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ORIGINAL PAPER

Dendroclimatic signals of pedunculate oak (*Quercus robur* L.) in Estonia

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Abstract This study investigates the climate impact on the radial increment of pedunculate oak (*Quercus robur* L.) in Estonia at the species' northern distribution limit. Tree-ring width series of 162 living oaks were compiled into three regional chronologies—western (1646–2008), northeastern (1736–2011), and southeastern Estonia (1912–2011). Although these regional growth patterns are similar to each other and even to the growth patterns in adjacent regions, spatial differences in growth responses to climate were established. Thus, oaks growing on shallow soil in western Estonia are positively influenced by summer (June–August) precipitation, and oaks on the deeper soil in northeastern Estonia are favoured by June temperature, while oaks in the southeastern part of the country depend on both July precipitation and temperature. These relationships are pronounced especially in pointer years. However, due to the impact of regional weather fluctuations on tree growth, there is a lack of correspondence between the local and the pan-European pointer years. In addition, our research presents the first tree-ring-based palaeoclimatic reconstruction for the country. Although the created model has relatively low predictive skill describing less than a quarter of the variance in actual summer precipitation in western Estonia, it has passable capacity of detecting past rainfall extremes.

Keywords Tree rings · Dendrochronology · Climate–growth relationships · Pointer years · Climate proxy · Palaeoclimatic reconstruction

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Introduction

Dendroclimatology is based on the concept that climate is the main factor for tree growth in a given year, particularly near the ecological margin of a tree species (Fritts 1976). Pedunculate oak (*Quercus robur* L.) is widely distributed throughout Europe, spreading from Ireland to the Ural Mts. and from southern Italy to the southern edge of Fennoscandia (e.g. Axelrod 1983; Meusel and Jäger 1992; Dahl 1998). In Estonia, pedunculate oak is the only oak species as sessile oak [*Q. petraea* (Matt.) Liebl.] has not reached thus far north. But in European dendrochronology, the two oak species are treated in common as they, in fact, cannot be distinguished only upon wood anatomy. Due to its long lifespan, distinct tree rings, high natural durability, and strength, oak is one of the most investigated tree genera in European dendrochronology (e.g. Eckstein 1983; Schweingruber 1993; Haneca et al. 2009). The most recent and comprehensive as well as balanced review on this topic is given by Čufar (2007).

A chronology of living trees can be cross-dated against older construction timber, archaeological wood, and subfossils from sediments in the region and thus extended into the distant past in annual resolution. These regional chronologies can be compared to annual phenomena, for example to weather records, and used for pre-instrumental palaeoreconstructions. Thus, there are a large number of long oak (*Quercus* spp.) tree-ring chronologies in Europe. For example, the Hohenheim oak chronology from Germany reaches back to 8480 BC, and combined with pine back to 10461 BC, which gives a 12,460-year-long period from AD 2000 (Friedrich et al. 2004), and the Belfast oak chronology starts from 5289 BC (Pilcher et al. 1984; Brown et al. 1986).

In Central Europe, the dendroclimatic signal of oak as disclosed by its tree-ring widths shows considerable spatial variations. Moreover, the connection between the main two factors, temperature and precipitation, is diffuse and its relevance for oak growth varies both in time and space (e.g. Eckstein and Schmidt 1974; Pilcher and Gray 1982; Bridge et al. 1996; Lebourgeois et al. 2004; Friedrichs et al. 2009). Generally, during a wet and warm growing season, a tree develops a considerably wider ring, and vice versa. However, in Slovenia where Alpine, Mediterranean, and continental climates clash, June rainfall has a positive and June temperature a negative effect on the tree-ring width of oak (Čufar et al. 2008a, b). The same is observed in Mediterranean environments (Santini et al. 1994; Tessier et al. 1994) and in Atlantic Spain (Rozas 2001, 2005) where high amounts of precipitation create favourable and high temperatures unfavourable growth conditions during summer. Poor oak growth in eastern and northern Europe is also mainly ascribed to water deficit (Bednarz and Ptak 1990; Wazny and Eckstein 1991; Askeyev et al. 2005; Cedro 2007; Drobyshev et al. 2008). Even at the oak's northern border in southern Finland, precipitation seems to be the main limiting factor (Helama et al. 2009; Hilasvuori and Berninger 2010; Sohar et al. 2014). In addition to the meteorological conditions during the current growing season, oak tree-ring series correlate with weather characteristics of the previous year or the dormancy period (Pilcher and Gray 1982; Drobyshev et al. 2008; Helama et al. 2009). In more detail, the earlywood growth may be positively associated with the preceding year's latewood width and the previous autumn and winter temperatures, while the latewood growth is related to the current growing season rainfall (Eckstein and Schmidt 1974; Nola 1996; Doležal et al. 2010).

In Estonia, pedunculate oak grows almost at its northernmost border. According to radiocarbon-dated pollen diagrams, oak arrived in Estonia between 8700 and 8300 cal BP and spread between 7600 and 4500 cal BP, with its maximum between 4700 and 3300 cal BP (Saarse and Veski 2001). Subsequently, oak forests started to decline due to a climate cooling and an increasing competition with spruce around 3200 cal BP (Saarse et al. 1999). Oak forests also diminished due to clearances for agriculture and grazing (Laasimer 1965). Timber felling, for instance, for the Imperial Russian shipbuilding industry was also a devastating factor during the eighteenth century (Daniel 1929). Nowadays, oak is dominant in only 0.3 % of the forested land (Metsakaitse- ja Metsauuenduskeskus 2009). The most common tree species in Estonia are Scots pine (*Pinus sylvestris* L.) and Norway spruce [*Picea abies* (L.) H. Karst.]; therefore, these species have already been the subject of dendroclimatic studies (e.g. Läänelaid and Eckstein 2003, 2012; Pärn 2003; Hordo et al. 2009). The response of oak growth to climatic factors, however, has been examined only in one old forest stand on the Saaremaa Island, western Estonia (Läänelaid et al. 2008).

The objectives of this study are (1) to construct a network of oak tree-ring width site and regional chronologies for Estonia, (2) to assess their climatic signals, and (3) to explore their potential as a climatic proxy.

Materials and methods

Study area and tree-ring data

Estonia is located between 57.5° and 59.5° N at the eastern coast of the Baltic Sea. It has an east–west extension of 350 km and a north–south extension of 240 km. It is lowland with an average elevation of 50 m a.s.l. reaching up to 318 m in the southeastern part of the country. The climate in the western part is affected by the sea, while in the centre and east, it becomes gradually more continental. Thus, the annual mean temperature is lower in the eastern part (4.3 °C) and increases gradually westwards (6.5 °C). The biggest spatial differences in temperature occur during winter. The annual precipitation fluctuates between 550 and 750 mm and varies spatially more during the warm half-year, based on the years 1966–1998 (Jaagus 1999). Accordingly, rainfall is higher in the southeastern Estonia during the spring and the first half of summer and lower in the western part, and vice versa during the end of summer and the autumn. In Estonia, the thermal growing season (daily mean air temperature permanently above +5 °C) starts with the climatic spring on 24 April as averaged over the whole country and ends in late autumn on 27 October, based on the years 1946–1998 (Jaagus and Ahas 2000). The thermal growing season is 10 days longer in the western and southeastern part than in the central and northeastern part of the country (Eesti Entsüklopeediakirjastus 2005).

Tree-ring samples of 162 living oak trees from 12 sites all over Estonia were collected (Fig. 1). As the tree-ring series from two close sites on the Saaremaa Island showed a high similarity (Baillie–Pilcher's *t*-value (t_{BP}) (Baillie and Pilcher 1973) 11.0 and the *Gleichläufigkeit* (GLK) (Eckstein and Bauch 1969) 73.6 %; an overlap of 165 years), these sites were combined into one. Thus, a total of 11 sites were

Fig. 1 Map of Estonia showing the sample plots (*dots*) and the meteorological stations (*triangles*)

analysed further. As oak is the dominant tree species in only 0.3 % of forest (Metsakaitse- ja Metsauuenduskeskus 2009), suitable sites were limited. Therefore, park forests and wooded meadows were also taken for sampling in addition to typical forests. Rendzic and cambic soils cover the western sites, cambic soils and Luvisols the northeastern sites, and Luvisols and Albeluvisols the southeastern sites (Estonian Soil Map 1:10,000, classification by Uuemaa et al. (2008)). The samples were taken with a 40-cm or 50-cm increment corer from the height between 100 and 130 cm and preferably from the northern side of the trunk. All the fieldwork was carried out from 1997 to 2011.

The tree-ring widths were measured to the nearest 0.01 mm on a Lintab measuring table (Heidelberg, Germany) equipped with a Leica incident light microscope. The measured values were recorded and the graphs displayed with the TSAP-Win software (Rinn 2003). The measurement quality was controlled visually from the graphs and with the COFECHA software from the Dendrochronology Program Library (DPL) (Holmes 1983). According to Fritts (1976), the first-formed rings in an inner part of stem show poorest agreement among different radii and thus yield the least information on climate. Therefore, in cases of poor synchronisation, juvenile growth rings were removed from the tree-ring series to avoid mistakes in further data processing.

Then, the tree-ring width series were standardised into residual site chronologies using the ARSTAN program (Cook 1985) or the DPL routine CRN (Holmes 1983) if sample size exceeded 95 series (i.e. computing country-wide chronology). Age-related growth trends were eliminated to reduce non-climatic variance (i.e. low-frequency noise) by detrending the raw ring series using a cubic smoothing spline that preserves 50 % of the variance at a wavelength of 60 years (Cook and Peters 1981). The curve was fitted individually to each series, and the tree-ring indices were derived from the curve as ratios between the observed ring width and the corresponding value of the curve. The tree-index series were further pre-whitened using an autoregressive model to remove autocorrelation. The annual indices were averaged across all series using a biweight robust mean estimation to reduce the effect of outliers (Cook et al. 1990). These residual site chronologies were used for the subsequent analyses.

Subsample signal strength (SSS) (Wigley et al. 1984) with a threshold of 0.85 was calculated by ARSTAN in order to estimate sample size adequacy for dendroclimatological and pointer year analysis. The sample size fulfilling the required threshold was expected to capture the theoretical population signal in the tree-ring variation.

The similarities between the residual site chronologies were assessed by the t_{BP} and GLK calculated for a common overlap period 1934–1997 in the TSAP-Win software (Rinn 2003). In order to group the site chronologies, an S-mode principal component analysis (PCA) was carried out with the STATISTICA 7 software package. The initial data matrix consisted of the tree-ring indices at 11 sites during the common period 1934–1997.

We assessed teleconnection, i.e. similarity between the chronologies from distant sites (Kaennel and Schweingruber 1995), between our chronologies and oak data from the neighbouring areas—Finland (Helama et al. 2009; Sohar et al. 2012, 2014), Latvia and Lithuania (Sohar et al. 2012), and Poland (Wazny and Eckstein 1991; NOAA International Tree-Ring Data Bank, www.ncdc.noaa.gov/paleo/treering.html), calculating the previously mentioned similarities between the residual chronologies for a maximal overlap period between each data set pair. We observed heteroconnection, i.e. similarity between the chronologies of different tree species from the same area (e.g. Čufar et al. 2008b), between our oak and the local conifer chronologies (Läänelaid et al. 2012; Läänelaid and Eckstein 2012).

Meteorological data

The tree-ring width variability in each of the eleven sites was correlated with the data from the nearest available meteorological station, provided by the Estonian Meteorological and Hydrological Institute (EMHI). Monthly mean temperature, monthly minimum temperature in April, May, and June, and monthly precipitation were used. The latter was interpolated for the sites based on the four closest stations. The gaps in the temperature time series were filled with data from the neighbouring stations using a linear regression model. Meteorological data homogeneity was tested through cumulative differences. In the regional dendroclimatological analysis, we used average weather data from the stations.

In addition, monthly North Atlantic Oscillation (NAO) indices as measures of the intensity of westerlies were used (Hurrell 1995; NAO Index Data provided by the Climate Analysis Section, NCAR, Boulder, USA, http://climatedataguide.ucar.edu/guidance/hurrell-north-atlantic-oscillation-nao-index-station-based). The NAO index is calculated as the difference of normalised sea level pressure between Lisbon, Portugal, and Stykkisholmur/Reykjavik, Iceland, since 1864. Its positive values are associated with stronger westerlies, while negative values reflect weaker westerly airflow and mostly meridional circulation.

Dendroclimatological analysis

The relationships between tree-ring width and the meteorological data were examined using the DendroClim2002 program (Biondi and Waikul 2004). It uses bootstrapped confidence intervals to estimate the significance ($p < 0.05$) of Pearson's correlation (r) and response function (R) coefficients. In response functions, the coefficients are multivariate estimates from a principal component regression model (Briffa and Cook 1990). Here, the 17-month window from previous May through to current year September was used. As the recorded climate series differed in length, the analysed time interval varied among the sites. The NAO index series was the longest one, extending back to 1865, and the correlation dynamics were calculated by moving 60-year intervals.

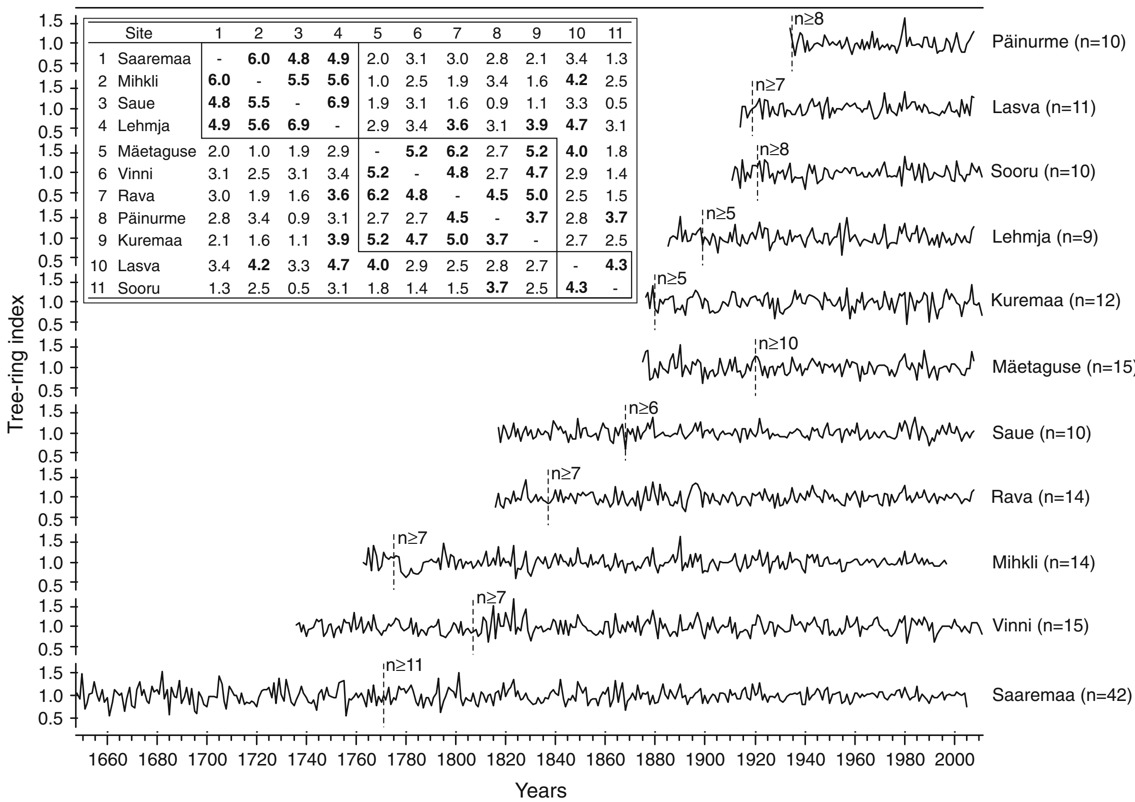
Pointer years, which indicate years with conspicuous features like exceptionally narrow or wide rings within a group of trees (Schweingruber et al. 1990), were calculated using the Weiser program (García González 2001). Combined criteria of pointer interval (threshold 75 %) and pointer value (5-year window; threshold 50 %) were used. The climate–growth relationships within the pointer years were quantified using Spearman's rank correlation (ρ).

Climate reconstruction

The most important weather variable for tree growth was chosen for the historical reconstruction. A transfer function was used, where the tree-ring data serve as the predictor and the climatic data as the predictand variable (Fritts 1976). In this study, a simple linear regression was used to develop a model for reconstructing the climatic variable.

In order to test the reliability of the model, a cross-calibration/verification procedure (e.g. Briffa et al. 1988) was adopted. First, the full overlap period (1920–2008) between the tree-ring set and the instrumental weather data was divided into two subperiods (1920–1963 and 1964–2008). The early period was used for calibration and the late period for verification, and vice versa. The statistics used for the verification were the reduction of error (RE), coefficient of efficiency (CE), and the first difference sign test (ST) (e.g. Fritts 1976; Briffa et al. 1988; Fritts et al. 1990). RE and CE can range from negative infinity to a maximum value of 1.0, and any positive value indicates that the model has some skill. The first difference sign test is a nonparametric procedure that counts the number of agreements and disagreements between the actual and the reconstructed series subtracting the value of a year from the value of the previous year.

Finally, the reconstruction equation was recalibrated using the entire overlap period. In the new tree-ring-based palaeoclimatic reconstruction, two classes of positive and negative deviations from the mean were determined. Reconstructed values outside the mean $\pm$ 1.28 standard deviation (SD) refer to years with "strong" weather conditions, and values outside the mean $\pm$ 1.645 SD refer to years



Site	1	2	3	4	5	6	7	8	9	10	11
1 Saaremaa	-	**6.0**	**4.8**	**4.9**	2.0	3.1	3.0	2.8	2.1	3.4	1.3
2 Mihkli	**6.0**	-	**5.5**	**5.6**	1.0	2.5	1.9	3.4	1.6	**4.2**	2.5
3 Saue	**4.8**	**5.5**	-	**6.9**	1.9	3.1	1.6	0.9	1.1	3.3	0.5
4 Lehmja	**4.9**	**5.6**	**6.9**	-	2.9	3.4	**3.6**	3.1	**3.9**	**4.7**	3.1
5 Mäetaguse	2.0	1.0	1.9	2.9	-	**5.2**	**6.2**	2.7	**5.2**	**4.0**	1.8
6 Vinni	3.1	2.5	3.1	3.4	**5.2**	-	**4.8**	2.7	**4.7**	2.9	1.4
7 Rava	3.0	1.9	1.6	**3.6**	**6.2**	**4.8**	-	**4.5**	**5.0**	2.5	1.5
8 Päinurme	2.8	3.4	0.9	3.1	2.7	2.7	**4.5**	-	**3.7**	2.8	**3.7**
9 Kuremaa	2.1	1.6	1.1	**3.9**	**5.2**	**4.7**	**5.0**	**3.7**	-	2.7	2.5
10 Lasva	3.4	**4.2**	3.3	**4.7**	**4.0**	2.9	2.5	2.8	2.7	-	**4.3**
11 Sooru	1.3	2.5	0.5	3.1	1.8	1.4	1.5	**3.7**	2.5	**4.3**	-

Fig. 2 The 11 Estonian oak site chronologies; the *short dashed lines* mark the year from which on SSS $\geq$ 0.85. The t_{BP}-values between the chronologies refer to the common period 1934–1997, values $\geq$3.5 are in **bold** (*inset*)

with "extreme" weather conditions (Neuwirth et al. 2007; Čufar et al. 2008a). Subsequently, these years in the reconstructed time series were validated with the historical extraordinary weather events in Estonia from 1713–1870, as compiled from several sources by Vahtre (1970), in addition to the instrumentally recorded data from the EMHI.

Results

Chronologies

The 11 site chronologies were 75 up to 358 years long (Fig. 2). According to the t_{BP}-values, three regional groups were distinguished during the common interval 1934–1997: the western (Saaremaa, Mihkli, Saue, Lehmja), the northeastern (Mäetaguse, Vinni, Päinurme, Kuremaa), and the southeastern group (Lasva, Sooru). Tree-ring width averaged over all measurements was 1.2, 1.7, and 2.6 mm at the western, the northeastern, and the southeastern sites, respectively. The mean sensitivity indicating the year-to-year variability between adjacent ring widths (Fritts 1976) was 0.19, 0.21, and 0.21 in the respective regions.

The PCA of the 11 site chronologies confirmed their aforementioned discrimination in three regional groups (Fig. 3). The PC1 described 43 %, the PC2 13 %, and the PC3 10 % of the variance in the chronologies. The distribution of the site chronologies along the PC1-axis did not show any grouping, suggesting that the PC1 contained a high amount of common variance throughout the whole country; only the distribution of the site chronologies along the PC2-axis resulted in a clear geographical grouping into three clusters. The PC1 could be associated with the countrywide summer (June–August) precipitation ($r = -0.37$; $p < 0.05$) and did not vary much across the sites ($-0.5 \ldots -0.7$). Accordingly, during wet summers, considerably wider rings were built than during dry summers. The PC2 correlated both with the countrywide summer precipitation ($r = 0.33$; $p < 0.05$) and summer temperature ($r = -0.32$; $p < 0.05$), i.e. it reflected dry/warm, respectively, wet/cool summers. Thus, the impact of drought on tree rings was more pronounced in the western sites than in the eastern sites. Along the PC3-axis, the northeastern and the western sites could not be distinguished from each other; only the two southeastern sites were separated into their own group. The PC3 reflected the prior winter conditions as it significantly correlated with winter (December–February) precipitation in southern Estonia ($r = -0.28$) and with January temperature in western Estonia ($r = -0.25$).

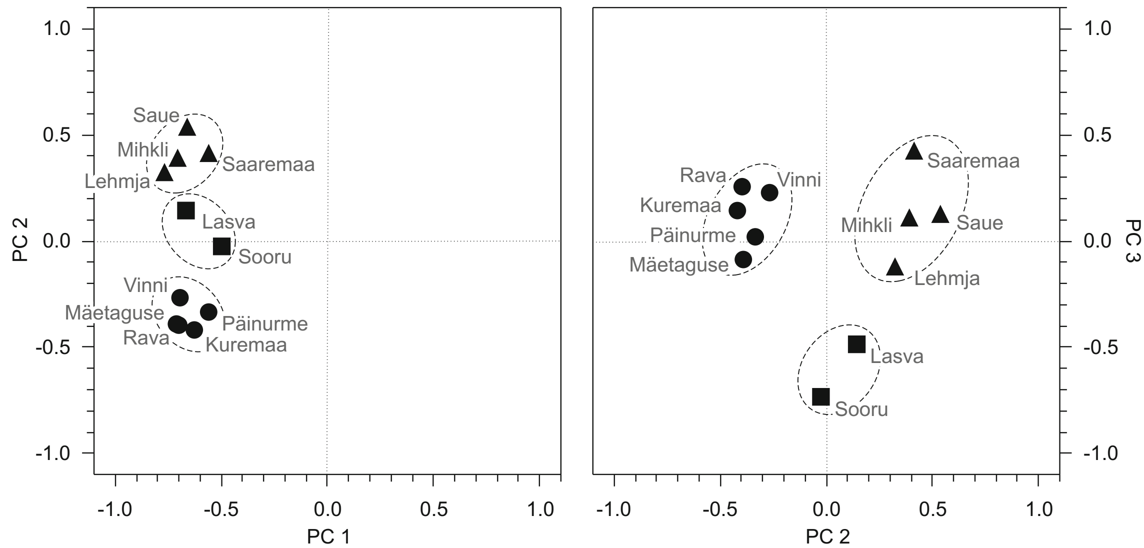


Fig. 3 Distribution of the site chronologies along the PC1-axis versus the PC2-axis (*left*) and along the PC2-axis versus the PC3-axis (*right*); *filled triangle* western, *filled circle* northeastern, *filled square* southeastern sites

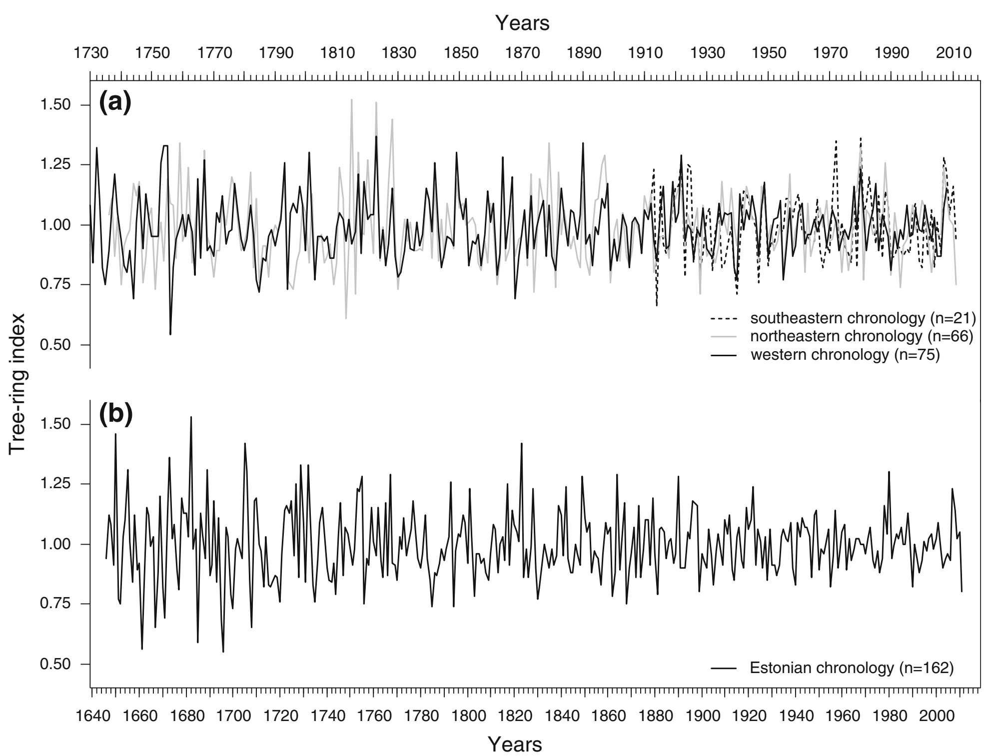


Fig. 4 Three regional residual oak chronologies within their overlap period (**a**) and the countrywide Estonian residual oak chronology (**b**)

The regional chronologies are presented in Fig. 4a: the western (1646–2008; the period 1730–2008 is shown in the figure), the northeastern (1736–2011), the southeastern Estonian chronology (1912–2011), and the total countrywide chronology based on the 162 oaks (1646–2011) in Fig. 4b. The three regional chronologies displayed mutual similarity; the t_{BP}-value between the western and the northeastern chronology was 8.5 (273 overlapped years), 4.8 (97) between the western and the southeastern, and 4.8 (100) between the northeastern and the southeastern chronology. The t_{BP}-values and the GLK between the average Estonian oak chronology and the adjacent regional chronologies were as follows: 10.3/68 % with 193 overlapped years with the Latvian chronology; 8.5/69 % and 269 with

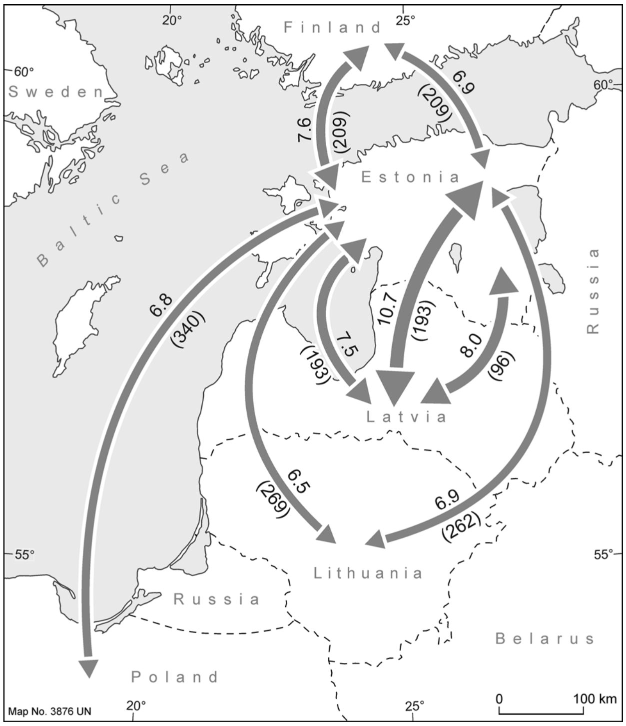


Fig. 5 Similarities between the three Estonian regional oak chronologies and Finnish, Latvian, Lithuanian, and East Pomeranian (northern Polish) regional oak chronologies; t_{BP}-values ≥ 4 and the number of overlap years (in *brackets*) are given

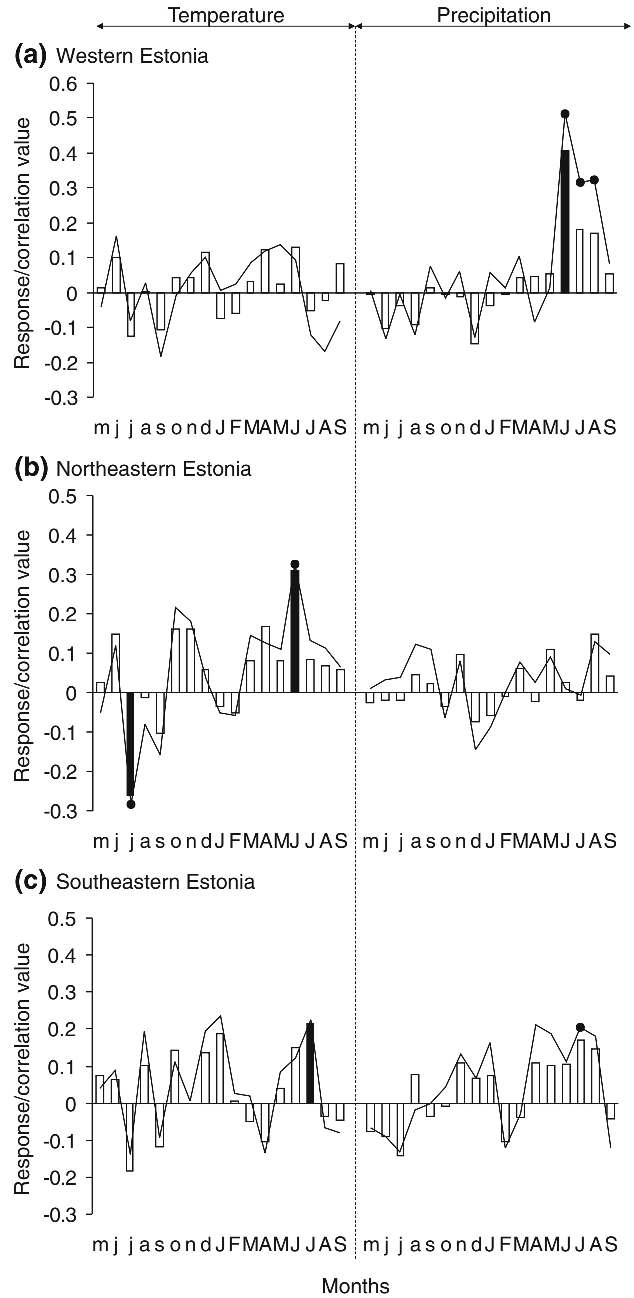


Fig. 6 Correlation coefficients (*lines*) and response values (*bars*) between the tree-ring widths and the monthly meteorological variables from the previous (*lower case letters*) and current years (*capital letters*) during 1945–2008; statistically significant relationships ($p < 0.05$) are indicated by *dots on the lines* and by *filled bars*

the Lithuanian chronology; 7.8/65 % and 209 with the Finnish chronology; and 7.1/63 % and 340 with the East Pomeranian (northern Polish) chronology. Figure 5 shows the teleconnection between three Estonian regional chronologies and adjacent countries in more detail. However, there was no significant similarity across the tree species in Estonia as the t_{BP}-values between the oak, the pine (Läänelaid et al. 2012), and the spruce chronologies (Läänelaid and Eckstein 2012) remained below four.

According to the SSS, the chronologies with the shorter extensions for the western (1769–2008; at least 15 trees), the northeastern (1815–2008; 11), and the southeastern region (1919–2008; 13) were used in the dendroclimatological analyses hereafter. For the total Estonian chronology, the period 1769–2008 with at least 22 trees was considered representative.

Weather–growth relationships

The bootstrapped correlation and response functions revealed that June (in Saaremaa, Saue, Lehmja) or all summer precipitation (in Mihkli) positively influenced oak tree-ring width in the western sites. To a lesser degree, growth was negatively influenced by the previous year's June precipitation (in Saaremaa, Lehmja) and by the previous year's July temperature (in Lehmja, Saue), too. In general, the western regional oak chronology was positively correlated with June, July, and August precipitation ($r = 0.51$; $r = 0.32$; $r = 0.32$, respectively, $p < 0.05$), with a positive response coefficient to June rainfall only ($R = 0.41$, $p < 0.05$). No previous year's weather characteristic was significant (Fig. 6a).

The results in the northeastern sites were less uniform. June temperature was the main limiting factor in Mäetaguse, Rava, and Vinni. In Mäetaguse July temperature and in Vinni April temperature and September precipitation were also positive factors. In Päinurme, September temperature and August rainfall controlled growth positively. The previous year's July temperature was a negative factor in Mäetaguse and Rava, while the previous year's June temperature was a positive factor in Päinurme. In Kuremaa, no significant climatic variable could be identified. In general, the regional northeastern oak chronology showed a positive correlation with June temperature ($r = 0.33$ and $R = 0.31$, $p < 0.05$) and a negative correlation with the previous year's July temperature ($r = -0.28$ and $R = -0.26$, $p < 0.05$) (Fig. 6b).

In the southeastern sites, the relationships between growth and the weather variables were weaker than in the western and northeastern sites. Yet, in Lasva, growth was positively influenced by May and July precipitation and in Sooru by April precipitation and July temperature. In general, July precipitation ($R = 0.21$) and July temperature ($r = 0.22$) were the significant factors to growth in the southeastern region. No previous year's weather characteristic was significant (Fig. 6c).

Correlations between the tree-ring indices with April, May, and June monthly minimum temperatures showed no statistically significant positive relationships. It appears that occasional frosts at the beginning of the vegetation periods did not significantly affect the tree-ring development during the ongoing growing season. Alternatively, occasional frosts may have lacked in the monthly minimum temperature record.

The March NAO index was positively related to oak growth in the northeastern region during 1866–2008 ($r = 0.29$; $p < 0.05$). In the southeastern region, the NAO indices of previous December and May correlated with growth during 1919–2008 ($r = 0.22$ and $r = 0.28$, respectively, $p < 0.05$). In the western region, the relationships were statistically insignificant. There was a continuous significant correlation between the March NAO index and northeastern oak growth during most of the observed period (Fig. 7).

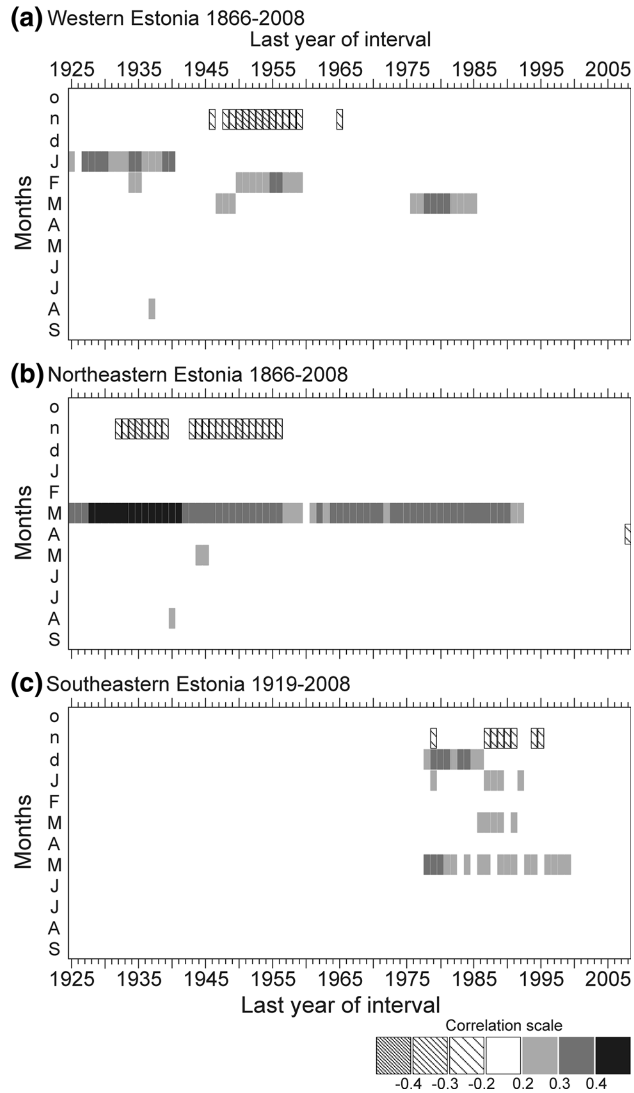


Fig. 7 Moving correlation coefficients ($p < 0.05$) between the chronologies and the monthly NAO indices of the previous (*lower case letters*) and the current years (*capital letters*) using a 60-year interval

Pointer years

Altogether, 19 positive and 19 negative pointer years, with exceptionally wide or narrow rings, respectively, were identified for the period 1769–2008, covered by at least 22 trees in the Estonian chronology (Table 1).

In the western region with 15–75 trees (1769–2008), the analysis revealed 23 positive and 28 negative pointer years (Table 1). There, the pointer-year tree-ring indices were positively correlated with June precipitation (Spearman's correlation $\rho = 0.70$; $p < 0.05$) and with June–August precipitation ($\rho = 0.56$; $p < 0.05$). According to the *t* test, mean June precipitation and mean June–August precipitation in the negative pointer years were significantly lower than during the ordinary years, while in the positive pointer years, the precipitation did not differ significantly from the ordinary years ($p > 0.05$).

In the northeastern region with 11–66 trees (1815–2008), we observed 23 negative and 23 positive pointer years (Table 1). Similarly, to the western region, June weather was important to the pointer-year tree-ring width indices, but in this region, it was June temperature that mattered ($\rho = 0.64$; $p < 0.05$). Temperature differed significantly from the multi-annual average only in the negative pointer years ($p < 0.05$) as precipitation did in the western region.

The southeastern region with 13–21 trees (1919–2008) showed 13 exceptionally narrow and 13 exceptionally wide

Table 1 Positive (+) and negative (−) pointer years in the Estonian oak chronologies

Year	EST	W	NE	Year	EST	W	NE	SE
1770	−	−		1901		−		
1777		+		1905	−	−		
1782	+	+		1909		−		
1785	−	−		1910			+	
1793	+	+		1914	−	−		
1794	−	−		1916	+	+		
1800	−	−		1919		+		
1801	+	+		1922	+	+		+
1803	−	−		1923				−
1811	+	+		1924				+
1815			+	1928			−	−
1816			−	1932				−
1817	+	+	+	1935			+	
1818		−		1938			+	
1820			+	1940	−	−		
1822			−	1942				+
1823	+	+	+	1947	−	−	−	−
1826	−	−	−	1949		+		+
1828	+	+	+	1950		−		−
1830	−		−	1955	−	−	−	
1833		+		1956				+
1834			+	1957	+	+	+	
1841			−	1962			−	
1842	+	+	+	1966				+
1845			−	1969		−		
1846			+	1972				+
1849	+	+	+	1973		−		
1853		−		1974			−	
1857	−		−	1977				−
1860			+	1978		+		+
1862	−	−	−	1979				−
1864	+	+	+	1980	+	+	+	+
1867	+			1981			−	
1868	−	−		1982		−		
1872	−	−	−	1985		+		−
1873	+	+	+	1986		−		
1874	−		−	1987				−
1876			+	1988			+	+
1878		−		1990	−	−	−	−
1879	+		+	1993			−	
1881	−	−	−	1997			+	+
1883		+		1999				−
1885		−		2001				+
1889			−	2003			−	
1890	+	+	+	2004				−
1892			−	2006				−
1893		−		2007	+		+	+
1899			−					

EST Estonian, *W* western, *NE* northeastern, and *SE* southeastern Estonian chronology

rings, i.e. pointer years (Table 1). No significant correlations yielded from the pointer-year analysis in that region.

Precipitation reconstruction

As summer rainfall displayed the highest association with tree-ring width in the western part of the country for the period 1920–2008 ($r = 0.45$; $p < 0.01$), this feature could be reconstructed most accurately. Since only the current year's precipitation was significant, the single predictor could be used in the transfer function. Figure 8 shows the instrumentally recorded precipitation against its tree-ring-based estimation, with the cross-calibration/verification statistics. The two subperiod models had an evenly significant predictive skill as both explain 21 % of the variance ($p < 0.01$). Two of the verification statistics, RE and CE, were positive and thus indicated a reasonable model. As a caveat, ST was not statistically significant (24 agreements against 19 disagreements) for the early period.

The full calibration was performed over the common period 1920–2008. The final transfer function was

$$P_t = 2.712 \times TRWI_t - 71.685 \quad (1)$$

where P_t was the reconstructed summer precipitation (June–August) for year t, and $TRWI_t$ was the tree-ring width index for the year t. This model explained 21 % of the variance in the instrumentally observed precipitation series.

As the western tree-ring chronology captured the climatic signal since the year 1769 (according to the SSS statistic), the precipitation reconstruction was extended until that date. Figure 9 illustrates the precipitation anomalies as deviations from the reconstruction mean (195 mm). The years with extreme positive deviations (the mean + 1.645 SD), i.e. the wettest years were as follows: 1793, 1801, 1817, 1823, 1842, 1849, 1864, 1867, and 1890 and with strong positive deviations (the mean + 1.28 SD): 1777, 1798, 1819, 1828, 1839, 1883, 1898, 1916, and 1919. Years with extreme negative deviations (the mean − 1.645 SD), i.e. the driest years were as follows: 1784, 1785, 1794, 1803, and 1868 and with strong negative deviations (the mean − 1.28 SD): 1830, 1831, 1844, 1862, 1881, 1899, and 1905. The extreme droughts and rainfalls described in the historic sources (Vahtre 1970) coincided partly with the pointer years identified in the western tree-ring chronology (Fig. 9). The moderate agreement between the reconstruction anomalies and the

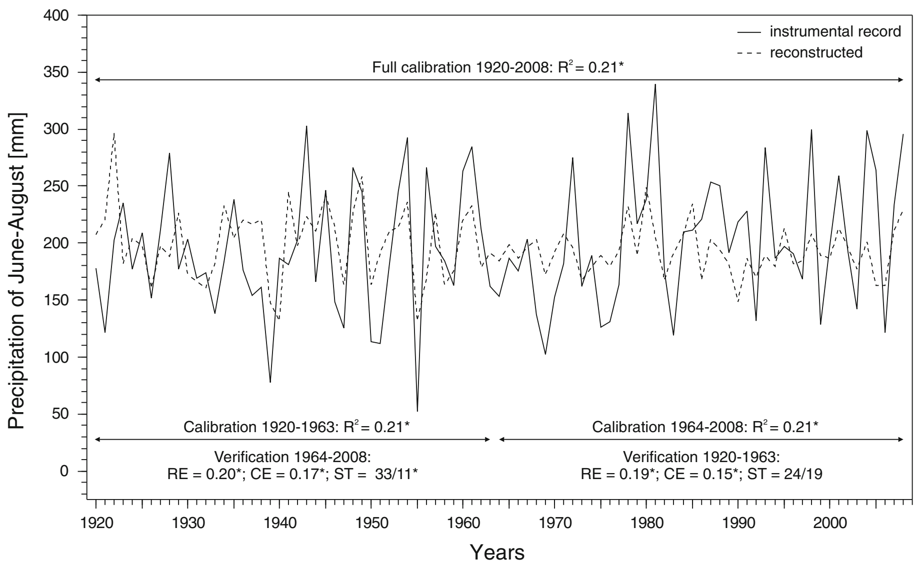


Fig. 8 Calibration and verification statistics for the tree-ring-based reconstruction of summer precipitation. The full calibration period (1920–2008) is divided into two subperiods for the cross-verification. The statistics are the coefficient of determination (R^2), reduction of error (*RE*), coefficient of efficiency (*CE*), and the first difference sign test (*ST*); significance at $p < 0.01$ is marked with an *asterisk*

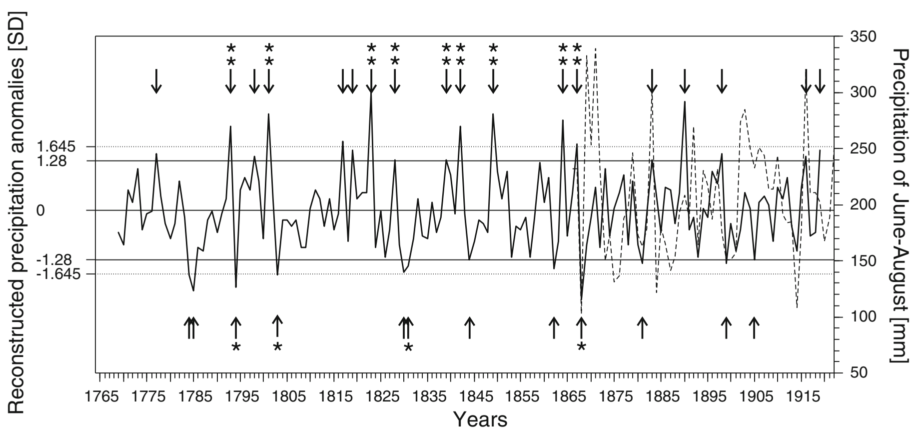


Fig. 9 Reconstructed summer precipitation (*solid line*) for the period 1769–1919 in western Estonia and instrumentally recorded summer precipitation (*dashed line*) in Estonia. The *arrows* show the years with strong (mean ± 1.28 SD) and extreme (mean ± 1.645 SD) weather conditions in the reconstructed precipitation series, and *single asterisks* represent extreme droughts and *double asterisks* extreme rainfall during the summer according to historical sources in Estonia until 1870 (Vahtre 1970)

historical indications made sense as the reconstructed western precipitation did not show a significant relationship with the instrumentally recorded summer precipitation over the whole Estonia (1866–1919; $r = 0.26$; $p > 0.05$). That is, the reconstruction may still have been spatially representative of the precipitation variability in the target region.

Discussion

Regional pattern

The analysed 162 oak samples constitute the Estonian oak chronology. However, no older trees accrued as compared to the earlier tree-ring study of oaks on the Saaremaa Island (Läänelaid et al. 2008). We distinguished three groups among the Estonian oak data set (Figs. 2, 3). The PC1 showed no evidential grouping and can be associated with summer precipitation as a common transregional factor. The PC2 identified three groups: the western, the northeastern, and the southeastern sites. This factor may be ascribed to summer drought. The third PC reflected the cold season differences. The spatial differences can be attributed to the regional climatic differences caused by the influence of the Baltic Sea as described in "Study area and tree-ring data" section.

In the larger scale, the regional tree-ring pattern in Estonia resembles the Latvian oaks (Fig. 5). The western ($n = 75$) and the northeastern oaks ($n = 66$) are similar to the oaks growing in Finland and in Lithuania as well. Only the western oak chronology shows similarity with the East Pomeranian (northern Polish) oaks. Both of these represent Baltic coastal areas under sub-Atlantic climate. Thus, northern Poland is the southern limit of the region in which some teleconnection with Estonian oaks can be established. For example, there is no remarkable similarity with the Czech chronology (Kolář et al. 2012). The weak similarity between the southeastern chronology and the farther regions (t_{BP}-values < 4) may at least partially be caused by a lower sample replication ($n = 21$) and therefore a larger influence of site-specific factors in the chronology. In the future, more samples from the southern and central regions should be added to the Estonian chronology. According to previous pine-ring studies, Estonia belongs to the Baltic Sea dendrochronological region (Läänelaid 2001; Läänelaid et al. 2012). However, the Estonian pine chronologies show a better similarity with the western (Swedish) chronologies than with the northern (Finnish) and the southern (Latvian) chronologies. Similarly, both previously published pine chronologies and our oak-ring series from western Estonia correlate well with their intraspecific Polish chronologies. In the future, the teleconnection on the westward–eastward gradient should be studied. It can be assumed that the northeastern and/or the southeastern chronology matches with the Russian one, and the western chronology with the Swedish one. Due to the divergence between oak and conifers, heteroconnection with other deciduous species (e.g. ash) should be investigated as soon as these chronologies will be created.

Climatic signals

Our dendroclimatic analysis showed that the western oak chronology reflects mostly the summer (June) rainfall variability (Fig. 6a). As these sites are located on shallow soils on carbonate rock (rendzic soils), dry summers likely cause water stress. The importance of summer precipitation for oak growth has been known for long (Stewart 1913) and has been described widely around Europe (e.g. Pilcher and Gray 1982; Santini et al. 1994; Tessier et al. 1994; Bridge et al. 1996; Rozas 2001, 2005; Lebourgeois et al. 2004; Čufar et al. 2008a, b; Friedrichs et al. 2009). These findings are supported by similar regions from Finland (Hilasvuori and Berninger 2010), Sweden (Drobyshev et al. 2008), and Poland (Cedro 2007; Bronisz et al. 2012). Similar to our findings here, the vulnerability of oaks to water deficit was increased in the shallow soil in southern Finland (Helama et al. 2009; Sohar et al. 2014).

By contrast, the northeastern Estonian chronology demonstrated an enhancing June temperature effect, while precipitation did not significantly impact growth (Fig. 6b). The lack of summer precipitation effect could be attributed to the deeper and drought-resistant soils where roots are more steadily provided with water. Matisons et al. (2013) have demonstrated that oak growth depends positively on spring and summer temperatures in the subcontinental western part of Latvia, similar to our results from northeastern and southeastern Estonia with similar soils. On the other hand, the oaks in the continental eastern Latvia prefer milder winters and suffer from excess soil water. According to Ruseckas (2006), the positive correlation between summer temperature and tree-ring width occurs only in the temporarily inundated sites in Lithuania; the oaks growing in well-drained sites prefer a moist, warm summer. However, other studies from the eastern Baltic region have shown a negative effect of summer temperature (Wazny and Eckstein 1991; Cedro 2007; Drobyshev et al. 2008). There is a negative correlation between summer precipitation and temperature in Estonia (e.g. $r = -0.34$ ($p < 0.05$) based on the period 1934–1997), which distinguishes dry and warm from wet and cool summers. The relationship is stronger in continental mainland ($r = -0.40$; $p < 0.05$) and weaker in submaritime areas ($r = -0.28$; $p < 0.05$). Thus, cool weather can enhance oak radial growth only through increased rainfall. High summer temperatures do not limit oak growth on drought-resistant soils near the species' northern distribution limit, i.e. temperature does not exceed the optimum there.

In southeastern Estonia, the climate impact is not as pronounced as in other regions, but both a moist and a warm growing season seems favourable (Fig. 6c). As these sites lay on sandy soils which are more vulnerable for droughts, the positive effect of soil moisture makes sense.

It is known that oak radial growth can depend on weather characteristics of the preceding year or the dormancy period (e.g. Pilcher and Gray 1982; Drobyshev et al. 2008; Helama et al. 2009). In this work, only temperature-dependent oaks from the northeastern region showed a significant negative impact of the previous year's July temperature on radial growth (Fig. 6b). This inverse relationship is hard to explain, but a hypothesis may be that during a warm and effective growing season, structural carbohydrate reserves deplete and thus following year's growth is scarce, as it has been shown on beech (Drobyshev et al. 2010).

The importance of June climate conditions, pertaining to both temperature and precipitation, is evident for the western and northeastern regions. Oak earlywood vessels enlarge within a short time in spring, between the bud break and the leaf expansion (Sass-Klaassen et al. 2011). According to leaf phenophases, oak in Estonia starts to foliate on 22 May on average, based on the years 1948–1996 (Ahas et al. 2000). Depending on the early- or late-foliating variety, oak leaves in Estonia can expand between the first decade of May and the end of the month (Laas et al. 2011). Thus, earlywood formation can be associated with May and/or the previous autumn and winter temperatures (Eckstein and Schmidt 1974; Nola 1996; Doležal et al. 2010). As annual ring width varies more in accordance with latewood than with earlywood (Doležal et al. 2010; Matisons and Brūmelis 2012; Sohar et al. 2014), it can be assumed that in Estonia the latewood width is predetermined mainly by the June conditions.

In addition to temperature and precipitation, tree-ring width can be efficiently correlated with the large-scale atmospheric circulation using, for example, the Southern Oscillation index (e.g. Rozas and García González 2012) or the North Atlantic Oscillation index (e.g. Roig et al. 2009). The latter describes the intensity of the westerlies and is correlated with air temperature, precipitation, snow cover, and sea ice during the winter in northern and central Europe (Hurrell 1995; Hurrell and van Loon 1997; Jaagus 2006a, b). Based on our results, oak growth is less clearly defined by the NAO indices (Fig. 7) in comparison with pine growth in Estonia (Läänelaid et al. 2012). Oak tree-ring width is affected significantly by the March NAO-index only in the northeastern sites (Fig. 7b). Generally, this means that on these sites, wider tree rings form during the years with a positive NAO phase, which describes intense westerlies with mild, snowless winters. In such years, spring starts earlier and probably the vegetation period is longer; hence, wider tree rings can form.

In general, it can be suggested that oak radial growth is more complex and cannot be defined strictly by monthly weather parameters. Therefore, more detailed weather data should be used to achieve stronger relationships in the future; for example, daily or weekly data for calculating real growing season length (e.g. Lebourgeois et al. 2004, Beck et al. 2013). In addition, increasing the sample replication at least in the southeastern region in the future may lead to a stronger climatic signal.

Pointer years in European context

The identified pointer years reflected regional weather extremes, especially the narrow tree rings coinciding with the dry summers in the western region and with the cool summers in the northeastern part of the country. However, comparing our pointer years with the pan-European oak signature years (Kelly et al. 2002), we have to admit a lack of correspondence. The coincidence between the local and the large-scale negative pointer years is pronounced in the year 1940 and less in the years 1909, 1923, and 1928, during which the growth decreased but only in some parts of Estonia. The positive pointer years coincided only in some parts of the country in 1910, 1924, and 1978. There are even years that show a contrary course to the pan-European data sets (1950, 1956, 1962, and 1979). This may be caused by the higher sample size and the westward-tilted geographical distribution of the European-wide data set. The differences imply that the Estonian pointer years reflect the local weather variations. Similar results have been concluded upon Swedish oaks as well (Drobyshev et al. 2008). Nevertheless, comparing the Estonian pointer years with the adjacent Latvian pointer years (Matisons et al. 2013), more similarities become evident. For instance, common negative pointer years occurred in 1909, 1914, 1928, 1932, 1940, 1947, 1955, 1977, 1986, 1993, and 2004 and common positive pointer years in 1919, 1922, 1938, 1957, 1978, 1980, 2001, and 2007, both on country or regional scale. Also, common negative pointer years with Swedish oaks are observed in 1868, 1940, and 1947 (Drobyshev et al. 2008). In addition to these years, a pronounced growth decrease was observed in 1990 all over Estonia. Countrywide negative pointer years during the twentieth century can be coupled with drier June (less precipitation than one standard deviation from the mean; years 1905, 1940, and 1990) or drier summer (June–August; years 1914, 1947, and 1955). On the other hand, not all dry growing seasons promote exceptionally narrow tree rings (e.g. summer 1992), and thus, there may be other climatic reasons behind the conspicuous tree-ring growth decrease.

Reconstructed precipitation

The western chronology explained 21 % of the variance in the instrumentally observed summer precipitation. This result is rather modest compared to other oak tree-ring width-based reconstructions of European hydroclimates. For instance, models with 32–35 % predictive skill have been produced for the spring–summer precipitation in southern England (Cooper et al. 2013; Wilson et al. 2013) and 37–38 % for annual precipitation in western Hungary (Kern et al. 2009). Drought index reconstructions have explained ca 30 and 44 % of the instrumentally observed variance in southern Sweden (Drobyshev et al. 2011) and 20–47 % in southeastern Slovenia (Čufar et al. 2008a). Nevertheless, the western Estonian summer rainfall reconstruction extends back to year 1769 (Fig. 9). The lack of similarity with average summer precipitation across Estonia during 1866–1919 may be associated with the great spatial variability of precipitation (Jaagus 1999). Also, the earlier instrumental records mainly originate from Tartu (southeastern Estonia), which is poorly representative of western Estonia.

The pre-instrumental period of our precipitation reconstruction was validated against historical information from the chronicles as compiled by Vahtre (1970) (Fig. 9). Accordingly, the strong and extreme negative peaks in the reconstructed series were associated with water deficit: the summers in years 1794, 1803, 1831, and 1868 were described by severe droughts, water shortage, and crop failures as combined with extreme heat in some cases (1803 and 1868). However, the rest of the negative years in the reconstruction could not be coupled with droughts described in the chronicles. The strong and extreme positive years in the reconstructed series can be mainly associated with a chilly and rainy summer (1793, 1801, 1849, and 1867), which was warm but too rainy in 1823 and 1839 as well. The year 1828 was chilly and very rainy with numerous thunderstorms and hails as well as summers in 1864 and 1867 with floods. In 1842, warm and dry periods varied with chilly and moist periods during the summer. Generally, it can be stated that the positive pointer years showed a somewhat better agreement with moist conditions (9 cases out of 13) than the negative years which tend to coincide only partly with the reported severe droughts (4 cases out of 9). Thus, the reconstruction passably reproduced extremely dry and wet years.

Conclusions

The presented work is the first countrywide pedunculate oak (*Q. robur* L.) dendroclimatological study in Estonia at the northern distribution limit of the species. Based on 162 living oak trees, we have established a ca 350-year chronology. This is a good basis to extend it back to the past with historical and archaeological timber. The growth pattern is rather similar across the country. Still, three regional groups—western, northeastern, and southeastern—can be distinguished owing to spatial climate differences. The oak chronologies are most similar with adjacent Latvian oaks, but evidential similarity is established with farther regions like Finland, Lithuania, and even Poland.

The dendroclimatological analyses revealed that oak radial growth on the shallow soil in western Estonia is positively affected by the summer precipitation sum, while the radial growth on the deeper and more drought-resistant soil in northeastern Estonia is enhanced by June temperature. The southeastern sites with the lowest sample replication showed a positive influence of warm and wet summers on radial increment. The oak growth pattern reflects most probably local weather variations as there is a lack of correspondence between the Estonian and pan-European pointer years, while there is higher agreement with the Latvian oaks.

The presented palaeoclimatic reconstruction is the first attempt to use tree rings as a climate proxy in Estonia. The created model has low predictive skill describing only less than a quarter of the variance in actual summer rainfall of western Estonia. This derives from the fact that precipitation in general has great spatial variance. On the other hand, the pointer years identified in the retrodiction passably agree with the extreme weather events reported in the historic sources. Thus, the reconstruction model can detect extremely dry and wet summers.

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