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SUB-FOSSIL WOOD FROM THE RUCIANKA RAISED BOG (NE POLAND) AS AN INDICATOR OF CLIMATIC CHANGES IN THE FIRST MILLENNIUM BC

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Abstract: The dendrochronological studies were carried out on very well preserved sub-fossil pine wood found in the biogenic deposits of the Rucianka raised bog (NE Poland). Local floating chronologies, covering the period 990-460 cal BC, were dated on the basis of radiocarbon analyses. Growth depressions in annual tree-ring widths indicated periodical deterioration of the environmental conditions, which affected tree growth. Identified germination and dying-off phases (GDO) should be related to the wetter climatic periods. The extinction of trees took place during periods of higher groundwater level which, in turn, caused favourable conditions for growth of young pines.

Keywords: dendrochronology, sub-fossil wood, *Pinus sylvestris*, Holocene, NE Poland.

1. INTRODUCTION

Pieces of wood very well preserved in peat could be a source of information about environmental conditions in the past. The tree-ring width changes reflected conditions of the environment and could be analyzed with the dendrochronological method. This method was applied in research on sub-fossil wood from numerous individual sites in Europe (Pilcher *et al.*, 1995; Piksryte, 1996 and Pukienė, 2001) and in regional studies, in which many peat bogs were examined (Bridge *et al.*, 1990; Moir *et al.*, 2010; Eckstein *et al.*, 2009, 2011 and Edvardsson *et al.*, 2012). In this study the dendrochronological method was used to analyze the tree-ring patterns of pine wood from the Rucianka bog, which is one of several dozen raised bogs in N and NE Poland. The aim of the research was to build the radiocarbon dated floating chronologies, as well as to reconstruct the woodland phases on the raised bog connected with hydrological regime and climatic variability.

2. MATERIALS

The Rucianka raised bog, located in NE Poland (54°15'22"N, 19°44'14"E), covers an area of 240 ha. Genetically the bog is connected with the Vistulian glaciation and was formed in a trough originally filled by a lake. The bog consists of fen and sphagnum peat developed on sandy deposits. Primarily the average peat thickness was around 2.7 m, while the maximum was 4.5 m. Exploitation of the peat started before the Second World War and after 1949 was continued by the state-owned enterprise (Pawłat, 1996). At present, 60% of the total

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bog area consists of a peat mine, where the peat excavation is conducted on half of the area, while the post-mining pit and already reclaimed lands cover the other half.

For dendrochronological analysis 41 pine wood samples and one oak sample were taken from wood heaps located along the harvesting site using machine chain saw (**Figs. 1B**, **C**). Samples were collected preferably from trunks above the roots and from other parts of trunks, avoiding roots and branches. In the collected materials reaction wood, narrow-ringed wood, and fire scars could be observed, as well as the last ring (the youngest, external increment) in some samples. Almost half of wooden discs counts from 100 to 150 tree rings, whereas less than 100 and more than 150 were observed at respectively 13 and 9 samples (**Table 1**). The biggest potential for dendrochronological research have wooden samples counting 150-200 and more tree rings (Pilcher *et al*., 1995).

3. METHODS

In this study the standard dendrochronological methodology was used (Schweingruber, 1988; Zielski and Krąpiec, 2004). Sample preparation was made using Olfa blades, which made tree-rings boundary visible under the microscope on transversal cross-section along several radial sections. Measurements of tree-ring widths were carried out with a precision of 0.01 mm using DENDROLAB 1.0 apparatus and program Quercus (Walanus, 2005). In each sample, tree-ring widths were measured twice, along different radial sections, and then the values obtained were averaged to construct an individual curve for each tree. When narrow-ringed wood and missing rings were observed, measurements along two different radii were insufficient. In some cases tree-ring widths were measured up to ten times along several radial sections. Statistical analysis of individual series of tree-ring widths was made using TREE-RINGS program set (Krawczyk and Krąpiec, 1995), in order to construct local chronologies. The tree-ring series were mutually cross-dated, and finally checked by visual comparisons of their dendrographs. Local chronologies were constructed on the basis of samples for which 't' value and correlation coefficient 'r' were the highest (Baillie and Pilcher, 1973). The correctness of the chronologies built was

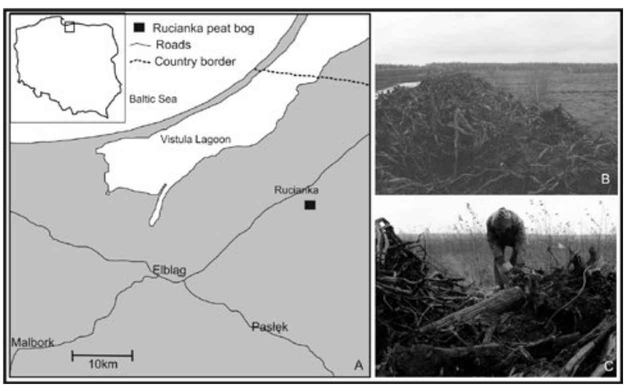

Fig. 1. *Rucianka raised bog: A – location map, B – wood heap along the harvesting site and reclaimed lands, C – sampling.*

Table 1. *Characteristics of investigated pine wood; „+?" – possible presence of the last ring.*

Laboratory code	Part of chronology	Presence of the last ring	Number of tree rings	Narrow-ring wood (external zone)	Presence of the fire scar
2RUC1		+?	50		
2RUC2		+?	81		
2RUC3		+	80	+	
2RUC4z	+	+	104		
2RUC5	+	+?	124		
2RUC6		+, bark	160		
2RUC7		+	196		
2RUC8	+	+	108		
2RUC9	+	+	107	+	
2RUC10			58		
2RUC11z	+	+	140		+
2RUC12	+	+, bark	148	+	+
2RUC13			62	+	
2RUC14		+	103		
2RUC15			59		
2RUC16		+?	50		
2RUC17		+	155		
2RUC18	+	+, bark	143	+	
2RUC19	+	+	128		
2RUC20			35		
2RUC21		+	142	+	
2RUC22			86	+	
2RUC23	+	+	170	+	
2RUC24		+	120		
2RUC25			50		
2RUC26			133		
2RUC27	+	+	134	+	
2RUC28		+	86		
RUC29			103		
2RUC30		+?	94		
2RUC31	+	+?	105		
2RUC32		+	148	+	
2RUC33		+	153		+
2RUC34		+	166		
2RUC35		+?	113		
2RUC36	+	+	106	+	
2RUC37		+	182		
2RUC38	+	+	100		
2RUC39		+	166		+
2RUC40	+		133		
2RUC41		+	194		
2RUC42			84		

checked with the COFECHA program (Holmes, 1983) and plotted by visual matching of the dendrographs.

Radiocarbon dating was carried out with the scintillation technique in the Laboratory of Absolute Dating in Skała near Cracow (Poland, MKL-symbol) and in the Kiev Radiocarbon Laboratory of National Academy of Sciences of Ukraine (Ki-symbol). For radiocarbon dating samples containing annual growth rings of selected pines were chosen. The timbers were preliminary chemically prepared using the AAA method (*Acid–Alkali–Acid*). In the next step, benzene was obtained from charred samples (Skripkin and Kovalyukh, 1994). The measurements of the ^{14}C concentrations were made with the low-background scintillator of a new generation HIDEX 300 SL in Skała (Krąpiec and Walanus, 2011) and with the Quantulus 1220 spectrometer in Kiev.

The age of relatively dated samples was determined with the wiggle-matching method (Bronk Ramsey *et al.*, 2001). This method allows to determine the age of chronology with a higher accuracy than in case of single radiocarbon measurements (Pearson, 1986). The analysis was made on three pairs of samples containing annual growth rings of examined pines, which were relatively dated using the dendrochronological method and were included into the floating chronologies. The curve corresponding to the section of the calibration curve was obtained thanks to radiocarbon dated wood samples and the time interval between the middles of sections represented by dated tree rings. The best fitting of the curve obtained to the calibration curve IntCal09 (Reimer *et al.*, 2009) was determined with the help of the OxCal program (4.1.7 version) (Bronk Ramsey, 2001; 2009).

4. RESULTS

The oldest analyzed piece of wood, the oak sample counting 100 tree rings, was dated to 3190±50 BP (Ki–13850, **Table 2**). Unfortunately, it was impossible to construct the local chronology because of lack of other oak samples.

Correlation of individual tree-ring sequences and visual comparison of dendrographs for each tree allowed to identify groups of samples of the same age. The mean curves – chronologies (labelled as S3, S2, S1) were con-

Table 2. *Results of radiocarbon analysis; a – name of dated sample, species; b – Kiev Radiocarbon Laboratory, Ukraine; c – Laboratory of Absolute Dating in Skała, Poland; i – internal tree rings (the oldest one); e – external tree rings (the youngest one).*

Sample description[a]/ chronology code	Radiocarbon laboratory code[b, c]	^{14}C age (BP)	Age range (68%) (cal. BC)	Age range (95.4%) (cal. BC)	No. of tree ring width series	No. of ^{14}C dated rings/ their cross-dated position in chronology
2RUC19 *Pinus sylvestris*/ S1	Ki–13846[b]	2570±60	809-748 (33.1%) 688-666 (9.9%) 644-590 (18.7%) 580-558 (6.5%)	839-508 (94.5%) 438-420 (0.9%)	128	45i/ 1-45
	MKL–1664[c]	2360±40	508-438 (38%) 420-389 (30.2%)	732-691 (5%) 661-651 (0.8%) 545-372 (89.6%)		15e/ 114-128
2RUC21 *Pinus sylvestris*/ -	Ki–13847[b]	2660±50	893-876 (11.1%) 847-794 (57.1%)	919-771 (95.4%)	142	32i/ 1-32
2RUC23 *Pinus sylvestris*/ S2	Ki–13848[b]	2420±60	735-690 (13.8%) 662-649 (3.7%) 546-404 (50.7%)	670-397 (75.8%) 759-683 (19.6%)	170	46i/ 1-46
	MKL–1665[c]	2520±60	790-731 (19.9%) 692-660 (11.2%) 651-544 (37.2%)	800-486 (90.4%) 463-448 (1.7%) 443-416 (3.3%)		30e/ 141-170
2RUC27 *Pinus sylvestris*/ S3	Ki–13849[b]	2820±50	1041-910 (68.2%)	1123-843 (95.4%)	134	35i/ 1-35
	MKL–1666[c]	2740±40	917-834 (68.2%)	976-810 (95.4%)		25e/ 110-134
2RUC41 *Pinus sylvestris*/ -	MKL–1301[c]	2790±40	1001-901 (68.2%)	1041-836 (95.4%)	194	60i
RUC29 *Quercus*/ -	Ki–13850[b]	3190±50	1504-1417 (68.2%)	1333-1325 (0.7%) 1561-1384 (90.0%) 1608-1570 (4.7%)	103	19i

structed for each group of samples (**Figs. 2**, **3**, **4**). The longest chronology S2, counting 170 tree rings, was built on the basis of five individual curves, which displayed the highest correlation coefficients. Chronologies S1 and S3, consisting of 128 and 134 tree rings, were based on respectively three and two individual tree-ring curves.

The chronologies were based on samples counting from 100 to 150 annual growth rings. Shorter sequences of tree-ring widths (100 and less measurements) were not taken into account, because of low correlation coefficients. Due to lack of similarities between the chronologies constructed and these short individual curves, the latter were excluded from further analysis. Because of low correlation coefficient and 't' values ($t<3.5$) between the chronologies, their positions in the time scale were based on the radiocarbon dating (**Table 2**).

Results obtained by radiocarbon analysis demonstrated that the chronology S3 is the oldest one from all the mean curves constructed. The dependent calibration of the oldest and the youngest annual tree rings from the sample 2RUC27 indicated that the chronology S3 covers the period ca. 950-850 cal BC. The chronologies S2 and S1 represented periods ca. 740-570 cal BC and 590-460 cal BC, respectively. In case of the chronology S2 the inversion of radiocarbon dates results from *plateau* of the calibration curve (Walanus, 2009).

The wide- and narrow-ringed wood zones, distinguished on the basis of the number of tree-rings (at least three annual growths), were noticed in collected pine discs. Narrow-ringed wood (growth depressions) occurred periodically in tree-ring width series. This variability of tree-ring patterns is especially noticeable at individual series of trees from the chronology S2 (**Fig. 3**). Growth depressions appeared there at intervals of over a dozen or several dozen years. Narrow-ringed wood zones were also recorded in sample 2RUC41 and in tree-ring series of the chronology S3 (**Fig. 2**). Characteristic growth depressions counting from 10 to 25 tree-rings were noticed at the end of the pine's life (the youngest annual growths of pines e.g. 2RUC21, 2RUC23, 2RUC27) (**Table 1**, **Figs. 2**, **3**).

Presence of the waney edge, which occurred in about 30% of the samples, is an important feature of the collected pine wood. In some cases the bark was also preserved, which proved high fossilization potential of peat and gave possibilities of exact dating of dying off trees. Moreover, some fires on the Rucianka raised bog were recorded in the collected samples. The fire scars were observed in four wooden discs (**Table 1**). Based on radiocarbon dating the approximate dates of the fires were determined around 710 BC (sample 2RUC11) and around 670 BC (sample 2RUC12) (**Fig. 3**).

5. DISCUSSION

In some samples dendrochronological research revealed presence of narrow-ringed wood zones. Growth depressions in tree-ring width, formed over several years, occurred in the beginning of individual curves of the chronology S3; they were dated about 990 cal BC, and somewhat later ca. 930 cal BC. Long-term decrease in width of increments could be a result of humidity fluctuations in the habitat. The studies conducted by Leuschner *et al*. (2002), on the basis of dendrochronological analysis of sub-fossil oaks from Ireland, confirmed such view and pointed to an increase of climate humidity in the tenth

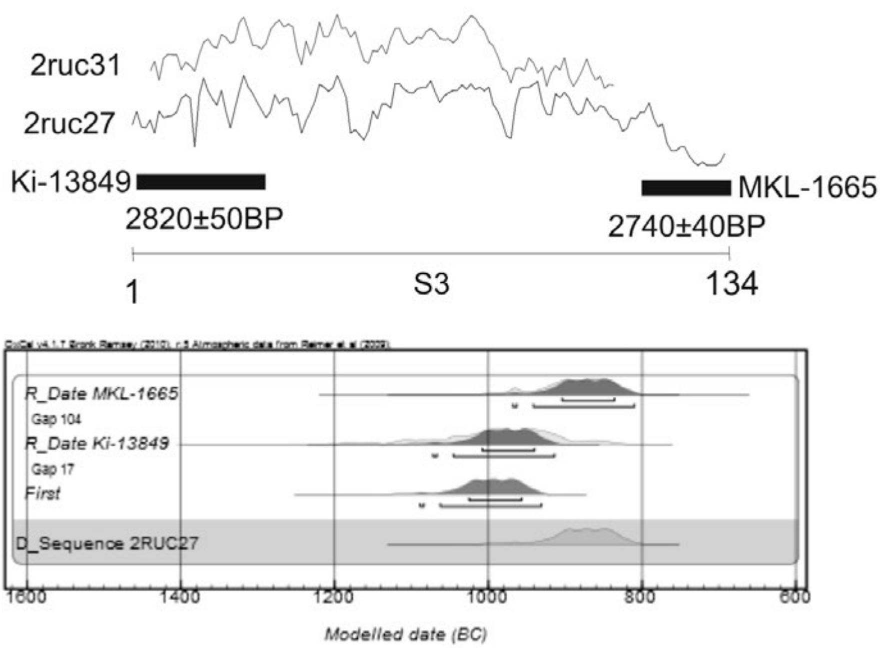

Fig. 2. *Individual tree-ring curves plotted for trees from the chronology S3 and age of samples obtained by the wiggle-matching method.*

century BC. Higher water level in lakes and revival of river fluvial activity were also observed in Belarus (3200-2700 BP, 1500-800 cal BC, Kalicki, 2006). Very narrow annual rings visible in the curve plotted for pine 2RUC27 about 850 cal BC (**Fig. 2**) could be correlated with growth depression from the middle of the 2RUC41 curve. It follows that worse site conditions around 850 cal BC, probably connected with a rise of groundwater table, caused dying-off of some pines and/or the presence of narrow-ringed wood zones in other trees. Dendrochronological analysis of an archeological oak from Biskupin settlement revealed growth depressions in tree-ring pattern in a similar period (845-830 BC, Ważny, 2001). Likewise, sub-fossil oaks from peat bogs from Lower Saxony showed growth reductions in the years 855-835 BC (Leuschner, 1992). Results of dendrochronological research conducted on peat bogs (Leuschner *et al*., 2002; Sass-Klaassen and Hanraets, 2006) show that decline of trees as a result of wetter phase in bog development had positive effects for future colonization by pine trees. Dying-off of old trees created vegetation gaps for growing young pines (germination and dying-off phases, GDO). The changes in hydrology regime were considered as the main factor of woodland dynamic on mires. The study of sub-fossil pine wood from the Rucianka raised bog allowed to conclude that GDO phase on the bog probably took place around 850 cal BC. The tree-ring width pattern for sample 2RUC21 indicated convenient environmental conditions for growth of pine woodlands in the period 850-750 cal BC. Taking into account the results of investigations of Stążki Balitc bog (Lamentowicz *et al*., 2010), where the wetter phase of mire development was noticed in that period, such favourable site conditions on the Rucianka bog had probably a local range. Around 740 cal BC climate humidity raised again, which was reflected in the beginning of individual pine curves from the chronology S2 (**Fig. 3**), in which growth depressions occurred. Narrow-ringed wood zones formed later could be triggered by the same factors as growth depressions ca. 735-715 and 705-685 BC described by Leuschner (1992) and Ważny (2001). Short-term improvement of site conditions recorded in growth of pines and visible on dendrographs of the chronology S2, preceded the dying-off phase around 570 cal BC. Rapid deterioration of site conditions in that time was marked in the tree-ring pattern of one pine (sample 2RUC23, **Fig. 3**), which survived though unfavourable ecological site conditions and formed very narrow annual growth in its external zone, under bark. Growth depressions occurred also in the beginning of the chronology S1, in curves plotted for samples 2RUC5 and 2RUC19 (**Fig. 4**). They could correspond to the narrow-ringed wood dated around 570 cal BC in trees which germinated ca. 590 cal BC. Decrease of tree-ring widths, clearly noticeable around 520-510 cal BC, should be connected with wetter climate period (Lamentowicz *et al*., 2010). Probably higher level of groundwater table around 460 cal BC was a cause of dying-off phase in bog woodlands. Sub-fossil

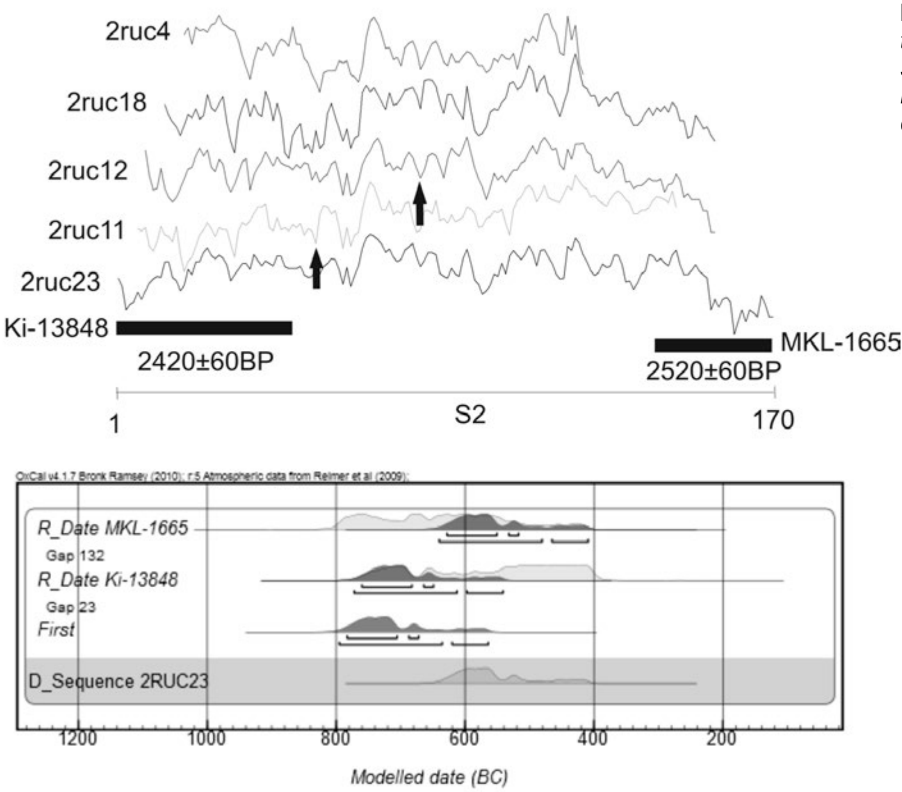

Fig. 3. *Individual tree-ring curves plotted for trees from the chronology S2 and age of samples obtained by the wiggle-matching method. The fire scars, visible on wooden discs, are marked with arrows.*

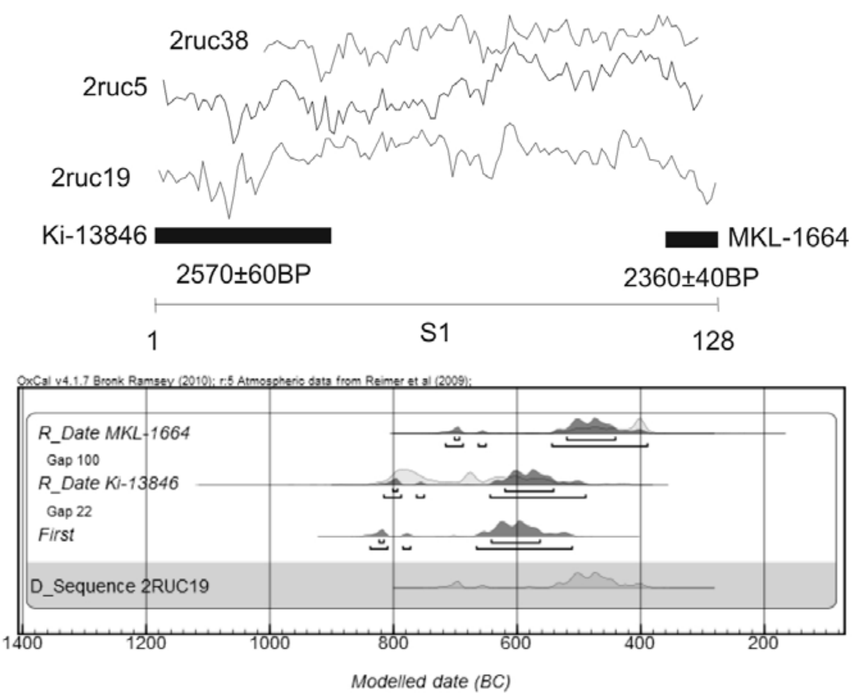

Fig. 4. *Individual tree-ring curves plotted for trees from the chronology S1 and age of samples obtained by the wiggle-matching method.*

oaks in Willia deposits in Niemen Basin (Belarus), provided an increase of fluvial activity in that time (Kalicki, 2006).

Dendrochronological analysis allowed to identify distinct woodland generations on the Rucianka raised bog separated by GDO phases. The oak forest had existed on the bog before pine woodland occurred (sample RUC29, **Table 2**). The oak sample could be an indicator of change between bog phases: the minerotrophic fen and the ombrotrophic bog phase (see Leuschner and Sass-Klaassen, 2003). First of the investigated pines germinated at mire around 990 cal BC and probably started dying-off around 850 cal BC. In that time, the second phase of germination and pines growth began, which lasted until ca. 710 cal BC (sample 2RUC21, **Table 2**). Increase of climate humidity around 740-700 cal BC was the reason of the dying-off phase. As a result, favourable site conditions were followed for young pines and germination of the third generation of trees could be noticed (S2, **Fig. 3**). The youngest generation of pines existed around 590-460 cal BC.

The hydrology regime on the mire could have a local character. However, dendrochronological studies on sub-fossil wood from peat bogs in Europe, increasingly conducted, indicate a relationship between fluctuations of groundwater level and climate change (Leuschner and Sass-Klaassen, 2003; Sass-Klaassen and Hanraets, 2006). The potential of information recorded in wood remains buried in peat gives an opportunity for palaeoclimatic reconstruction and should be used in Poland on a wider scale. From this point of view, the Rucianka raised bog with a lot of sub-fossil pine wood, become an interesting object for dendrochronological studies. The importance of the bog increased because of the fact that the sub-fossil wood was dated to the first half of the first millennium BC. Problems with finding wood from that period are commonly known and particularly noticeable by teams constructing chronologies in central Europe (see Becker, 1981; Krąpiec, 1992). Therefore, systematic collection of wood samples with the progress of peat exploitation should allow to build the dendrochronological standard covering hundreds of years (1000-450 BC).

6. CONCLUSIONS

The conducted dendrochronological research has a preliminary character in view of the small number of sub-fossil wood samples. However, the study allowed to construct chronologies covering a period of over 400 years in the first half of the first millennium BC, which is very important from the point of view of palaeoclimatological interpretations. The woodland phases were initially identified, but continuation of sampling of pine wood should allow to establish germination and dying-off phases. Narrow-ringed wood zones appearing in pine samples corresponded with oak growth depressions described in other countries in Europe and connected with wetter climatic periods. Taking into account above, sampling of pine wood with the progress of peat harvesting, especially stumps *in situ*, should yield more information on the bog development and document dry and wetter climate phases over the last few hundred years BC.

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