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# The palaeoclimatic potential of recent oak tree-ring width chronologies from southwest Ukraine

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**Abstract**

Better insights into spatio-temporal climate signals are needed to understand more clearly the applicability to palaeoclimatic analysis and dendrochronological dating of the long tree-ring oak chronologies currently being compiled in Eastern Europe. This study investigates the climate sensitivity of two recent oak tree-ring width (TRW) chronologies from Transcarpathian and Ciscarpathian Ukraine and their coherence with 35 oak chronologies from Ukraine, Poland, Slovakia, Romania, and Hungary. The new Transcarpathian chronology consists of 247 TRW series of living trees from 13 sites covering the period 1836-2020, while the new Ciscarpathian chronology consists of 215 TRW series from 13 sites and spans the period 1775-2020. Despite the strong similarity between these two chronologies, their responses to climate differ significantly. Growing-season precipitation and particularly drought (three-month SPEI index) were found to be the primary drivers of oak growth on the border between the Carpathians and the northeastern Pannonian Basin. Spatial correlations of the Transcarpathian chronology show particularly high explained variability in the April-August SPEI index, roughly between 18.5-28.5°E and 45-52°N. In the Ciscarpathian, June precipitation primarily influenced oak radial growth but the spatial correlation was quite low. While the Transcarpathian TRW chronology was strongly correlated with eastern Slovakian and northwestern Romanian chronologies, the Ciscarpathian chronology revealed very low correlations with surrounding chronologies. This study indicates the great dendroarchaeological and palaeoclimatic potential of the Transcarpathian chronology and points to the need to analyse additional living trees from the Ciscarpathian region to understand the spatial variability of oak growth and its climate signal better.

**Keywords**: Quercus spp., Carpathian mountains, tree-ring width chronology, Eastern Europe, hydroclimate, teleconnection

**Introduction**

In recent decades, many multi-centennial and multi-millennial oak TRW chronologies have been compiled in western (Wilson et al., 2012; Tegel et al., 2010), central (Krąpiec, 1998; Prokop et al., 2016; Kolář et al., 2012a; Büntgen et al., 2011), southern (Čufar et al., 2008a;

Griggs et al., 2007) and eastern parts of Europe (Knysh and Yermokhin, 2023; Nechita et al., 2018; Ważny et al., 2014; Roibu et al., 2021). However, no well-replicated chronology has been compiled for western Ukraine (Sochová et al., 2021a). Despite the strong teleconnection between individual European oak chronologies, their applicability to dating as a rule decreases with increasing distance from the location where the trees grew (Kolář et al., 2012a). The extent of the spatial signal of reference chronologies depends on many factors, such as species, climate, growth conditions and more, and thus cannot be clearly delimited. Therefore, dense networks of well-replicated oak reference TRW chronologies in different parts of Europe have been used to test their spatial coherency and climate sensitivity (Ważny et al., 2014; Čufar et al., 2014).

Since about 42% of the Ukrainian part of the Carpathian mountains is covered by forest (Secretariat of the Cabinet of Ministers of Ukraine, 2021; Anfodillo et al., 2008), this area has great potential for compiling long TRW chronologies. European oaks belong to the second most represented genus in the area (constituting about 28%) and to the most widespread deciduous trees in Europe (EUFORGEN, 2009a, 2009b). In Europe, oaks are mainly represented by the pedunculate oak (*Quercus robur* L.) and sessile oak (*Quercus petraea* (Matt.) Liebl.). These two species require different conditions for optimal growth; in particular, the natural environment of pedunculate oak is characterised by lower altitudes (below 500 m a.s.l.) and the proximity of rivers (Dobrovolný et al., 2016). We distinguish two ecotypes of pedunculate oak: the first occurs in lowland forests and is demanding of moisture, and the second is tolerant of shallow and fairly dry soil (Úradníček et al., 2001; Kolář et al., 2012b). In contrast, sessile oak is found at higher altitudes and tolerates a lack of moisture, so it can also grow in very dry soil (Úradníček et al. 2001; Kolář et al., 2012b). However, it was found that the response of two oaks to climatic conditions is negligible (Dobrovolný et al., 2016), their wood is anatomically indistinguishable (Schoch et al., 2004) and their tree-ring width (TRW) chronologies are well cross-dated (Dobrovolný et al., 2016; Rybníček et al., 2016). Therefore, the two oaks are often considered one species, especially in parts of chronologies based on historical wood; thus long oak TRW chronologies include data from both species (Prokop et al., 2016; Nechita et al., 2017; Tegel et al., 2010).

Oaks (*Quercus* spp.) are sensitive to the availability of water (Čufar et al., 2008b, 2014; Kasper et al., 2022) and their drought sensitivity has been analysed in much of Europe (Bose et al., 2021; Popa et al., 2013) including the foothills of the western Carpathians (Nechita et al., 2019; Árvai et al., 2018; Mészáros et al., 2022) and the eastern side of the Ukrainian Carpathians (Nagavciuc et al., 2023; Netsvetov et al., 2017 and 2018; Mazepa et al., 2010). The long oak TRW chronologies in Europe that were found to have sufficiently significant sensitivity to climate have been widely used as a very important tool for investigating climate in past centuries and for palaeoclimatic reconstructions (Haneca et al., 2009; Büntgen et al., 2011; Čufar et al., 2008b). This knowledge is even more important in the context of today's climate change studies, which have revealed increasing temperatures and an increasing number of droughts in the last two centuries (Kolář et al., 2017). Indeed, palaeoclimatic analyses of dendrochronological data have been used to make recommendations on how to cope with these changes in the future (Haneca et al., 2009). However, the spatio-temporal distribution of this signal has not yet been quantified in the Ukrainian Carpathians. Previous studies suggest that considerable climate variability in the Carpathians has a significant influence on the growth of oak trees and its climate signal in tree rings, which may cause large differences in relatively close regional TRW chronologies (Sochová et al., 2021a; Ważny et al., 2014; Nechita et al., 2017).

Knowledge of the climate sensitivity and spatial distribution of the common dendrochronological signals are thus seen as essential for palaeoclimatic analysis and dendrochronological dating. The finding by Ważny et al. (2014) of weak teleconnection between chronologies divided by the Carpathian Arc leads to the assumption that the Carpathian Arc has a major influence on oak tree ring signals. Thus, in this study, we used recent oak tree-ring width chronologies from two regions, Transcarpathian and Ciscarpathian Ukraine, to achieve these objectives: i) to test climate signals in both chronologies; ii) to test regional differences in the climate response of oaks in the Carpathian mountains; iii) to quantify the spatial distribution of the strongest climatic signal; and iv) to test the coherence of TRW chronologies across Central, Eastern and South-Eastern Europe. Findings from these tests will help us to understand the area-wide potential of these chronologies for use in future dendroarchaeological and palaeoclimate studies.

## Materials and methods

### *Study area*

For this study, two regions of Western Ukraine, divided by the Carpathian mountains, were selected for sampling (Fig. 1). Samples from the Transcarpathian region were taken in the area from 22.27° to 24.02° east longitude and from 48.12° to 48.57° north latitude (Fig. 1). This territory falls into two biogeographic regions – Pannonian and Alpine – with mean precipitation fluctuating from 41.3 (March) to 93.9 mm/month (June) and with 736 mm/year; and mean temperature from –3.3°C (January) to 19.4°C (July) (EEA, 2023; CRU TS4.06 for 22-24°E 48-48.5°N, Fig. S1a). The Pannonian biogeographic region is mainly characterised by the contrast between wet weather coming in from the west and cooler temperatures coming from the Carpathians nearby, which cause sometimes dramatic thunderstorms to build up over the plains at various times of the year. A key role is played by the surrounding hills and mountains, which are an important source of water for this otherwise arid region (Sundseth and Barova, 2009a). The altitudes of the sites sampled in the Transcarpathian region are very heterogeneous and cover the elevations 140-600 m a.s.l. The region is covered by heavy clay soils (Vertisols) which give way in the north to young, highly porous dark soils (Andosols). These conditions mean that, in the Transcarpathian region, deciduous broadleaved forests are most common, covering almost the entire area at lower altitudes, with a very small amount of mixed forest at slightly higher altitudes and exclusively coniferous forest at high altitudes. (Buchhorn et al., 2020).

Samples from the Ciscarpathian region were taken in an area from 23.35 ° to 25.62 ° east longitude and from 48.25 ° to 49.53 ° north latitude. This region includes two different, biogeographic regions – Continental and Alpine. Mean precipitation ranges from 40.7 (March) to 99.8 mm/month (June) with 757 mm/year; and mean temperature from –4.8 °C (January) to 17.6 °C (July) (EEA, 2023; CRU TS4.06 for 23-25.5 °E 48-49.5 °N, Fig. S1b). The Continental biogeographic region is generally characterised by strong contrasts between cold winters and hot summers; the extreme conditions of hot and cold, wet and dry have a strong impact on the vegetation (Sundseth and Barova, 2009b). In the Ciscarpathian region, the altitudes are less varied and cover the range of 280-500 m a.s.l. Characteristic of this region are fertile soils in the south, mostly with clay accumulation (Luvisols), giving over to dark soils with organic rich topsoil in the north (Phaeozems) (BGR, 2005). Despite the large percentage of deciduous broadleaved forests, these conditions allow greater expansion of mixed forests than in Transcarpathia, especially in the foothills of the Carpathians.

It is clear that conditions in the regions differ significantly. Although both are connected with the common Alpine region, characterised by a relatively cold and harsh climate (Sundseth and Barova, 2009c) and both have a common distribution zone with young soils of moderate horizon development (Cambisols), soil conditions differ significantly between the two regions (BGR, 2005). The average altitude of the sampled sites is very similar in Transcarpathia (308 m a.s.l.) and Ciscarpathia (342 m a.s.l.), nevertheless the representation of lower and higher altitudes differs significantly. All these conditions result in different vegetation in the two regions.

*Ukrainian samples*

In the Transcarpathian region, 13 sampling sites were selected with elevations from 140 to 600 m a.s.l. (Table 1, Fig. 1). A total of 247 live pedunculated oak and sessile oak trees (from 12 to 28 trees per site) were sampled in this area by taking cores using an increment borer (Haglöf Sweden AB) at chest height (1.3 m above ground) or as discs from felled trees using a chainsaw. In the Ciscarpathian region, a total of 215 live oak trees (from seven to 28 trees per site) also from 13 sampling sites, with elevations from 290 to 500 m a.s.l. were sampled using the same methodology as in the Transcarpathian region (Table 1, Fig. 1).

All samples were sanded and afterwards tree-ring width was measured using a VIAS TimeTable measuring system (©SCIEM) with an accuracy of 0.01 mm. TRW series were cross-dated using PAST4 (©SCIEM). The degrees of similarity among tree-ring series were assessed using t-tests (TBP – Baillie and Pilcher, 1973; THO – Hollstein, 1980), Gleichläufigkeit (Eckstein and Bauch, 1969) and a visual comparison of the TRW series, which is crucial for the final cross-dating (Rybníček et al., 2010). The critical value of the Student's t-distribution with a $p$=0.001 significance level is 4.0 for an overlap of ~100 rings and 3.7 for an overlap of more than 120 rings (Fowler and Bridge 2017), so these values were taken as thresholds.

The TRW chronology for each site was assembled from the individual TRW series, which significantly correlated with each other. The expressed population signal (EPS; Wigley et al., 1984) and the inter-series correlation (Rbar) with a 30-year window and 15-year overlap were calculated to assess the quality of each TRW chronology (Fig. 2).

*Dendroclimatic analysis*

TRW series were standardised in the ARSTAN program using a cubic smoothing spline with a 50% frequency response at 32 years to remove age-related growth trends and other non-climatic signals. Because of the relatively short length of the TRW series, we used a flexible cubic smoothing spline to emphasise the high frequency (inter-annual to decadal) variability in the data. Three versions of the chronologies (standard, residual and ARSTAN) were routinely generated from the ARSTAN software (Cook and Krusic, 2005). Transcarpathian and Ciscarpathian regional residual index chronologies were used for further dendroclimatic analysis. Using variance-stabilised residuals should have avoided the possibility of ratio bias problems (Cook and Peters, 1997). TRW indices were calculated as residuals between the measured TRWs and the corresponding fitted values after applying an adaptive power transformation (Cook and Peters, 1997). The mean chronologies were calculated using robust bi-weight means (Mosteller and Tukey, 1977) to remove biases caused by outliers. Subsequently, for verifying common variability in tree-ring chronology, principal component analysis was carried out using the factoextra (Kassambara and Mundt, 2017), FactoMineR (Lê et al., 2008) and corrplot (Wei et al., 2017) packages in the Rstudio program (R Core Team, 2022). Negative pointer years were calculated for both chronologies as years when tree-ring width indices were equal to or less than the mean value minus one standard deviation (Schweingruber et al., 1990). The threshold value of standard deviation was arbitrarily defined to yield a sufficient number of extreme years. Subsequently, logistic regression analysis (Quinn and Keough 2002) was used to determine the relationships between significant years and climate data and was performed in the Rstudio program using the Generalised linear model (GLM) function. In this analysis, we coded the binary response as a ‘normal’ year (value zero) or a negative/positive extreme year (value 1); this analysis was chosen because of its ability to significantly reduce the influence of the various noises that are in the indexed TRW data due to random factors. We report only results with a significance level of $p$=0.001.

As climatic data, we used monthly mean temperatures, precipitation totals and three-month Standardised Precipitation-Evapotranspiration Index (SPEI) from the CRU TS4.06 database (for area 22-24°E 48-48.5°N for Transcarpathia and area 23-25.5°E 48-49.5°N for Ciscarpathia; Harris et al., 2020) for subsequent analyses. Static and moving correlations of the Transcarpathian and Ciscarpathian chronologies with climate data were calculated using the dcc function of the treeclim package (Zang and Biondi, 2015) in Rstudio from the previous September to the current September (for years 1951-2018, for which climate data are available from most meteorological stations). The strongest correlations were analysed to find spatial distribution (WMO, 2022) (Fig. 3).

*Chronologies from the surrounding area*

The Transcarpathian and Ciscarpathian chronologies were compared in the PAST program with 35 local chronologies from the surrounding area. For these local chronologies, in total, 835 recent samples of pedunculated (*Quercus robur* L) and sessile (*Quercus petraea* (Matt.) Liebl.) oak were collected from forests and sawmills in Ciscarpathian Ukraine, Poland, Slovakia, Romania and Hungary in an area lying approximately between 46.5-49.0°N and 20.4-24.1°E (Fig. 1, Table 2). This sampling area is situated from 125 to 685 m a.s.l., and covers the entire natural elevational distribution of oaks at this latitude (Fig. 1, Tables 1 and 2, Eaton et al., 2016).

Sampling sites fall into three biogeographical regions – Pannonian, Continental and Alpine (EEA, 2023). T-tests and Gleichläufigkeit were calculated to establish any correlation among tree-ring chronologies.

## Results and discussion

### *Transcarpathian and Ciscarpathian chronologies*

TRW series (n=247) were used to compile a regional oak TRW chronology for Transcarpathian Ukraine. The chronology is 185 years long, covering the period 1836-2020, and consists of more than 10 samples since 1856 (Fig. 2). In contrast, the Ciscarpathian oak TRW chronology is considerably longer (246 years), but is compiled from fewer samples (n=215) and covers the period 1775-2020. Since 1815, it consists of more than 10 samples, a more extended period than in the Transcarpathian chronology, which is covered by only a few samples (Fig. 2b, 2c).

The mean tree-ring width values for the Transcarpathian samples vary from 1.051 to 4.411 mm with an average of 2.057 mm. The TRW range for the Ciscarpathian region is almost twice as big (from 1.075 to 7.615 mm, with an average of 2.465 mm). Although the average lengths of the series are similar, the overall values are again more varied for the Ciscarpathian chronology (34-245 years) than for the Transcarpathian (51-171 years) (Fig. 2b). It is obvious that the length of the TRW series used for the Transcarpathian chronology is the more homogeneous of the two. Although some longer TRW series can be found in the Ciscarpathian chronology, almost 28 % of series are shorter than 80 years and 32 % of samples are longer than 120 years in contrast to only 6 % of samples shorter than 80 years and 25 % longer than 120 years in the

Transcarpathian chronology. Nevertheless, overall the relationship between AGR and MSL (average growth rate, mean segment length) for both chronologies follows a classic growth trend (Fig. 2a). Thus, in the Ciscarpathian chronology, a larger proportion of samples with juvenile wood was found, which resulted in a higher AGR (Fig. 2a). The mean of the interseries correlations (Rbar) was calculated as 0.235 for the Transcarpathian chronology (0.219-0.697 for each sampling site) and 0.242 for the Ciscarpathian chronology (0.312-0.652 for each sampling site). The mean values of expressed population signal (EPS) are higher than 0.9 in the period for which at least 10 samples are presented and overall EPS values are higher than the threshold of 0.85 for both TRW chronologies, as well as for all sites with a higher sample depth than 15 (Fig. 2e, Table 1).

In both chronologies there are noticeable differences in variability in altitude among the sites used for compiling chronologies. Especially for the Transcarpathian region, the altitudes range from 140 to 600 m a.s.l. and it is assumed that different types of oaks grow there (sessile oak can be found in altitudes over 500 m a.s.l.; Úradníček et al., 2001). Contrariwise, in the Ciscarpathian region the altitude variability is more homogeneous and ranges from 280 to 500 m a.s.l. Nevertheless, the similarity among sites with a significantly different altitude is not lower than for sites with comparable elevation. For example, in the Transcarpathian region, the similarity (based on t-tests and Gleichläufigkeit) between two distant sites that are both above 500 m a.s.l. – the Mukachevo (no. UA5 in Fig. 1 and Table 1, 600 m a.s.l.) and Chorna hora (no. UA7 in Fig. 1 and Table 1, 550 m a.s.l.) sites – are 6.9/8.3/79.7 (1912-2007), which is comparable to the similarity between Mukachevo and the second lowest site, Beregujfalu (no. UA1 in Fig. 1 and Table 1, 140 m a.s.l.), which are very close (6.5/7.3/71.9, same period). This suggests that neither altitude nor oak type has a decisive effect on the climate response of oaks in this area.

The quality and usability of chronologies assessed by EPS, Rbar, length of chronologies and sample depth confirm that they are strong fundamentals for future long standard TRW oak chronologies for these two regions. When chronologies are prolonged by using samples from historical buildings and archaeological findings, they will be suitable for palaeoclimate reconstruction and archaeological dating (Sochová et al., 2021b; Roibu et al., 2021; Land et al., 2019; Dobrovolný et al. 2018; Nechita et al., 2018; Prokop et al., 2017; Čufar et al, 2008b).

The similarity between these two regional chronologies in the common period was determined by t-tests: TBP – 6.58, THO – 4.49 and Gleichläufigkeit 65.1% with an overlap of 185 years (1836-2020) (for 1836-2011 the values are TBP – 5.02, THO – 4.37 and Gl - 65.1%). The detected t-test results are higher than the critical value. However, the distance between the two Ukrainian regions is only 120 km. If we compare two other well-replicated chronologies from Europe for the same or even a greater distance, we reach much higher values of t-tests though we are aware that distance is not the only factor affecting the similarity of chronologies. For example, Roibu et al. (2021), in nearby Romania, showed close similarity (6.37/6.76/62.8) between Suceava and Maramures oak chronologies at distances of about 150-200 km. Likewise, Prokop et al. (2016) showed similarity (8.97/9.11/72.2) between Slovakia and Bohemia chronologies at an approximate distance of 400 km, while Kolář et al. (2012) found similarity (5.56/5.53/60.8) even between Czech and Maramures chronologies with a distance of over 450 km. Additionally, a relatively low number (nine) of common negative pointer years was found for these two regional chronologies, which represents only 28% of all Transcarpathian and 31% of all Ciscarpathian significant negative years (Fig. 2d).

The low similarity of the chronologies may also be due to the climate conditions defined by the biogeographic regions, which pronouncedly influence the oaks' growth and response to climate parameters, as well as the altitude and soil conditions of the regions. It is obvious from Figure S1 that in Ciscarpathia the temperature is on average 1.8 °C lower, especially in the growing season (even 1.9 °C) with slightly higher total precipitation than in Transcarpathia. The Pannonian biogeographic region is otherwise arid and dependent on precipitation from the hills and mountains. This suggests that the oak trees here will suffer less from drought. The different composition of the forests in both areas is also evidence of this. As all these parameters differ in the two regions, it is obvious that they can cause great differences between oak growth in the regions and subsequently in chronologies.

*Dendroclimatic analysis*

In this study, we found that, in particular, precipitation during the current vegetative period (May-August), especially in June ($r$= 0.395), stimulated oak growth in the Transcarpathian region (Fig. 3a). Contrariwise, growth was limited by the April-September drought indicated by SPEI index (mean $r$=0.394) (Fig. 3a). Regression analysis shows that the main cause of significant negative years for the Transcarpathian region was drought in summer and during the growing season (Table 3). These results fully correspond to findings in other studies from nearby areas that summer hydroclimate conditions prevailing during the year of tree-ring formation are the most important factor influencing oak growth (Kasper et al., 2022; Mészáros et al., 2022; Árvai et al., 2018; Čufar et al., 2014; Nechita et al., 2017; Prokop et al., 2016; Kern et al., 2009). The strong correlation between TRW and precipitation in summer can be explained by the increase in tree water demand during the long photoperiod, higher temperature, water deficit and evapotranspiration during the months with presumably high growth rates (Netsvetov et al., 2017; Mészáros et al., 2022; Čufar et al., 2014).

Higher precipitation during September ($r$=0.165) and December ($r$=0.186) of the previous year and during March of the current year ($r$=0.210), as well as a warm January (r=0.210), were found to be other parameters positively influencing the growth of oaks in the Transcarpathian region (Fig. 3a). By contrast, the temperature in May (r=-0.227) and June (r=-0.275) negatively influences the growth of these oaks. The strong influence of the previous year's climate on tree-ring formation in oak has been confirmed in several studies (e.g., Scharnweber et al., 2011; Tegel et al., 2014; Rybníček et al., 2015; Árvai et al., 2018; Knysh and Yermokhin, 2023). The effect is a consequence of the storage of non-structural carbohydrates in the oak during the late summer and autumn. Since early wood begins to form approximately three weeks before bud break (Bergès et al., 2008; Puchałka et al., 2017), oaks use these stored carbohydrates for spring growth (Kimák and Leuenberger, 2015). The negative correlation of growth with temperature in early summer, also found in the Donetsk region (Netsvetov et al., 2017), may be related to the high rate of evapotranspiration caused by higher temperature, which increases the soil water deficit (Mészáros et al., 2022).

Spatial correlation and moving correlation analysis showed that drought during April-September was the main driver of growth in the Transcarpathian region (Fig. 3). The spatial correlation indicates particularly high explained variability of growth due to drought during the vegetative period roughly between 18.5-28.5°E and 45-52°N, which includes most of Slovakia, the eastern half of Hungary, the northwestern part of Romania and the western part of Ukraine (Fig. 3b).

Although the correlation between the Transcarpathian chronology and SPEI during the growing season was significant over the entire studied period (1951-2018), a pronounced decrease appeared between the late 1980s and 2000, when correlation decreased below the overall average value, while the values did not fall below 0.5 (Fig. 3c). Overall, the long-term dependence of oaks in the Transcarpathian region on soil water availability does not show any clear trend over the last 68 years. To find a link between the correlation coefficient and SPEI-3 values in April-August we compared graphs of both values in a moving 20-year window for the same period and for the same region (Fig. 3c and S2).

The Ciscarpathian oak chronology showed a weak climate-growth relationship. The climate response of the oaks in this region was similar to those in Transcarpathia, but the correlations were considerably weaker. Although the Continental biogeographic region is influenced by the contrast of hot summers and cold winters, the influence of very fertile soil types and slightly higher precipitation during the summer seems to create optimal conditions for oak growth. One can assume that these conditions, then, can cause the trees to be less sensitive to the climate. The Ciscarpathian chronology shows that the radial growth of oaks is positively related to June precipitation ($r$=0.249) and negatively to April temperature ($r$=–0.225) and July drought index ($r$=0.170) (Fig. 3a). Positive correlations with precipitation in June were also found for southeastern (Netsvetov et al., 2017) and northcentral Ukraine (Netsvetov et al., 2018). Since excessive temperatures in spring and during April might slow down cambial activity (Čufar et al., 2014), this parameter was confirmed as a limiting factor in other studies from Ukraine (Koval and Kostyashkin, 2015; Vakoljuk, 2009). After regression analysis, no clear climatic factor causing significantly negative pointer years was found for the Ciscarpathian region.

Precipitation in June was identified as the main driver, so it was used to investigate the spatial correlation and moving correlation. The spatial correlation analysis shows that Ciscarpathian chronology explained variability of it in west Ukraine, southeastern Belarus and southwestern Russia, roughly between 25-35°E and 48-53.5°N (Fig. 3b). The situation is different in the moving correlation between the Ciscarpathian chronology and precipitation in June (Fig. 3c). There is a noticeable downward trend from the 1970s, and the correlation coefficient dropped below the significance threshold from the 1990s. This trend has been reversing in the last 10 years and an upward trend is evident during this period (Fig. 3c). As with the Transcarpathian region, after comparing this moving correlation with the moving average values of precipitation in June, it can be seen that the correlation trends follow the decreasing precipitation trends (Fig. 3c and S3), which shows their dependence on the amount of precipitation. As the amount of June precipitation has been increasing in this region in recent years, we expect the positive correlations to increase as well.

*Coherency of the Transcarpathian and Ciscarpathian oak chronologies with local chronologies*

A comparison of the Transcarpathian chronology with all 48 local chronologies from surrounding areas showed a high correlation (with the t-test above 6 and Gleichläufigkeit above 70%) with eastern Slovakia (t-tests 6.69–12.7) and northwestern Romania (t-tests 6.91–12.7, Figure 4a). Despite the close location of Hungarian chronologies, the correlation with the Transcarpathian chronology is significantly lower and considerably decreases westward (in Fig. 1, Table 2 numbered HU06, HU07). That could be caused by a different reaction of oaks to climate in the Great Hungarian Plains and in areas farther from the Transcarpathian region. Although annual precipitation in the east Hungarian lowlands is significantly less than in western Ukraine (EEA, 2023), the precipitation signal was found to be similar for chronologies from both regions – positive for the previous winter and current summer (Mészáros et al., 2022; Árvai et al., 2018; Čufar et al., 2014). Thus, differences in Hungarian and Transcarpathian chronologies can be caused by some secondary reactions, for example with temperature. For the Transcarpathian region, we found the highest negative temperature correlation with June, whereas for the Debrecen chronology (in Fig. 1, Table 2 numbered HU02-HU04), there was a positive correlation with the previous December and current September. In contrast, for Sikfőkút (in Fig. 1, numbered HU07), only a negative correlation with the May and August temperature has been found (Mészáros et al., 2022; Árvai et al., 2018). Čufar et al. (2014) for central and eastern Hungary found no significant positive correlation with temperature, but a negative correlation with April temperature for one chronology. These differences in the response of oaks to climate in Hungary and the Transcarpathian regions may cause differences between the chronologies, even though the areas are close.

Although comparison of the Ciscarpathian chronology with 48 local chronologies from the surrounding area revealed some correlation, especially with the nearest area Mukachevo (about 150 km away, t-test 6.54, in Fig. 1, Table 1 numbered UA15), a clear pattern of correlations is not visible (Fig. 4b). That may be caused mainly by the low replication of nearby chronologies and the different oak response to climate because Ciscarpathia falls into a different biogeographical region from the northeastern Pannonian Basin, is represented by different soil type and the sampled sites differ in altitude.

## Conclusion

Even if dendrochronological agreement between Transcarpathian and Ciscarpathian oak chronologies can be found, their growth response to climate differs considerably. While the growth of oaks in the westernmost part of Ukraine (the Transcarpathian region) is mainly limited by drought during the vegetative period, and this behaviour is stable over the period 1951-2018, the growth of oaks on the opposite side of the Carpathians (the Ciscarpathian region) is controlled by June precipitation and has a decreasing trend. The TRW oak chronology from the Transcarpathian region is shown to have great palaeoclimatic potential and introduces the prospect of climate reconstruction in western Ukraine, while the TRW oak chronology from the Ciscarpathian region must be further investigated in detail.

As spatial correlation analysis suggests, the signal of vegetative period drought of the Transcarpathian chronology is strong for a wide area. The new oak TRW chronology enables dendroarchaeological dating of historical buildings in the Transcarpathian area, which is rich in such structures (Sochová et al., 2021b).

Although the Ciscarpathian chronology shows a weaker climatic signal and spatial correlations, and a lower correlation with surrounding chronologies, we assume that this is mainly due to low replication, especially in the 18th and 19th centuries, and the unavailability of more chronologies from the area for comparison. After supplementing the chronology with additional samples from this area, it should be re-investigated and subjected to analysis in the future.

Since the two chronologies display considerable differences, separate TRW chronologies for the Transcarpathian and Ciscarpathian regions should be compiled.

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**Figure captions**

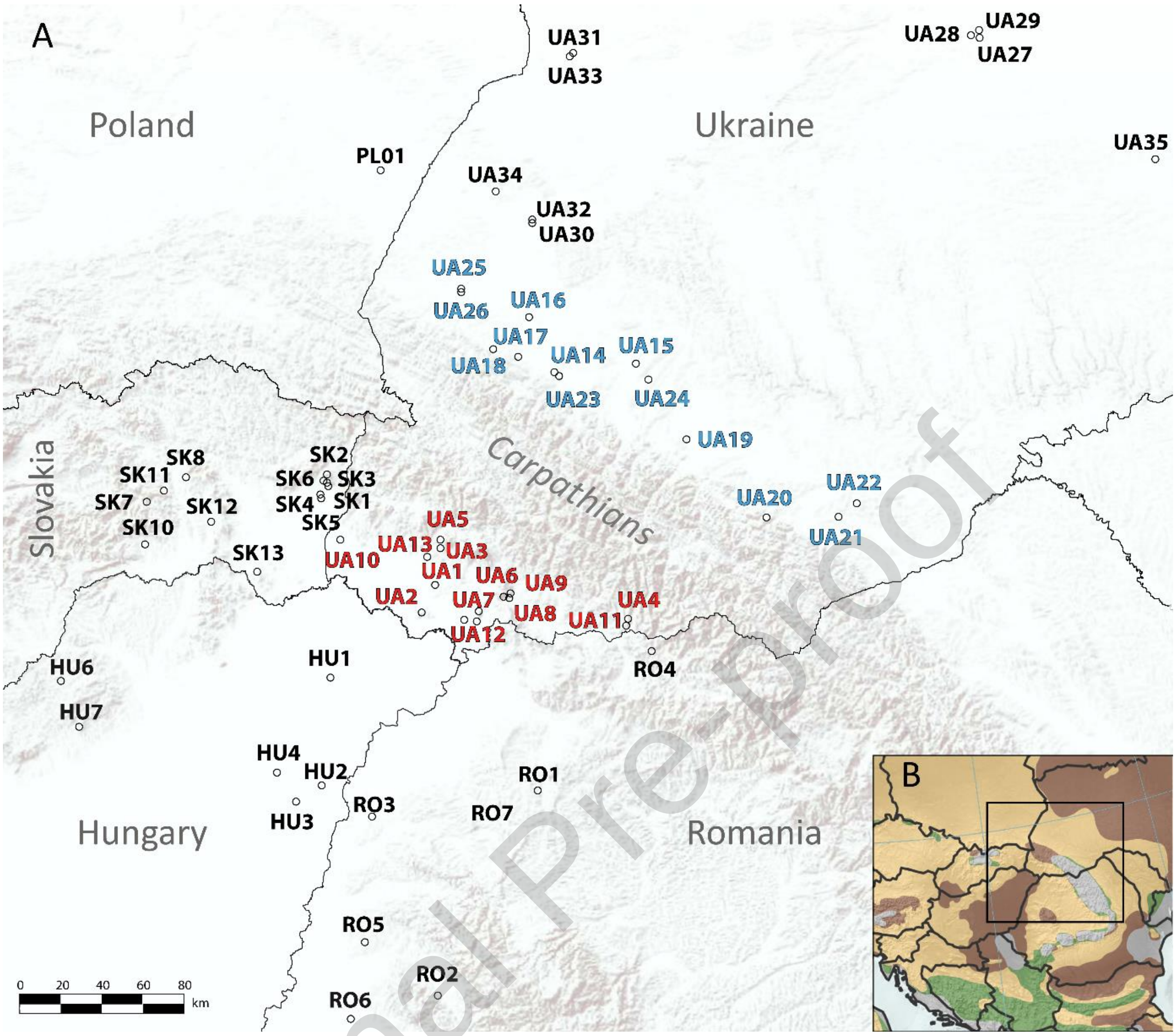


**Figure 1:** (A) Map indicating study sites used to compile Ciscarpathian (blue) and Transcarpathian (red) TRW chronologies, (B) spatial distribution of *Quercus petraea* (green), *Quercus robur* (brown) and both species (yellow) with study area (black rectangle).

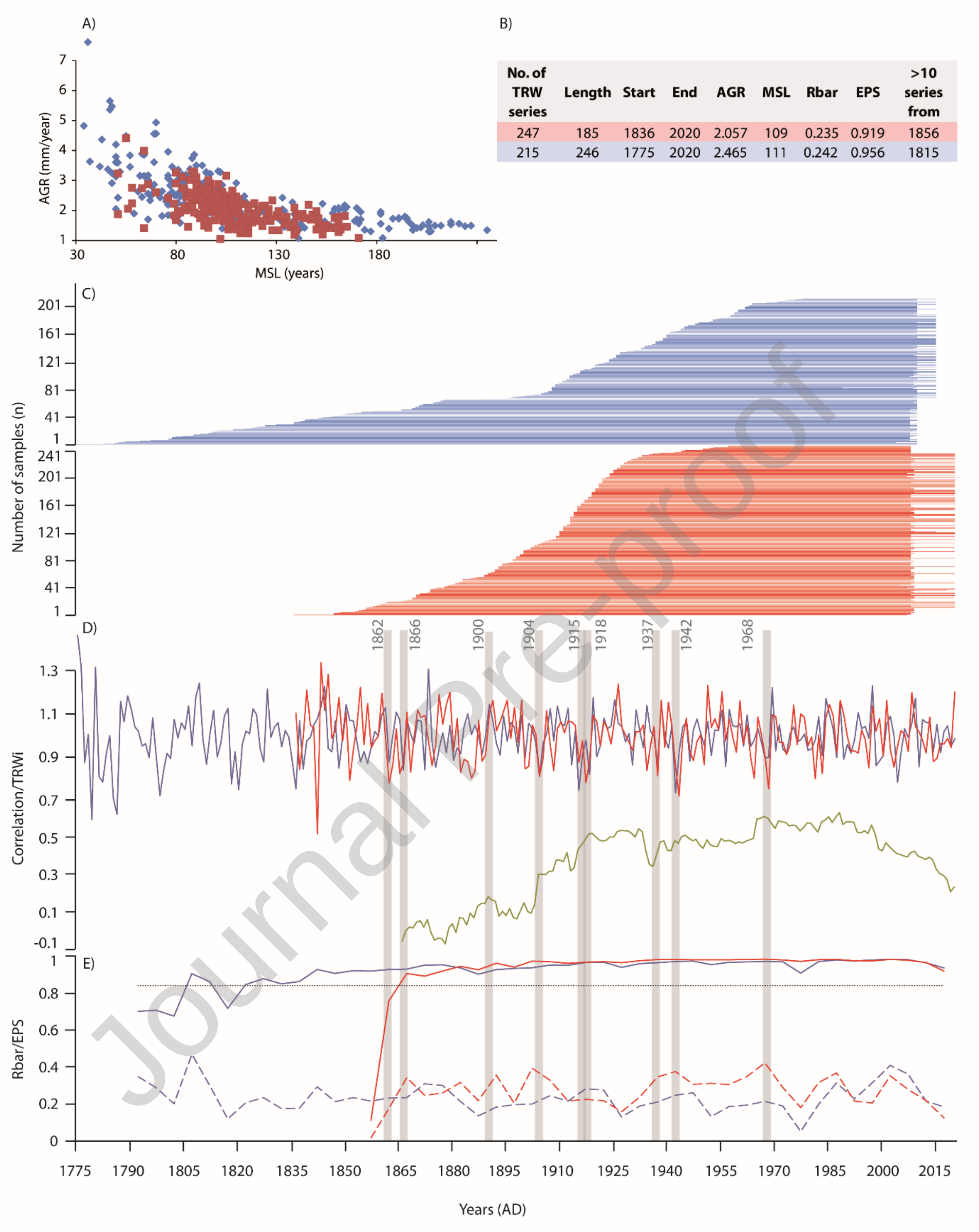


**Figure 2:** (A) The relationship between the average growth rate (AGR) in mm/year and the mean segment length (MSL) in years of each sample, (B) Table of characteristics of Ciscarpathian (blue) and Transcarpathian (red) chronologies (mean AGR (mm), mean MSL (years)), (C) Sample size of Ciscarpathian (blue) and Transcarpathian (red) chronologies, (D)

indexed TRWi based regional Ciscarpathian (blue) and Transcarpathian (red) chronologies detrended after power-transformation by 32-year cubic smoothing splines with highlighted common negative pointer years (grey), and 30-year backward moving correlation between Ciscarpathian and Transcarpathian chronologies (green), (E) the expressed population signal (EPS) (full line) with marked threshold value (orange dotted line) and the inter-series correlation (Rbar) (dashed line) calculated over 10-year windows lagged by five years.

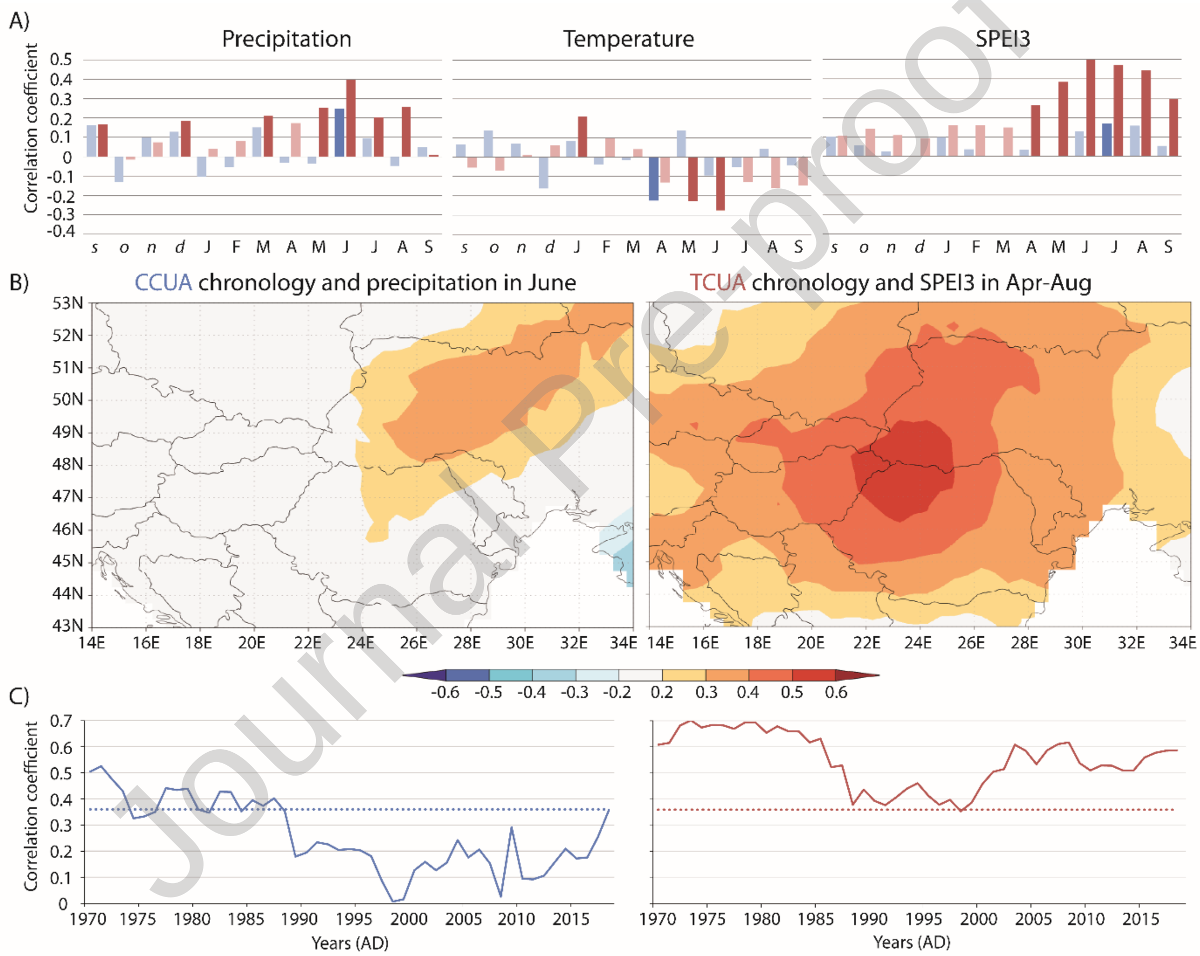


**Figure 3:** (A) Correlation between Transcarpathian (TCUA - red) and Ciscarpathian (CCUA - blue) TRW chronologies and climate from the previous September to September of the given year with highlighted significant correlation (darker colour); (B) Spatial correlations between Ciscarpathian TRW chronology and precipitation in June (left), and Transcarpathian TRW chronology and SPEI3 in April-August for TCUA (right) from CRU TS4.06 for the period

1951-2018; (C) Moving correlations between tree-ring width and most significant correlations as in (B), calculated over the previous 20 years with the significance threshold values (dotted lines).

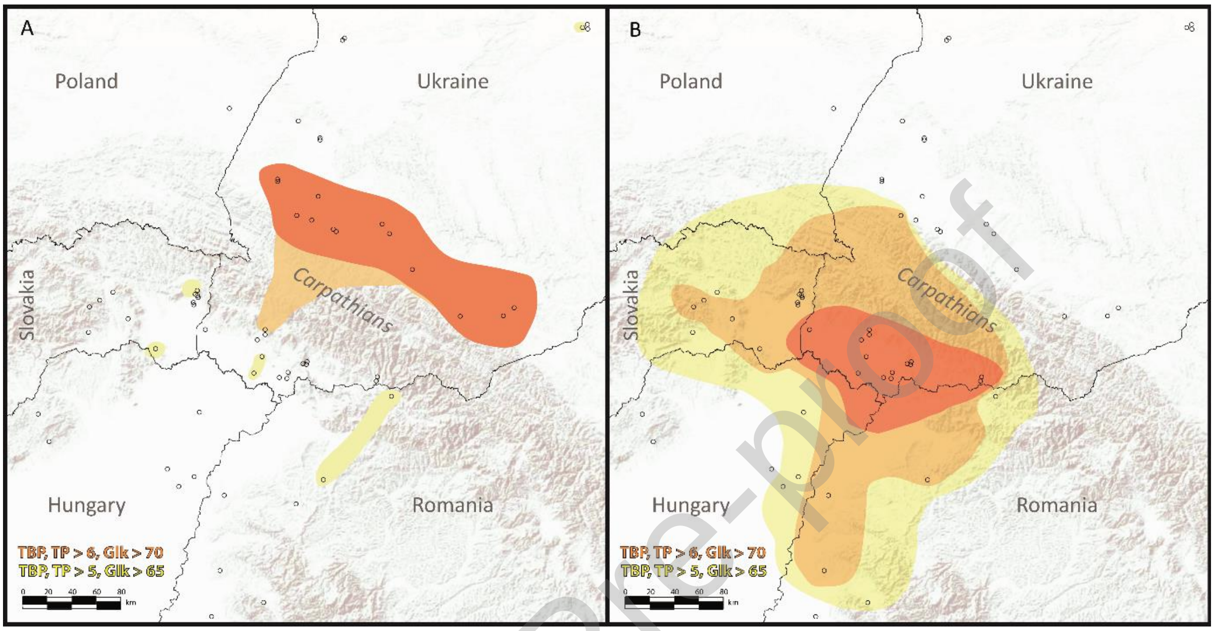


**Figure 4:** Spatial correlations of composed Ciscarpathian (A) and Transcarpathian (B) TRW chronologies with local TRW chronologies from Slovakia, Hungary, Romania, Poland and western Ukraine for the period 1931-2001; the orange area indicates correlation with t-test above 6 and Gleichläufigkeit above 70%, the yellow area t-tests above 5 and Gleichläufigkeit above 65%



**Supplementary figure captions**

**Figure S1:** Climatic diagram with average monthly mean temperature (line) and average monthly sum of precipitation (bars) for (A) Ciscarpathian and (B) Transcarpathian region for period 1951-2020, assembled from data from the CRU TS4.06 database (for area 22-24 °E, 48-48.5 °N for Transcarpathia and area 23-25.5 °E, 48-49.5 °N for Ciscarpathia).

**Figure S2:** (A) Moving correlations between Transcarpathian TRW chronology and SPEI April-August, calculated over the previous 20 years (dark red), (B) moving values of temperature (light red), (C) precipitation (blue), (D) mean SPEI-3 (green) in April-August in Transcarpathian region.

**Figure S3:** (A) Moving correlations between Ciscarpathian TRW chronology and precipitation in June (dark blue), calculated over the previous 20 years, (B) moving values of precipitation in June (light blue) in this region.

## Tables

| Site code | Location | elevation (m a.s.l.) | latitude (N) | altitude (E) | No. of samples | Length | Start | End | Rbar | EPS |
|---|---|---|---|---|---|---|---|---|---|---|
| Transcarpathia | | | | | | | | | | |
| UA 1 | Beregujfalu | 150 | 48.3075 | 22.8272 | 20 | 108 | 1900 | 2007 | 0.421 | 0.952 |
| UA 2 | Berehovo | 250 | 48.1954 | 22.7052 | 28 | 103 | 1918 | 2020 | 0.509 | 0.967 |
| UA 3 | Mukachevo | 400 | 48.4558 | 22.8931 | 22 | 121 | 1900 | 2020 | 0.491 | 0.936 |
| UA 4 | Velyki-Bychkiv | 330 | 48.0039 | 24.0160 | 16 | 161 | 1848 | 2008 | 0.546 | 0.927 |
| UA 5 | Mukachevo | 600 | 48.4963 | 22.9075 | 21 | 109 | 1912 | 2020 | 0.697 | 0.933 |
| UA 6 | Chertizh | 230 | 48.1978 | 23.2496 | 13 | 172 | 1836 | 2007 | 0.270 | 0.833 |
| UA 7 | Chorna hora | 550 | 48.1534 | 23.0695 | 12 | 102 | 1906 | 2007 | 0.537 | 0.872 |
| UA 8 | Khust | 270 | 48.1916 | 23.2750 | 14 | 154 | 1855 | 2008 | 0.219 | 0.875 |
| UA 9 | Khust | 300 | 48.2083 | 23.2790 | 16 | 142 | 1867 | 2008 | 0.362 | 0.910 |
| UA 10 | Lazy | 280 | 48.5694 | 22.2667 | 19 | 119 | 1889 | 2007 | 0.463 | 0.929 |
| UA 11 | Vodiane | 310 | 47.9792 | 23.9889 | 18 | 99 | 1910 | 2008 | 0.605 | 0.932 |
| UA 12 | Onok_Vyhogradiv | 140 | 48.1250 | 23.0056 | 26 | 118 | 1890 | 2007 | 0.320 | 0.935 |
| UA 13 | Mukachevo | 200 | 48.4339 | 22.8044 | 22 | 165 | 1856 | 2020 | 0.373 | 0.939 |
| Ciscarpathia | | | | | | | | | | |
| UA 14 | Morshyn | 393 | 49.1169 | 23.8469 | 15 | 223 | 1787 | 2009 | 0.323 | 0.773 |
| UA 15 | Kopanky | 287 | 49.0972 | 24.3803 | 10 | 114 | 1896 | 2009 | 0.420 | 0.882 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| UA16 | Drohobych | 300 | 49.3697 | 23.7352 | 22 | 124 | 1897 | 2020 | 0.384 | 0.942 |
| UA17 | Drohobych | 400 | 49.2051 | 23.6174 | 23 | 109 | 1912 | 2020 | 0.652 | 0.949 |
| UA18 | Drohobych | 500 | 49.2562 | 23.4763 | 19 | 101 | 1920 | 2020 | 0.474 | 0.888 |
| UA19 | Kopachivka | 370-420 | 48.7312 | 24.6001 | 14 | 76 | 1945 | 2020 | 0.425 | 0.749 |
| UA20 | Kobaky | 280 | 48.3270 | 25.0200 | 11 | 111 | 1898 | 2008 | 0.570 | 0.849 |
| UA21 | Valy_Vakhnivtsi | 380 | 48.3618 | 25.4784 | 28 | 77 | 1933 | 2009 | 0.325 | 0.947 |
| UA22 | Babyne | 290 | 48.3180 | 25.6114 | 26 | 155 | 1855 | 2009 | 0.397 | 0.940 |
| UA23 | Morshyn | 389 | 49.1044 | 23.8681 | 7 | 97 | 1913 | 2009 | 0.312 | 0.769 |
| UA24 | Vistova | 298 | 49.0164 | 24.4556 | 17 | 235 | 1775 | 2009 | 0.609 | 0.941 |
| UA25 | Kornalovychi | 294 | 49.5356 | 23.3392 | 12 | 212 | 1796 | 2007 | 0.463 | 0.888 |
| UA26 | Kornalovychi | 297 | 49.5322 | 23.3367 | 11 | 203 | 1805 | 2007 | 0.442 | 0.903 |

**Table 1:** List of study sites used for compilation of Transcarpathian and Ciscarpathian tree-ring width chronologies with their specifications. Study-site numbers correspond with site numbers in Figure 1.

| Site code | Location | elevation (m a.s.l.) | latitude (N) | altitude (E) | References | No. of samples | Length | Start | End |
|---|---|---|---|---|---|---|---|---|---|
| **Hungary** | | | | | | | | | |
| HU1 | Baktalórántháza | 139 | 47.9920 | 22.0480 | Kern et al., 2013 | 11 | 279 | 1731 | 2009 |
| HU2 | Debrecen E | 125 | 47.5250 | 21.8110 | Árvai et al., 2018 | 11 | 116 | 1894 | 2009 |
| HU3 | Debrecen N1 | 128 | 47.5850 | 21.6200 | | 14 | 185 | 1820 | 2004 |
| HU4 | Debrecen N2 | 128 | 47.5850 | 21.6200 | | 9 | 213 | 1789 | 2001 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| HU6 | Ózd | 260-321 | 48.2060 | 20.3500 | Morgós, unpubl. | 11 | 103 | 1899 | 2001 |
| HU7 | Sikfőkút | 310 | 47.9300 | 20.4400 | Mészáros et al., 2022 | 80 | 110 | 1910 | 2019 |
| **Slovakia** | | | | | | | | | |
| SK1 | Hlivistia | 280 | 48.8013 | 22.2407 | Sochová et al., unpubl. | 26 | 135 | 1886 | 2020 |
| SK2 | Hlivistia | 630 | 48.8403 | 22.2440 | | 14 | 174 | 1847 | 2020 |
| SK3 | Hlivistia | 400-430 | 48.8166 | 22.2372 | | 30 | 134 | 1887 | 2020 |
| SK4+5 | Sobrance | 130 | 48.7674 | 22.1921 | | 28 | 142 | 1879 | 2020 |
| SK6 | Hlivistia | 520 | 48.8270 | 22.2236 | | 27 | 199 | 1822 | 2020 |
| SK7 | Bujanov sawmill | > 400 | 48.8676 | 21.0694 | Prokop et al., 2016 | 34 | 297 | 1716 | 2012 |
| SK8 | Kokošovce sawmill | > 450 | 48.9558 | 21.3595 | | 32 | 174 | 1840 | 2013 |
| SK10 | Rudník - Čierna Moldava sawmill | > 300 | 48.6980 | 20.7823 | | 21 | 122 | 1891 | 2012 |
| SK11 | Ruské Pekľany sawmill | > 350 | 48.9012 | 21.1879 | | 38 | 132 | 1881 | 2012 |
| SK12 | Svinica sawmill | > 300 | 48.7346 | 21.4634 | | 30 | 149 | 1865 | 2013 |
| SK13 | Veľká Trňa | 285 | 48.4913 | 21.6994 | Sochová et al., unpubl. | 40 | 125 | 1897 | 2021 |
| **Romania** | | | | | | | | | |
| RO1 | Bicatei | 357 | 47.3420 | 23.2338 | Roibu et al., unpubl. | 34 | 131 | 1891 | 2021 |
| RO2 | Cararoaia | 685 | 46.5076 | 22.3577 | | 31 | 121 | 1901 | 2021 |
| RO3 | Olosia | 40 | 47.3483 | 22.1554 | | 30 | 129 | 1893 | 2021 |
| RO4 | Ronisoara | 502 | 47.8597 | 24.1264 | | 30 | 122 | 1900 | 2021 |
| RO5 | Topile | 158 | 46.8020 | 21.9757 | | 32 | 131 | 1891 | 2021 |
| RO6 | Viznic | 124 | 46.4751 | 21.7687 | | 28 | 125 | 1897 | 2021 |
| RO7 | Vârșolț | 320 | 47.2245 | 22.9347 | Popa A., unpubl. | 20 | 91 | 1931 | 2021 |
| **Ciscarpathian Ukraine** | | | | | | | | | |
| UA27 | Shypetivka | 231 | 50.2167 | 27.0244 | Sopushynskyy and Vintoniv, unpubl. | 13 | 150 | 1858 | 2007 |
| UA28 | Kamyanka | 242 | 50.2186 | 26.9947 | | 15 | 158 | 1852 | 2009 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| UA29 | Kamyanka | 240 | 50.2606 | 27.0283 | | 11 | 184 | 1826 | 2009 |
| UA30 | Lapajvka | 325 | 49.7858 | 23.8822 | | 11 | 82 | 1925 | 2006 |
| UA31 | Sokal | 239 | 50.4611 | 24.3422 | | 11 | 130 | 1876 | 2005 |
| UA32 | Lapajvka | 329 | 49.8008 | 23.8883 | | 12 | 153 | 1854 | 2006 |
| UA33 | Sokal | 257 | 50.4553 | 24.3338 | | 11 | 87 | 1919 | 2005 |
| UA34 | Lelekhivka | 298 | 51.9583 | 23.6828 | | 30 | 204 | 1804 | 2007 |
| UA35 | Vinnycja region | 280-325 | 49.0500 | 27.9050 | Ważny et al., 2014 | 23 | 217 | 1793 | 2009 |
| **Poland** | | | | | | | | | |
| PL01 | Kosobudy/Roztocze | 290 | 50.6500 | 23.0500 | Ważny, 1990 | 22 | 207 | 1782 | 1988 |

**Table 2**: List of local chronologies used for the spatial correlation of Transcarpathian and Ciscarpathian oak chronologies. Study-site numbers correspond with site numbers in Figure 1.

| Extremes | Climatic Parameter | Estimate | Std. Error | z value | p(>\|z\|) |
|---|---|---|---|---|---|
| Negative | SPEI3 (May) | -0.5798 | 0.2895 | -2.0030 | 0.0452 |
| | SPEI3 (June) | -1.1867 | 0.3415 | -3.4750 | 0.0005 |
| | SPEI3 (July) | -0.7910 | 0.3080 | -2.5680 | 0.0102 |

**Table 3:** Logistic regressions between the negative extremes (years in which values exceeded ±1.0 standard deviation) of oak TRW in Transcarpathian Ukraine and the most significant climate factors for the period 1901-2018. Only the statistics of the independent variables are listed.



**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

## Highlights

- Climate sensitivity of oak TRW chronologies divided by the Carpathian Arc differs
- Transcarpathian chronology strongly reflects summer hydroclimate conditions
- Transcarpathian chronology correlates well with Slovakian and Romanian chronologies
- Ciscarpathian chronology shows very low correlations and needs further research