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# RADIOCARBON AND DENDROCHRONOLOGICAL DATING OF SUB-FOSSIL OAKS FROM SMARHOŃ RIVERINE SEDIMENTS

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**Abstract:** Sub-fossil oaks from Smarhoń in Belarus have been investigated and tree-ring chronologies were assembled. According to radiocarbon dating, the oldest oak grew from 5782–5612 cal BC and the youngest from 1575–1747 cal AD. Radiocarbon and dendrochronological dating of 97 samples, four single series, 10 mean curves (containing 2–9 series) and three chronologies (10–25 series) were constructed. The longest chronology (No. 16), covering 549 years, was absolutely dated against various oak chronologies of Polish/Baltic origin to AD 778–1326. Germination and dying-off phases were assessed from the three best replicated chronologies. A spectral analysis of the chronologies provided cycles of variable length, on average of 25 years.

**Keywords:** sub-fossil oak, tree-ring widths, dendrochronology, radiocarbon, Smarhoń.

## 1. INTRODUCTION

Long-term oak (*Quercus* spp.) chronologies have been successfully applied for reconstructing environmental, hydrological and climatic conditions during the Holocene (Briffa and Matthews, 2002; Kalicki and Krąpiec, 1995; Spurk *et al.*, 2002) as well as for radiocarbon calibration (Spurk *et al.*, 1998). Sub-fossil wood excavated from riverine sediments has been one of the sources for constructing millennia-long oak chronologies in Europe. Such long-term oak chronologies have, for example, been developed for the Czech Republic (Kolar *et al.*, 2009), Germany (Delorme, 1977); Ireland (Pilcher *et al.*, 1984), Poland (Starkel and Krąpiec, 1995), Romania (Dumitriu-Tataranu and Popescu, 1988) and other countries.

Sub-fossil oak wood in the Baltic States and Belarus is not yet adequately explored by dendrochronology (Pukienė, 2003; Vitas and Zunde, 2007). The majority of studies until now were limited by a small number of samples available (Vitas and Zunde, 2007).

Sub-fossil oaks excavated in the vicinity of Smarhoń (Belarus) have been in the attention of scientists since the 1960s (Bitvinskas *et al.*, 1972). Initial difficulties were caused by the lack of sufficiently precise radiocarbon dates and missing oak reference chronologies in the Baltic region (Bitvinskas *et al.*, 1978a; 1978b; Bitvinskas, 1984).

The aim of this study is to explore the tree-ring series from sub-fossil oaks found in Smarhoń riverine deposits, to construct precisely dated chronologies documenting forest history in Lithuania during the Holocene, and to assess its potential as reference chronologies for Baltic oak timber.

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## 2. METHODS

### Field description and materials

The research site (Smarhoń in Belarusian language, Smurgainys in Lithuanian) is located in the Grodno district in Belarus, 85 km south-east from the Lithuanian capital Vilnius and 52 km from the present state border of Lithuania (**Fig. 1**). Trunks of oak were excavated in the 1960s and 1970s during the exploitation of a gravel pit, located on the bank of the river Viliya (Neris), approximately 10 km to the east from the Smarhoń town (Bitvinskas, 1978a; 1978b; 1984). The trunks buried under the gravel by the meandering river (Bitvinskas, 1974; 1978a) were excavated in huge amounts. Besides oak, wood of conifers was also identified but not collected.

The trunks were of variable size; some samples exceeded 1.5 m in diameter. They were found at 3–8 m depth and usually pulled out with remains of the stump and big roots (**Fig. 2**). The wood was well preserved under the gravel (Bitvinskas *et al.*, 1972). The majority of cross-sections were collected in 1968, 1969, 1970, 1971, and 1972; in total 129 samples were obtained. At present, 109 cross-sections are being stored in the repository of the Laboratory. The wood of twenty samples was completely used for earlier isotope studies.


**Fig. 1.** *Research site in Belarus produced by Google maps.*

**Fig. 2.** *Oak trunk at Smarhon site investigated by workers of the Dendrochronological Laboratory; photo from the repository of the Group of Dendroclimatology and Radiometrics, Kaunas.*

### Methods

In the Soviet period, part of the samples was dated in several radiocarbon laboratories by using mainly self-made radiation counters: University of Tbilisi, Ural Pedagogical Institute and Institute of Botany in Vilnius (Bitvinskas *et al.*, 1978a; 1978b; Bitvinskas, 1984, see also list of $^{14}$C dates in the Appendix). At present, the majority of samples has been dated by the Group of Dendroclimatology and Radiometrics, Environmental Research Centre, Faculty of Nature Sciences, Vytautas Magnus University (Kaunas) and by the Radioisotope Research Laboratory, Institute of Geology and Geography, Nature Research Centre (Vilnius) by using commercially produced equipment. The $^{14}$C dates were calibrated to calendar years (Appendix) by using the OxCal 4.2 program (Bronk Ramsey *et al.*, 2010) with the IntCal13 calibration curve (Reimer *et al.*, 2013).

The quality of the radiocarbon dates was checked by applying the following criteria: (i) the most recent date was assumed to be more precise than the earlier ones if the sample was dated several times; (ii) if the sample was dated for more than three times, dates varying for more than 200 years were rejected; (iii) the dates were checked again after dendrochronological dates became available. The middle ring in the dated wood section was established and dates varying more than 100 years from the average were removed. The following principles have proved to be adequate when the chronology No. 16 was later absolutely dated with a 32-year bias in comparison to the average radiocarbon date.

The tree-ring widths of the sub-fossil oaks were measured using a Lintab tree-ring measuring table and Tsap computer program (F. Rinn Engineering Office and Distribution, Heidelberg). The tree-ring-width series were synchronized by visual comparison (Eckstein, 1987) of the ring-width graphs and statistically by calculating the coefficients of similarity "Gleichläufigkeit", correlation coefficients and t-values (Eckstein and Bauch, 1969; Baillie and Pilcher, 1973). Common statistics used in dendrochronology were calculated, such as mean tree-ring widths, similarity between the series, and mean sensitivity. Several European oak chronologies were used for the absolute dating of the floating chronology No. 16: East Pomerania, Poland (T. Wazny), Vilquro1, Lithuania (Pukienė, 2002), Baltic1 (Hillam and Tyers, 1995). The germination and die-off phases were assessed from three chronologies: No 4 (4191–3830 cal BC), No 10 (1137–716 cal BC) and No 16 (AD 778–1326). Each chronology is compiled from at least 10 individual series (**Table 1**).

Cycles expressed in the tree-ring chronologies were determined by using a single series Fourier (spectral) analysis (Statistica 6.0, StatSoft Inc.).

Event years were assessed from the absolutely dated chronology No. 16. The calculation using program Weiser (Gonzales, 2001) was performed for the period AD 872–1266 which was covered by at least three tree-ring series. The Zi index value (Schweingruber *et al.* 1990) was set to ≤ – 0.75 (narrow rings) and ≥ 0.75 (wide rings) and the threshold for pointer years was set to 80%. The higher values for both indicators were applied because of a comparatively small number of trees (3–19). The climatic anomalies from AD 1000–1266 were assessed from the compendium "The unusual natural phenomena in the territory of Lithuania in the 11th–20th centuries" by Bukantis (1998) which covers all chronicles available.

## 3. RESULTS

### Dating and chronology building

The number of data for our study was limited to 122 cross-sections. The tree-ring widths from 109 samples were measured. In addition, we used old measurements of 13 samples which were no longer available. Samples containing less than 80 rings (eight samples) or measurement with a lower measuring accuracy (0.05 instead of 0.01 mm), and lack of information about measuring direction of earlier measurements (five samples) were excluded from further analysis. Moreover, 12 samples failed to cross-date with any other samples. Hence, 97 samples were included into the mean curves and chronologies.

In total, 143 radiocarbon dates for 79 samples (18 samples were not dated) were available (Appendix), i.e. nearly two dates per sample (**Table 1**). According to cross-dating and radiocarbon dating, these 97 samples were arranged into 17 groups containing one to 25 series each (**Fig. 3**). The majority of samples were dated at least twice and some with four to six repetitions (Appendix). The percentage of reliable dates reaches 60–80%. The oldest tree grew approximately from 5782–5612 cal BC and the youngest from 1575–1747 cal AD (**Table 1**).

The longest gap, according to radiocarbon dates, exists between 2987 and 1137 cal BC; a short sample grew around 1900–1817 cal BC (**Table 1**, **Fig. 3**). The youngest sample (No. 17) was dated twice in two laboratories and the dates are 1653–1954 and 1524–1954 cal AD within 95.4% probability.

Tree-ring series are characterized by a high mean similarity, ranging from 0.50–0.70 for the majority of the samples in the chronologies (**Table 2**). A medium sensitivity (0.21–0.25) is typical of the majority of chronologies. The longest chronology, spanning 549 years, was radiocarbon-dated to 810–1358 cal AD.

A very high agreement between some samples (30 out of 97) indicates the possibility of duplicates in the collection, i.e. several samples were taken from the same trunk. The duplicates are characterized by correlation values from 0.70–0.94, "Gleichläufigkeit" from 72–94% and t-values from 9.6–34.8.

The chronology No. 16 was absolute dated against East Pomerania, Vilcuro1 and Baltic1 reference chronologies to AD 778–1326 (t = 5.4, 7.0 and 8.4, respectively) and was shifted by 32 years backwards in time (**Table 3**, **Fig. 4**).

**Table 1.** *Radiocarbon dating of floating series and chronologies; mean radiocarbon dates were based on reliably dated samples.*

| No | Samples | Dated samples | Number of dates | Reliable dates | Reliably dated samples | Mean radiocarbon dates (cal BC/AD) |
|---|---|---|---|---|---|---|
| **1** | 1 | 1 | 2 | 2 | 1 | 5782–5612 BC |
| **2** | 1 | 1 | 2 | 2 | 1 | 5546–5325 BC |
| **3** | 2 | 2 | 3 | 3 | 2 | 4669–4496 BC |
| **4** | 14 | 12 | 22 | 20 | 11 | 4191–3830 BC |
| **5** | 2 | 2 | 4 | 4 | 2 | 3542–3263 BC |
| **6** | 3 | 2 | 2 | 2 | 2 | 3428–3246 BC |
| **7** | 2 | 2 | 3 | 1 | 1 | 3254–3088 BC |
| **8** | 3 | 2 | 6 | 4 | 2 | 3097–2987 BC |
| **9** | 1 | 1 | 2 | 2 | 1 | 1900–1817 BC |
| **10** | 10 | 7 | 8 | 6 | 6 | 1137–716 BC |
| **11** | 2 | 2 | 3 | 1 | 1 | 595–382 BC |
| **12** | 9 | 8 | 24 | 15 | 7 | 320 BC–AD 162 |
| **13** | 9 | 6 | 7 | 6 | 5 | AD 190–421 |
| **14** | 8 | 7 | 10 | 8 | 6 | AD 246–556 |
| **15** | 4 | 4 | 10 | 7 | 4 | AD 547–718 |
| **16** | 25 | 18 | 33 | 29 | 17 | AD 810–1358 |
| **17** | 1 | 1 | 2 | 2 | 1 | AD 1575–1747 |

**Table 2.** *Tree-ring characteristics of floating mean curves; similarity was calculated for mean curves and chronologies, comprised from at least two series; N/A — not available.*

| No | Mean tree-ring width (mm) | Mean sensitivity | Length of the chronology (years) | Mean similarity (r) |
|---|---|---|---|---|
| **1** | 1.08 | 0.25 | 171 | N/A |
| **2** | 1.19 | 0.23 | 222 | N/A |
| **3** | 1.65 | 0.24 | 174 | 0.79 |
| **4** | 1.82 | 0.23 | 362 | 0.60 |
| **5** | 1.18 | 0.26 | 280 | 0.34 |
| **6** | 1.39 | 0.18 | 183 | 0.55 |
| **7** | 1.82 | 0.20 | 167 | 0.63 |
| **8** | 2.23 | 0.21 | 111 | 0.58 |
| **9** | 2.12 | 0.24 | 84 | N/A |
| **10** | 1.18 | 0.21 | 422 | 0.68 |
| **11** | 1.58 | 0.24 | 214 | 0.52 |
| **12** | 1.81 | 0.23 | 483 | 0.66 |
| **13** | 1.74 | 0.24 | 232 | 0.66 |
| **14** | 1.59 | 0.27 | 311 | 0.57 |
| **15** | 1.77 | 0.27 | 172 | 0.67 |
| **16** | 1.49 | 0.21 | 549 | 0.68 |
| **17** | 1.68 | 0.24 | 173 | N/A |

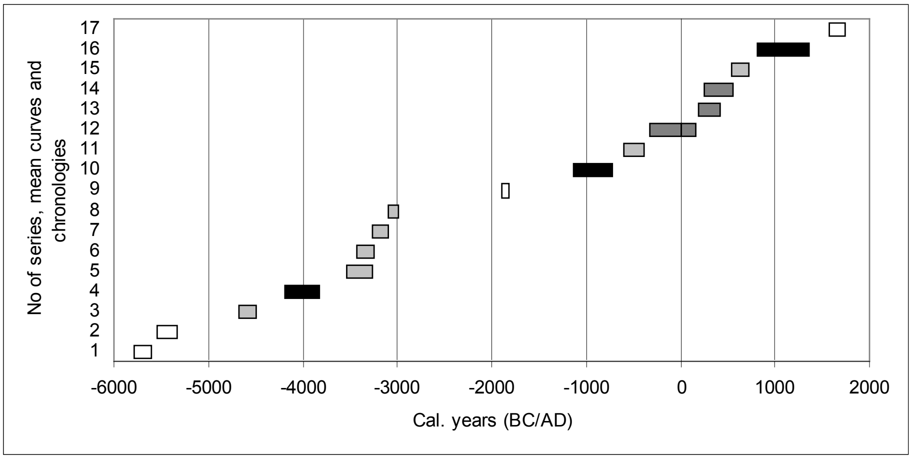


**Fig. 3.** *Floating individual tree-ring width series, mean curves and chronologies; white bars indicate individual series, light grey — mean curves from 2–5 and dark grey — 5–10 samples, black — chronologies of at least 10 samples.*

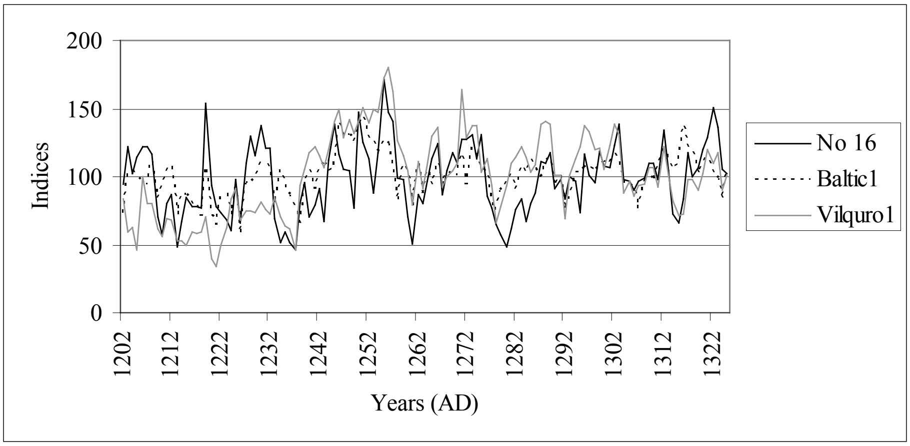


**Fig. 4.** *Tree-ring width pattern of chronologies No. 16, Vilquro 1 and Baltic 1 from 1202–1326 AD.*

**Table 3.** *Similarity of the chronology No. 16 (AD 778–1326) against Vilquro1, Pomerania and Baltic1 chronologies; OVL — overlap (years), GLK — coefficient of similarity, R — coefficient of correlation, TV — t-test.*

| Name | Span (AD) | OVL | GLK | R | TV |
|---|---|---|---|---|---|
| Pomerania, Poland (T. Wazny) | 778–1326 | 549 | 61 | 0.23 | 5.4 |
| Vilquro1, Vilnius, Lithuania (R. Pukienė) | 1202–1326 | 125 | 67 | 0.54 | 7.0 |
| Baltic1 (J. Hillam, I. Tyers) | 1156–1326 | 171 | 65 | 0.54 | 8.4 |

### Germination and die-off (GDO) phases in the chronologies

The replication (number of trees through time) of each chronology (**Fig. 5**) was divided into three phases: a) intense germination (G), the number of trees is increasing because of favourable environmental conditions, b) plateau phase (P), the number of samples is stable, trees have reached their mature age and new trees have not germinated because of worsened growth conditions, c) dying-off (DO) phase, dying of trees with different intensity due to a deterioration of environmental conditions.

The germination in the oldest chronology (No. 4) lasted from 4191–4084 cal BC and was followed by a short plateau phase from 4083–3960 cal BC (**Fig. 5**). The DO was prolonged in comparison to chronologies No. 10 and 14 and lasted for 129 years (from 3959–3830 cal BC). The chronology No. 10 has reached a plateau phase already after 75 years (1137–1062 cal BC); this phase has lasted from 1061–849 cal BC. The trees have died from 848–716 cal BC. The germination of trees included in the chronology No. 14 lasted from AD 778–970. The plateau phase was short (AD 971–1031), and then a rapid DO phase took place (AD 1032–1089). Shortly after, a short germination with a plateau phase has repeated from AD 1102–1157. Favourable germination conditions occurred from AD 1170–1244 BC. The last extremely rapid DO event took place from AD 1245–1270; during this 25-year period, the number of trees has decreased from seven to one (**Fig. 5**).

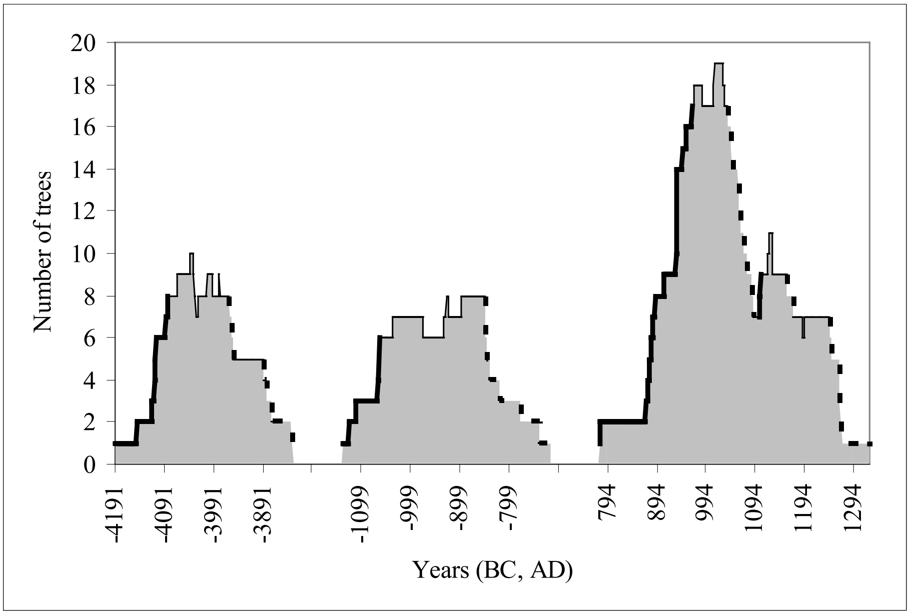


**Fig. 5.** *Replication (number of trees) of Smarhon oak chronologies No. 4, 10 and 16. Regeneration phase is shown in solid line, plateau phase — thin line and declining — solid dotted line.*

### Spectral density in oak chronologies

Ten major and statistically significant cyclical components in the oak chronologies were identified. The cycles range from 3 to 241 years and the average length from 11 to 56 years. Hence, the length of cycles is variable for individual chronologies. Similar cyclical components in two or three adjacent chronologies indicate that the environmental conditions reflected in the changes of tree-ring widths repeated with the same frequency for longer time spans. For the oldest chronologies (5782–5612, 5546–5325 and 4669–4496 cal BC), the average length of the cycles varied from 12–23 years. In 4191–3830, 3542–3263, 3428–3246 and 3254–3088 cal BC the length has increased to 23–39 years. Shorter 11–15-year cycles were characteristic for 3097–2987 and 1900–1817 cal BC, and then increased to 30–56 years in 1137–716 and 595–382 cal BC (**Table 4**). The following decrease in cycle length was a long-lasting event (320 cal BC–162 cal AD and 190–421 cal AD). This was followed by the increased length of cycles to 27–38 years in the last four chronologies (246–556 cal AD, 547–718 cal AD, AD 778–1326 and 1575–1747 cal AD).

### Event years

There were 24 negative and 20 positive event years from AD 871–1266 (**Table 5**). Because the information on climatic anomalies before AD 1000 is incomplete, the climatic evidences were assessed only from AD 1000–1266.

The occurrence of negative event years mostly coincided with periods of cold winters, e.g. from 1045–1047 and in 1125. In 1213, summer drought was responsible for the narrow tree-ring width. The growth increases (positive event years) could not be related to climatic phenomena because the chronicles usually highlight events causing negative impacts on human health or agricultural harvests and do not point on favourable climatic conditions.

## 4. DISCUSSION

The earlier radiocarbon age determinations of subfossil oaks already indicated that the dates are dispersed over the whole Holocene (Bitvinskas *et al.*, 1978b; Bitvinskas, 1984). Our investigation confirmed that the accumulation of oaks in the Viliya river valley was not a constant process, and that meandering was common for the river in the vicinity of Smarhoń. Furthermore, an

**Table 4.** *Major statistically significant cycles in the oak chronologies.*

| No | Period (BC/AD) | Cyclical components (years) |
|---|---|---|
| 1 | 5782–5612 cal BC | 3, 11, 12, 17, 21, 24, 42, 57, 85, 170 |
| 2 | 5546–5325 cal BC | 8, 9, 12, 12, 13, 16, 22, 25, 32, 56 |
| 3 | 4669–4496 cal BC | 4, 4, 5, 8, 10, 13, 17, 35, 44, 58 |
| 4 | 4191–3830 cal BC | 15, 17, 26, 28, 30, 33, 40, 72, 90, 121 |
| 5 | 3542–3263 cal BC | 8, 11, 19, 26, 31, 47, 56, 70, 93, 140 |
| 6 | 3428–3246 cal BC | 9, 12, 13, 18, 20, 26, 30, 36, 46, 182 |
| 7 | 3254–3088 cal BC | 6, 11, 15, 17, 24, 28, 33, 55, 83, 166 |
| 8 | 3097–2987 cal BC | 4, 6, 7, 8, 12, 18, 22, 37, 55, 110 |
| 9 | 1900–1817 cal BC | 6, 6, 7, 8, 10, 12, 17, 28, 42, 84 |
| 10 | 1137–716 cal BC | 7, 14, 15, 35, 42, 70, 84, 106, 141, 211 |
| 11 | 595–382 cal BC | 9, 13, 13, 15, 24, 36, 43, 54, 71, 214 |
| 12 | 320 cal BC–cal AD 162 | 5, 10, 10, 12, 17, 18, 27, 69, 161, 241 |
| 13 | cal AD 190–421 | 5, 8, 8, 12, 16, 23, 26, 58, 77, 232 |
| 14 | cal AD 246–556 | 9, 17, 18, 26, 31, 44, 52, 62, 78, 103 |
| 15 | cal AD 547–718 | 4, 5, 8, 11, 14, 29, 43, 57, 86, 172 |
| 16 | AD 778–1326 | 11, 15, 17, 24, 25, 39, 42, 55, 68, 91 |
| 17 | cal AD 1575–1747 | 12, 14, 16, 25, 29, 34, 43, 57, 86, 172 |

**Table 5.** *Event years in the chronology No. 16 (AD 871–1266).*

| Event year | | No of trees | Percentage of trees (%) | Event year | | No of trees | Percentage of trees (%) |
|---|---|---|---|---|---|---|---|
| **875** | - | 3 | 100 | **1051** | - | 14 | 93 |
| **894** | - | 8 | 88 | **1066** | - | 11 | 100 |
| **900** | + | 8 | 100 | **1068** | + | 11 | 82 |
| **902** | - | 8 | 88 | **1095** | + | 7 | 100 |
| **911** | + | 9 | 100 | **1107** | + | 9 | 89 |
| **912** | + | 9 | 89 | **1116** | - | 9 | 89 |
| **918** | + | 9 | 100 | **1122** | + | 10 | 90 |
| **919** | + | 9 | 100 | **1125** | - | 11 | 100 |
| **922** | - | 9 | 100 | **1136** | + | 9 | 100 |
| **928** | - | 9 | 100 | **1147** | - | 9 | 89 |
| **930** | + | 9 | 89 | **1150** | + | 9 | 89 |
| **931** | - | 9 | 100 | **1174** | + | 7 | 86 |
| **939** | - | 14 | 100 | **1178** | - | 7 | 100 |
| **960** | - | 16 | 81 | **1192** | - | 6 | 100 |
| **962** | + | 16 | 88 | **1201** | + | 7 | 86 |
| **963** | + | 16 | 81 | **1213** | - | 7 | 100 |
| **965** | - | 17 | 100 | **1219** | + | 7 | 100 |
| **980** | + | 18 | 94 | **1226** | - | 7 | 86 |
| **984** | - | 18 | 83 | **1243** | - | 7 | 86 |
| **999** | - | 17 | 100 | **1245** | + | 6 | 100 |
| **1026** | - | 19 | 90 | **1250** | + | 5 | 100 |
| **1046** | - | 14 | 93 | **1253** | - | 5 | 100 |

erosion of the eastern bank was observed in the 1970s by Bitvinskas and Kairaitis (1975). Cross-dating of the samples has indicated several periods during the Holocene with much higher numbers of accumulated oak trunks, e.g. in 4191–3830 cal BC, 1137–716 cal BC and 778–1326 AD. Becker (1972) has suggested a catastrophic flood event in the Subatlantic period. Later, channel migration (Florek, 1984) and lateral erosion (Kalicki, 1991; Spurk *et al.*, 2002) were proposed, supported by the intensified river activity (Becker, 1982; Kalicki, 2006) and water discharge (Spurk *et al.*, 2002) during wet periods (Krąpiec 1994). The human activity during the last 2000 years in the Vistula and Main river valleys has also been acknowledged (Krąpiec, 1994; Spurk *et al.*, 2002). Spurk *et al.* (2002) observed deposition anomalies triggered by a positive North Atlantic Oscillation (NAO) phase.

## Neolithic period

The tree-ring series from 5546–5325 and 4669–4496 cal BC coincide with a gravel accumulation phase in Germany from 5500–4500 BC (Spurk *et al.*, 1998). The period covered by the chronology No. 4 (4191–3830 cal BC) was characterized by a low deposition rate of oaks in Germany around 4100 BC. Wet conditions in Europe and greater depositions of river oaks in England are evidence for a higher runoff. The Greenland temperatures inferred from ice-cores show cooler conditions (Spurk *et al.*, 2002). This climate anomaly was caused by the Bond cycle which is associated with reduced thermohaline circulation and cooled the climate over Europe (Boecker *et al.*, 1985). However, chronology No. 4 based on 20 radiocarbon dates (**Table 1**) has shown that oaks at Smarhoń have germinated from 4191–4084 cal BC, while the DO phase was prolonged and lasted for 129 years (from 3959–3830 cal BC). Kalicki (2006) have documented an increased Vistula river activity from 6600–6000 BP.

The oaks dated to 3428–3246, 3254–3088 and 3097–2987 cal BC correspond to the floating chronologies derived for the Vistula valley by Krąpiec (1994), dated to 3385–3250 cal BC and 3168–2980 cal BC. An accumulation phase in the rivers of Belarus was recorded in 5050–5700 BP (Kalicki, 2006). The oak deposition anomalies in Germany in 2700, 2300 and 1700 BC (Spurk *et al.*, 2002) match with the longest gap in our dataset between 3060 and 1100 cal BC.

## Bronze Age

The chronology No. 10 (1137–716 cal BC), composed of 10 trees, represents cooler and wetter climate in Europe around 800 BC (van Geel *et al.*, 1998). Chronology from the Odra valley (1795–612 BC) in Poland was also compiled for this period (Krąpiec, 2001). The increased river activity near Cracow was documented from 3500–3000 BP (Kalicki, 2006).

## Iron Age

Several local oak chronologies have been compiled in Poland: Vistula 1 (174 BC–304 AD), Standard 1 (261–823 AD), Wielkopolska (449–1994 AD), Cracovia 1 (729–1141 AD), Lower Silesia (780–1994 AD), Małopolska (910–1977 AD) and Vistula 2 (1100–1529 AD) (Krąpiec, 1992; 1998; Starkel and Krąpiec, 1995). According to Krąpiec (1994), the accumulation of oaks in the Vistula valley took place from 375–325 BC, AD 425–575, AD 900–1150 and AD 1200–1325. At the Branice-Stryjów site, oaks were accumulated from 50 BC–AD 175, AD 950–1028 and AD 1210–1493 (Krąpiec, 1992). An intensified meandering activity was observed at the Kędzierz and Kujawy sites, Poland, from AD 408–540 and AD 440–560, respectively (Starkel and Krąpiec, 1995). This period is covered by one mean curve (No. 11). The climate in Germany between 300 BC and AD 950 was wetter. Therefore, accumulation of gravel was recorded from AD 400–1000 (Spurk *et al.*, 2002). This coincides with major dying phases of oaks in Germany in 300 and 100 BC (Delorme *et al.*, 1983). The Iron Age is represented by several well-replicated mean curves (No. 12, 13, 14) and by chronology No. 16, which coincides with the accumulation phases documented in rivers of Central Europe from 2200–1800 BP and around 1000 BP (Kalicki, 2006).

According to Krąpiec (1994), the accumulation of oaks in the Vistula took place until AD 1550. Hence, sample No. 17 dated to 1575–1747 cal AD, taking into account a possible dating bias of ± 100 years, might be derived from an accumulation period, recorded for the Vistula river.

During higher oak accumulation phases at Smarhoń, longer cyclical components, 32 and 23-years were identified in the tree-ring patterns (**Tables 1** and **4**). Longer cycles in tree-ring series are usually related to wet growing conditions as shown by Stasytytė *et al.* (2005) and Vitas (2009, 2010). This is in agreement with findings in Europe indicating wetter conditions and a higher river runoff (van Geel *et al.*, 1998; Krąpiec, 1994; Spurk *et al.*, 2002; Starkel and Krąpiec, 1995) during periods of high oak accumulation rates at Smarhoń.

## 5. CONCLUSIONS

Our study was limited by the small number of samples, and by missing data on their finding depth, soil type and position to the river channel. This fact did not allow answering questions related to the river meandering activity during different periods of the Holocene. However, the chronologies, especially the absolutely dated chronology No. 16, are an important contribution to oak dendrochronology in the Baltic region and are valuable for the dating of oak timber over the Baltic territory or imported timber from the Baltic region.

Our investigation has demonstrated that sub-fossil oaks at Smarhoń grew at least from 5782 cal BC to AD 1326. The high deposition rate of oak trunks in 4191–3830 and 1137–716 cal BC, 320 cal BC–162 cal AD, 190–421 cal AD and 246–556 cal AD as well as AD 778–1326 is closely related to an increased river runoff and wet periods in Europe. The oak chronology No. 16 was absolutely dated to AD 778–1326. This successful dating against several well-replicated chronologies indicates that climatic extremes triggering oak growth decrease or increase at Smarhoń were in operation over vast territories of Eastern Europe.

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## APPENDIX

The **Table S1** — Results of the radiocarbon analyses used for dating the floating chronologies — is provided as Supplementary Material and is available in electronic version of this article at http://dx.doi.org/10.2478/s13386-013-0150-5.

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