% confidence limits (e.g. Wazny and Eckstein, 1991) has been used to specify felling dates in the whole eastern Baltic region. For example, the median of 16 rings has been used dating the Vilnius Lower Castle in Lithuania (Pukienė and Ožalas, 2007). When applying our estimates, one has to remember that these have been derived of cores from living trees at breast height. Sapwood increases up the trunk, changes within the cross-section, and enlarges with the ageing of a tree (e.g. Hughes et al., 1981; Hillam et al., 1987), which must be considered while dating historical timber. In addition, factors like seasoning and stockpiling of timber as well as re-use and repair of objects should be taken into account (Miles, 2006).

The regional oak chronologies of living trees should be hereafter extended to the past, investigating local structural, art-historical, and archaeological timber in more detail. Constructing the eastern Baltic chronologies will help to explain the provenance of imported timbers in Western Europe more precisely. The reason why we were heretofore unable to supplement our data with historical material, is the lack of it in the Baltic States, especially in Estonia. All the oak artefacts we have found so far in Estonia, are furniture and commodity details, mostly without or only partial sapwood. There are also some floating chronologies of historical oak from Latvia and Lithuania (Vitas and Zunde, 2008). The Baltic reference chronologies (Hillam and Tyers, 1995) are used to date the panel paintings in Estonia (e.g. Läänelaid and Nurkse, 2006) and the constructions of the Vilnius Lower Castle (Pukienė and Ožalas, 2007).

Conclusions

Based on 660 oak samples it can be stated that there is less sapwood in oaks in the three Baltic countries and Finland than in Western Europe and even in nearby Poland. Thus, sapwood number by the colour criterion ranges from 4 to 21, 6 to 18, and 6 to 19 in southern Finland and western Estonia, in eastern Estonia, Latvia and Lithuania, and in the eastern Baltic region combined, respectively (95% confidence limits). The numbers are higher in the westward sites.

Assuming the similarity between the analysed site chronologies it can be said that oaks in Lithuania have a rather uniform growth pattern while in Estonia and Latvia it is more variable. Further works should focus on extending these local chronologies to the past.

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References

Axelrod, D.I., 1983. Biogeography of Oaks in the Arcto-Tertiary Province. Annals of the Missouri Botanical Garden 70, 629–657.

Baillie, M.G.L., Hillam, J., Briffa, K.R., Brown, D.M., 1985. Re-dating the English art-historical tree-ring chronologies. Nature 315, 317–319.

Bonde, N., Tyers, I., Wazny, T., 1997. Where does the timber come from? Dendrochronological evidence of the timber trade in Northern Europe. In: Sinclair, A., Slater, E., Gowlett, J. (Eds.), Archaeological Sciences 1995. Oxbow Books, Oxford, pp. 201–204.

Crone, A., Fawcett, R., 1998. Dendrochronology, documents and the timber trade: new evidence for the building history of Stirling Castle, Scotland. Medieval Archaeology 42, 68–87.

Daniel, O., 1929. Mets ja metsandus Eestis. Riigimetsade Valitsus, Tallinn, p. 62.

Eckstein, D., Wazny, T., Bauch, J., Klein, P., 1986. New evidence for the dendrochronological dating of Netherlandish paintings. Nature 320, 465–466.

Eckstein, D., Wrobel, D., 2007. Dendrochronological proof of origin of historic timber–retrospect and perspectives. In: Haneca, K., Verheyden, A., Beekmann, H., Gärtner, H., Helle, G., Schleser, G. (Eds.), Proceedings of the Symposium on Tree Rings in Archaeology, Climatology and Ecology, vol. 74, April 20–22, 2006. Tervuren, Belgium, Schriften des Forschungszentrums Jülich, Reihe Umwelt/Environment, pp. 8–20.

Grissino-Mayer, H.D., 2001. Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. Tree-Ring Research 57, 205–221.

Grynaeus, A., 2003. Dendrochronology and environmental history. In: Laszlovszky, J., Szabó, P. (Eds.), People and Nature in Historical Perspective. CEU Press, Budapest, pp. 175–193.

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, 261–271.

Haneca, K., Čufar, K., Beeckman, H., 2009. Oaks, tree-rings and wooden cultural heritage: a review of the main characteristics and applications of oak dendrochronology in Europe. Journal of Archaeological Science 36, 1–11.

Hillam, J., Morgan, R.A., Tyers, I., 1987. Sapwood estimates and the dating of short ring sequences. In: Ward, R.G.W. (Ed.), Applications of Tree-ring Studies: Current Research in Dendrochronology and Related Subjects. BAR International Series 333, Oxford, pp. 165–185.

Hillam, J., Tyers, I., 1995. Reliability and repeatability in dendrochronological analysis: tests using the Fletcher archive of panel-painting data. Archaeometry 37, 395–405.

Hollstein, E., 1980. Mitteleuropäische Eichenchronologie. Verlag Philipp von Zabern, Mainz, p. 273.

Holmes, R.L., 1983. Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bulletin 43, 69–78.

Hughes, M.K., Milsom, S.J., Leggett, P.A., 1981. Sapwood estimates in the interpretation of tree-ring dates. Journal of Archaeological Science 8, 381–390.

Hupel, A.W., 1777. Topographische Nachrichten von Lief- und Ehstland. J.F. Hartknoch, Riga, p. 544.

Kairaitis, J., 1978. Chronologies of oak (*Quercus robur* L.) stands in Lithuania SSR. In: Bitvinskas, T. (Ed.), Dendroclimatochronological Scales of the Soviet Union. Institute of Botany of the Academy of Sciences of the Lithuanian S.S.R, Kaunas, pp. 5–26 (in Russian).

Kremser, W., 1998. Epochen der Forstgeschichte Estlands. Tallinna Raamatutrükikoda, Tallinn, p. 280.

Laasimer, L., 1965. Eesti NSV taimkate. Valgus, Tallinn, p. 398.

Läänelaid, A., Nurkse, A., 2006. Dating of a 17th century painting by tree rings of Baltic oak. Baltic Forestry 12, 117–121.

Metsakaitse- ja Metsauuenduskeskus (Ed.), 2009. Aastaraamat Mets 2008. Yearbook Forest 2008. Keskkonnaministeerium, Metsakaitse- ja Metsauuenduskeskus, Tartu, p. 213.

Miles, D., 1997. The interpretation, presentation and use of tree-ring dates. Vernacular Architecture 28, 40–56.

Miles, D., 2006. Refinements in the interpretation of tree-ring dates for oak building timbers in England and Wales. Vernacular Architecture 37, 84–96.

Murmanis, L., 1975. Formation of tyloses in felled *Quercus rubra* L. Wood Science and Technology 9, 3–14.

Pukienė, R., Ožalas, E., 2007. Medieval oak chronology from the Vilnius lower castle. Dendrochronologia 24, 137–143.

Randsborg, K., Christensen, K., 2006. XII. The number of sapwood rings in the oak trees. Acta Archaeologica 77, 185–186.

Rybníček, M., Vavrčík, H., Hubený, R., 2006. Determination of the number of sapwood annual rings in oak in the region of southern Moravia. Journal of Forest Science 52, 141–146.

Savill, P.S., Kanowski, P.J., Gourlay, I.D., Jarvis, A.R., 1993. Short note: genetic and intra-tree variation in the number of sapwood rings in *Quercus robur* and *Q. petraea*. Silvae Genetica 42, 371–375.

Sochava, V.B., Isachenko, T.I., Karpenko, A.S., 1960. Division of the Baltic Soviet republics into vegetational zones based on the medium-scale geobotanical map of this territory. Botanicheskii Zhurnal 45, 795–804 (in Russian, with English summary).

Soom, A., 1940. Narva metsakaubandus ja metsatööstus XVII sajandi lõpul. The Estonian Historical Journal 2, 57–73.

State Forest Survey Service, 2009. Lithuanian Statistical Yearbook of Forestry. State Forest Survey Service, Kaunas, p. 151.

Vitas, A., Zunde, M., 2008. Dendrochronological investigation on historical English oak (*Quercus robur* L.) in Lithuania and Latvia: problems and potential. In: Elferts, D., Brumelis, G., Gärtner, H., Helle, G., Schleser, G. (Eds.), TRACE – Tree Rings in Archaeology, Climatology and Ecology, vol. 6: Proceedings of the DENDROSYMPOSIUM 2007, May 3rd–6th 2007. Scientific Technical Report STR 08/05. Riga, Latvia, GFZ Potsdam, pp. 124–127.

Wazny, T., Eckstein, D., 1987. Der Holzhandel von Danzig/Gdansk–Geschichte, Umfang und Reichweite. Holz als Roh- und Werkstoff 45, 509–513.

Wazny, T., Eckstein, D., 1991. The dendrochronological signal of oak (*Quercus* spp.) in Poland. Dendrochronologia 9, 181–191.

Wazny, T., 2002. Baltic timber in western Europe – an exciting dendrochronological question. Dendrochronologia 20, 313–320.

Wazny, T., 2005. The origin, assortments and transport of Baltic timber. In: van de Velde, C., Beeckman, H., van Acker, J., 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, pp. 115–126.

Wrobel, S., Eckstein, D., 1993. The capability of joint dendrochronological–architectural large-scale studies. In: Storsletten, O., Thun, T. (Eds.), Dendrochronology and the Investigation of Buildings. Proceedings of an International Seminar at the Academy of Science and Letters, 1–2 November 1991, Riksantikvarens Rapporter 22. Oslo, pp. 28–42.

Zunde, M., 1998–1999. Timber export from Old Riga and its impact on dendrochronological dating in Europe. Dendrochronologia 16–17, 119–130.