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RESEARCH REPORT

UPDATING THE CZECH MILLENNIA-LONG OAK TREE-RING WIDTH CHRONOLOGY

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ABSTRACT

In recent years, a millennia-long oak tree-ring width chronology, consisting of 3194 samples from 387 locations, was developed in the Czech Republic. Despite the collection of such a huge dataset, the replication in the 19th Century was very low and the natural oak distribution in the Czech Republic was insufficiently covered by recent samples, especially in Western Bohemia. This study aimed to remove these weaknesses, which have limited the paleoclimatic potential of this dataset, and to determine the number of sapwood rings, which is crucial for dendrochronological dating. Therefore, new recent samples were randomly collected at numerous sawmills along the Czech-German border. The historical material was usually sampled using a Pressler borer from church belfry constructions traditionally made from oak. In total, 252 recent and 90 historical tree-ring width series were incorporated into the chronology. The newly built chronology cumulatively consists of 3536 series, which covers the continuous period of A.D. 352–2014. The resulting tree-ring width record shows robust signal strength and homogeneous coverage of the territory. We show that the number of sapwood rings is constant over time. Therefore, we recommend using an estimate of 5–24 sapwood rings for a more precise dating of historical wood findings in the Czech Republic.

Keywords: Belfry construction, Czech Republic, dendrochronology, *Quercus*, sapwood rings.

INTRODUCTION

Multi-centennial and multi-millennial oak tree-ring width (TRW) chronologies have been constructed across Europe over recent decades (*e.g.* Baillie 1995; Haneca *et al.* 2009; Tegel *et al.* 2010; Büntgen *et al.* 2011; Kolář *et al.* 2012; Čufar *et al.* 2014; Sohar *et al.* 2014). The main purposes of the long TRW chronologies have been demonstrated mainly in dendroarchaeology (Ważny *et al.* 2014), paleo-climatology and paleo-ecology (Büntgen *et al.* 2013). However, quality and sample replication of the TRW chronologies are not always stable over the entire chronology (Haneca *et al.* 2009). Insufficient sample replication over time and diminished site control of the historic data affect expected outcomes (Büntgen *et al.* 2012). Such restrictions can cause complications when dating historical or archaeological artifacts (*e.g.* Kern *et al.* 2014) or reconstructing climate variabilities (Prokop *et al.* 2016). Therefore, TRW chronologies are treated as dynamic entities that need to be constantly improved (Haneca *et al.* 2009).

The extensive historical settlements in the Czech Republic provide abundant archaeological oak finds to support dendrochronological research. The first oak TRW chronology was established in 1995 (Poláček 2002) and has been gradually improved until present (Rybníček *et al.* 2010; Kolář *et al.* 2012; Dobrovolný *et al.* 2015). Although the chronology consisted of more than 3000 TRW series, it manifested two essential drawbacks. The main issues were very low replication in the 19th Century and the lack of recent samples from the entire territory of the Czech Republic. Here we present the latest update of the Czech TRW

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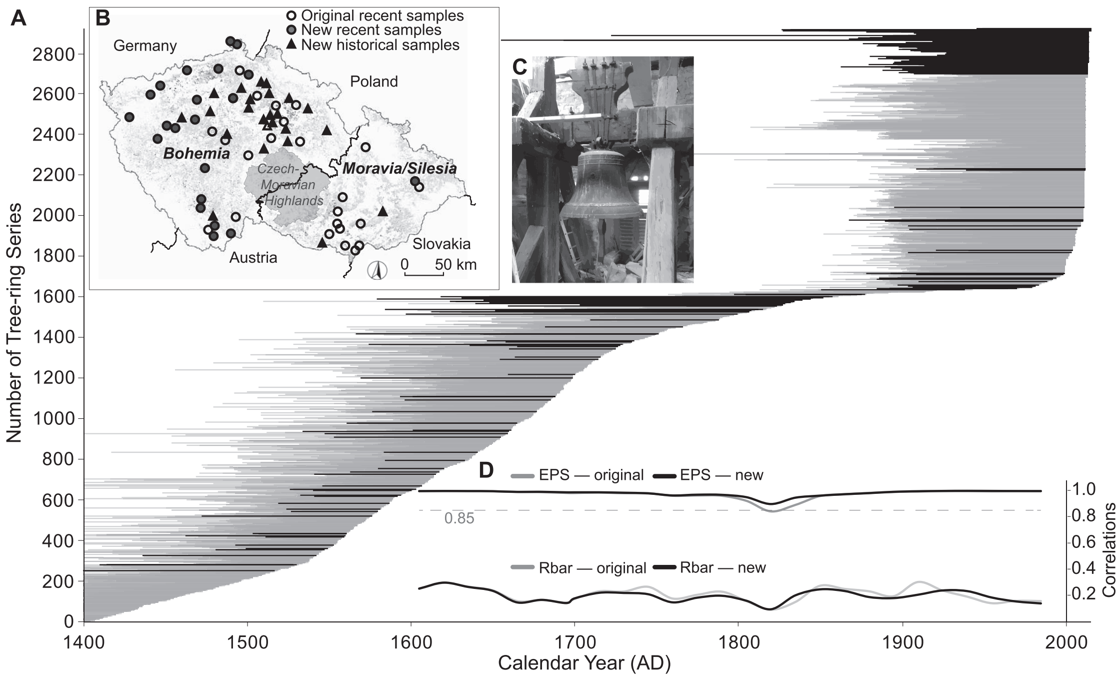

Figure 1. (A) Temporal distribution (only from 1400 to the present) of TRW series from previously (grey) and recently (black) collected samples. (B) The geographical distribution of the study sites across the Czech Republic. (C) Illustration of the belfry construction. (D) Expressed Population Signal (EPS) and inter-series correlation (Rbar).

chronology, which has removed these issues. In addition, 924 TRW measurements of original and new recent samples and 529 TRW measurements of original historical samples were used to explore the number of sapwood rings. This is crucial for precise dendrochronological dating of historical oak samples without waney edge.

MATERIAL AND METHODS

In the Czech Republic, oak is mainly represented by pedunculate oak (*Quercus robur* L.) and sessile oak (*Quercus petraea* (Matt.) Liebl.). The Czech Republic has two areas with extensive oak populations (Bohemia in the west and Moravia and Silesia in the east), which are separated by the Czech-Moravian Highlands, an area in which oak trees are rare (Figure 1B). Oak distribution and its frequent use in Central Europe is evidenced by many historical and archaeological constructions, *e.g.* church belfries (Kern *et al.* 2014), water and farm constructions (Tegel *et al.* 2012; Dejmal *et al.* 2014) or wooden vessels (Filková *et al.* 2015; Klein *et al.* 2014, 2016). In addition, oak distribution in the region throughout Holocene has been proven by discovery of subfossil trunks (*e.g.* Kolář and Rybníček 2011; Stacke *et al.* 2014).

In this study, we took samples from living trees and historical structures. To cover the entire territory of the Czech Republic by recent TRW oak series, we randomly sampled living trees by chainsaw at sawmills, especially from the western regions that were not represented in the old versions of the TRW chronology. The historical samples were taken using a Pressler borer mainly from church belfries, which were selected based on documentary evidence, *e.g.* parish and municipal chronicles and inscriptions on the structures. All samples were measured using the VIAS TimeTable measuring system devised by SCIEM. TRW series were measured (with an accuracy of 0.01 mm) and synchronized using PAST4 (©SCIEM). Compiled recent and historical mean TRW series were dated according to the latest version of the Czech TRW chronology. The degree of similarity between the TRW series was assessed by t-tests (Baillie and Pilcher

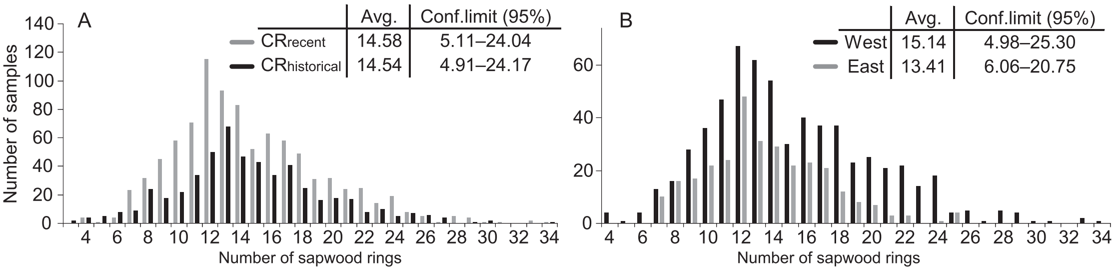

Figure 2. Number of sapwood rings of recent and historical samples for the Czech Republic (A) with average values and the 95% confidence limit. In addition, values for the recent samples were calculated separately for the east and the west (B).

1973; Hollstein 1980) and Gleichläufigkeit (Eckstein and Bauch 1969). Expressed Population Signal (EPS; Wigley *et al.* 1984) and inter-series correlation (Rbar) were calculated to assess the quality of the chronology. Both statistical metrics were computed over the 30-year windows lagged by 15 years. The recent and the historical samples with preserved waney edge were used to count the number of sapwood rings. The border between heartwood and sapwood was detected visually by difference in colour and missing tyloses in sapwood rings.

RESULTS

To update the existing oak chronology, we have taken 647 samples; out of which, 461 were from living trees and 186 were from historical structures. However, 305 samples of the obtained TRW series could not be reliably crossdated because of the low number of tree rings and growth anomalies; these TRW series had to be excluded from the chronology construction. Finally, we have increased the replication of the original chronology using 252 new TRW series from living trees (21 sites) and 90 series from 24 historical structures (Figure 1A, B)—primarily church belfries (Figure 1C). The newly built chronology consists of 3536 series, which covers the continuous period of A.D. 352–2014. We have increased the replication in the first half of the 19th Century by at least 38 TRW series. Because of this extension, the EPS in this period reached a value of 0.90 (Figure 1D). In addition, the chronology is replicated with at least 50 samples per year from A.D. 1028 to present. The Rbar value of the new TRW chronology ranges from 0.09 to 0.29. In comparison with the old TRW chronology version, the new Rbar value decreased at the beginning of the 20th Century from 0.30 to 0.21 (Figure 1D). The number of sapwood rings ranges from 4 to 34 with an average value of 14.6 for the Czech Republic (Figure 2A). Higher numbers of sapwood rings were calculated for the western regions (15.1) than for the eastern regions (13.4; Figure 2B). In the historical samples, the number of sapwood rings varies between 3 and 34 with almost the same average value (14.5) as in the recent subset.

DISCUSSION AND CONCLUSIONS

Although we have taken and processed 647 samples, only 342 samples could be used to improve the Czech TRW chronology. The remaining samples (305) were not reliably crossdated mainly because of growth anomalies in the wood, which were not detected during sampling, *e.g.* discontinuous rings (described in detail by Haneca *et al.* 2009). Most of the difficulties were caused by extremely narrow tree rings that only consisted of early wood vessels for which it is very difficult to recognize the tree-ring borders. Another reason for the dating failure was the insufficient number of tree rings, which is a crucial parameter for reliable dendrochronological dating. It is suggested that TRW series should not be shorter than 40 (Cook and Kairiūkštis 1990) or even 50 years (Haneca *et al.* 2009). Furthermore, TRW series were probably influenced by the cockchafer beetle in a few cases. Such TRW series are almost impossible to date by dendrochronological methods (Kolář *et al.* 2013).

The previous versions of the Czech TRW chronology were replicated at the beginning of the 19th Century with only 19 TRW series, mostly from the eastern part of the country (Kolář *et al.* 2012;

Dobrovolný *et al.* 2015). The lack of dated oak finds from this period motivated us to search for suitable oak constructions in the Czech Republic. Based on documentary evidence, *e.g.* church chronicles, we selected several oak constructions—mainly oak belfries. The subsequent dendrochronological dating shows that several historical records were imprecise and some timbers were older than from the 19th Century. These discrepancies were most likely caused by the removal of the outermost rings by woodworking techniques, and in other cases the historical records might be inaccurate. Thus, in many cases our results significantly contributed to the clarification of the chronicle records. In spite of this fact, the new samples increased the chronology replication to at least 57 TRW series in the 19th Century (Figure 1A).

A well-replicated recent TRW chronology constructed from oaks representing the whole Czech Republic is crucial in understanding the growth variability in this diverse region in detail and to evaluate the number of sapwood rings. The random sampling strategy was chosen for recent trees so that the artificial signal-degradation was as low as it is for the historical subset (Büntgen *et al.* 2012). The increase in the number of sites has strengthened the common signal, which leads to the increased likelihood of dendrochronological dating (Ważny *et al.* 2014). Adding a new dataset has significantly improved the replication and exceeded the generally accepted threshold of 0.85 EPS (Figure 1D; Wigley *et al.* 1984). When the EPS value drops below a predetermined level, the chronology starts to be dominated by the individual tree-level signal rather than a coherent stand-level signal (Speer 2010). The EPS, which considers the inter-series correlation and the sample size information and estimates how well a finite number of samples represents the theoretical population average (Esper *et al.* 2003), was improved from 0.84 to 0.90. This demonstrates a robust common signal strength. However, a relatively low mean Rbar value (0.20) was found among all TRW series contained within the chronology over the last four centuries. In addition, a significant decrease was observed at the beginning of the 20th Century as new samples from living trees, especially from Western Bohemia, have been added (Figure 1D). Generally, the Rbar values are much lower for the composite chronology than for the individual site chronologies (Wilson *et al.* 2012) because of the broad geographic scale of the samples (Büntgen *et al.* 2012).

The number of sapwood rings in living trees needs to be analyzed so that we are able to estimate the number of missing sapwood rings when buildings are dated (Sohar *et al.* 2012). The confidence interval (95%) of expected number of sapwood rings for western and eastern Czech Republic varies from 4.98 to 25.30 and 6.06 to 20.75, respectively (Figure 2B). These results are in agreement with a previous study conducted only in the southeastern region, in which the normal presence of 5–21 sapwood rings was determined (Rybníček *et al.* 2006). Furthermore, our study confirmed the general trend of a decreasing number of sapwood rings in Europe from west to east and their tighter range (Baillie *et al.* 1985). For example, values of the 95% confidence limit for the British Isles were established as 9.16–58.15 (Hillam *et al.* 1987), for France 15.25–43.26 (Pilcher 1987), for Germany 8.22–37.95 (Hollstein 1980) and for the Baltic area and Southern Finland 6.18–18.71 (Sohar *et al.* 2012). It is assumed that the number of sapwood rings has remained constant for the oak populations throughout history (Sohar *et al.* 2012). To confirm this hypothesis, we used historical and archaeological material mainly from the period of the 7th to the 19th Century. With respect to the historical timber trade and timber floating (Ważny 2002), we did not distinguish between the eastern and the western region of the country. The results show the same range in the recent and the historical subsets (Figure 2A). Therefore, we recommend an estimation of 5–24 sapwood rings for dating purposes of historical and archaeological objects in the Czech Republic.

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