

Growth response of sessile oak to climatic variability at two sites in West and Northeast Germany

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Introduction

Oaks have been comprehensively investigated dendroclimatologically, in order to assess the direct and indirect factors influencing tree growth (e.g., Gray & Pilcher 1983, Briffa et al. 1986, Lévy et al. 1992, Hartmann & Blank 1992, Baillie 1994). Previous investigations revealed that above average temperature and below average precipitation and associated parameters, e.g. soil moisture, were responsible for limiting tree growth (Garzía-González & Eckstein 2003, van der Werf et al. 2007, Mérian et al. 2011), and identified that above average precipitation in autumn of the previous year presumably supporting the additional storage of carbohydrates. Drought events have been considered to be one of the main predictors causing extreme negative growth reactions in oak (Kelly et al. 1989; Bréda et al. 1993; Lebourgeois et al. 2004, Michelot et al. 2012).

While most of the aforementioned dendroclimatic oak studies have been conducted at sites with significant growth limitations, the site selection of the current study was already pre-set by the fact that, for better comparability, the tree-ring records had to be collected near two lakes which have recently been sampled for lake sediment cores. The two lakes are part of a network of Terrestrial Environmental Observatories (TERENO) in Germany as an interdisciplinary research program (Zacharias et al. 2011). For a better understanding of the long-term hydrological dynamics TERENO (Terrestrial Environmental Observatories) focuses on precisely dated and synchronized long-term data from lake sediments and tree rings to reconstruct environmental parameters throughout the Holocene. The two lakes, Lake Holzmaar in the Eifel (TERENO West) and Lake Großer Fürstenseer See in the Mecklenburg lakes district (TERENO Northeast) and the surrounding forests have been selected for comprehensive analyses. In order to address the dynamic interactions of environmental systems, tree-ring analyses are highly suitable for palaeoclimatic studies (Speer 2010). Sessile oak (*Quercus petraea* [MATT.] LIEBL.) from surrounding forests were chosen for sampling and developing two new robust site chronologies. Sessile oak (*Quercus petraea* [MATT.] LIEBL.) from surrounding forests were chosen for developing two new robust site chronologies and for assessing their dendroclimatological potentials.

Since climate and soil conditions are generally poorer at the site in NE Germany, we hypothesise that trees at this site will be more drought-sensitive than at the western site. In order to test this we investigate the major growth-limiting parameters, temperature, precipitation as well as drought, to explore their effects on tree-ring widths of sessile oak at the two sites in W and NE Germany, which to our knowledge is the first east-west comparison of oak in this regard. Furthermore, we aim to estimate the driving factors of site-specific extreme growth reactions with regard to extreme climatic deviations.

Material and Methods

Study sites

The two study sites represent different geographical regions in Germany: the Eifel mid-range mountain region of West Germany (W Germany), and the Müritz National Park in the Northeast German lowlands (NE Germany) (Fig. 1).

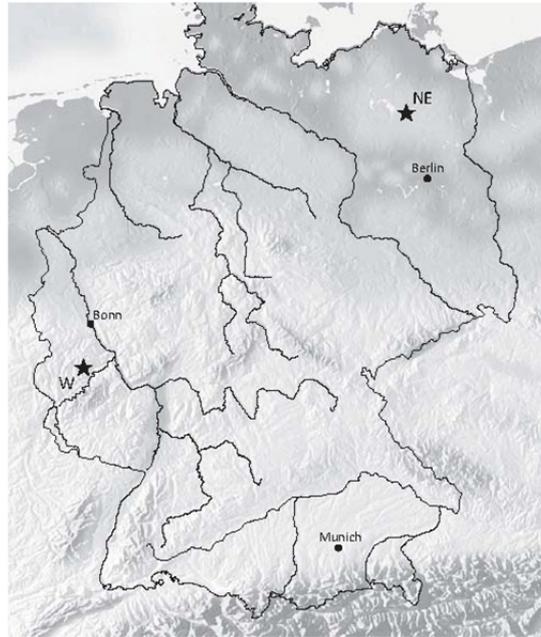


Figure 1: Location of the study areas in W and NE Germany.

The climatic situation of W Germany is dominated by moist oceanic conditions with milder winters and annual precipitation of approximately 800 mm. The soil is a well-drained and moderately developed dystric cambisol, and the soil texture varies from stony to sandy loams. In contrast, NE Germany generally experiences colder winters and less precipitation (approximately 600 mm). The annual mean temperatures in the two regions show only little differences, however, the rainfall variability is most pronounced during the summer month (Fig. 2).

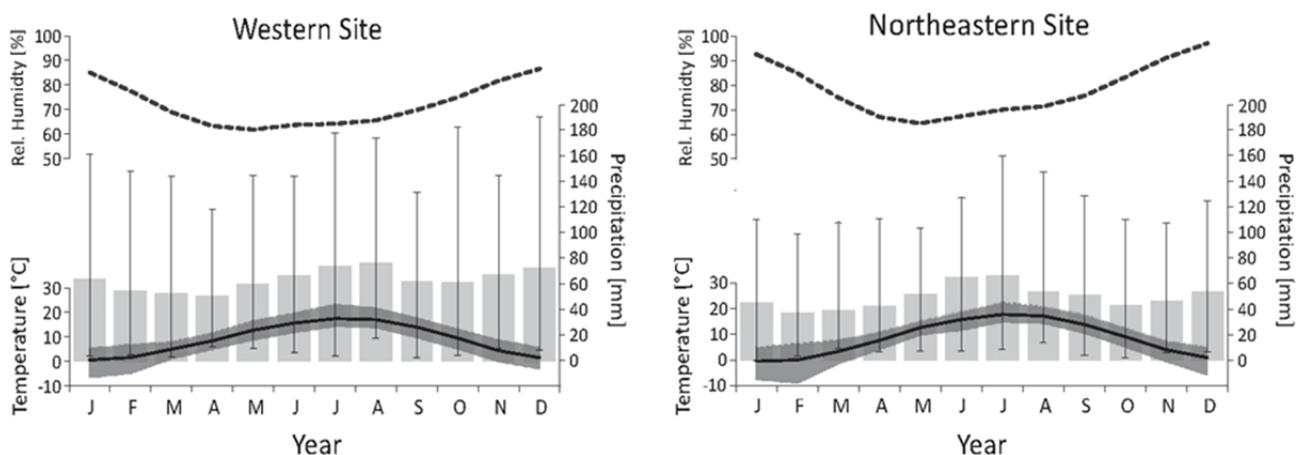


Figure 2: Climate diagrams for the sites in W and NE Germany. Monthly mean temperature (solid line), monthly precipitation sums (bars) and their absolute deviations (min/max) as well as monthly mean relative humidity (dashed line) for the period 1901 to 2006.

At the site in NE Germany, the main parent material for soil development is glaciofluvial sandy deposits and loamy ground moraines. The resulting soil types range from haplic gleysols to eutric cambisols, characterized by generally lower water-holding capacities (Soil Atlas of Europe 2005). Overall, the sites in W and NE Germany mainly differ concerning the rainfall regimes and soil moisture availability. Further details of the site conditions, which are, altitude, slope and elevation are given in Table 1.

Table 1: Site description and characteristics of the oak chronologies investigated in W and NE Germany.

	Western region	Northeastern region
site name	Holzmaar	Carpin
latitude/ longitude	6°52'/50°7'	13°21'/53°33'
elevation (a.s.l.)	430	106
slope (%)	10	2
vegetation	beech-oak forest	beech-oak forest
parent material	silty/ sandy loam	glaciofluvial sandy deposits
main soil type	dystric cambisol	haplic gleysol
mean temperature (°C)	9.0	8.5
min. temperature (°C)	4.0	3.8
max. temperature (°C)	13.2	12.6
mean precipitation (mm)	803	605

Tree-ring data

Sampling of *Quercus petraea* (MATT.) LIEBL. was carried out at two sites in closed canopy forests of W Germany and NE German during the autumns of 2005 and 2009, respectively. From each of the 30 trees, two cores were taken with an increment borer at breast height. Tree-ring width chronologies were developed for each site following standard dendrochronological techniques (Fritts 1976; Cook & Kairiuktis 1990). Annual rings were measured and visually cross-dated with TSAP Win (Rinn 2007) and WinDENDRO (2006). The accuracy of the cross-dating and measurements were verified using the computer program COFECHA (Holmes 1983). Core samples poorly correlated with the master chronology (correlation less than 0.5) were discarded and excluded from the final chronology. Detrending and indexation of each tree was conducted to remove non-climatic trends due to increasing tree age, size, and the effects of stand dynamics. Mean indexed chronologies were developed from the cross-dated ring-width series by applying the ARSTAN program (Cook 1985). For the raw ring-width series, the variance of the radial growth was stabilized using an adaptive power transformation (Druckenbrod & Shugart 2004). In order to keep the inter-annual to multi-decadal variability, each tree-ring series was detrended by fitting a cubic smoothing spline with a 50% frequency cut-off of 30 years of the length of the series (Cook & Peters 1997). After detrending, indices were calculated and individual series averaged by calculating bi-weight robust means resulting in mean site chronologies (Cook et al. 1990). Chronology qualities and signal strengths were estimated using the inter-series correlation (R_{bar}) and the expressed population signal (EPS) (Wigley et al. 1984). The mean site chronologies used for calibration and climate reconstruction purposes was then cut off at a critical EPS of 0.85.

For the analysis of the climate-growth relationships we used monthly resolved gridded ($0.5 \times 0.5^\circ$) precipitation sums, temperature means (CRU TS 3.1, Mitchell & Jones 2005), and the self-calibrating Palmer Drought Severity Index (scPDSI, van der Schrier et al. 2006). The relationship between oak growth and regional climate was examined using Pearson's simple correlation coefficients, which were computed between the climate data of the previous and current year and the tree-ring series for the period 1901-2002. The correlations were calculated from March of the year prior to ring formation to September of the current year as well as seasonal averages.

Pointer years were determined using the approach of Cropper (1979) to detect the intensity of single extreme years and the growth-limiting factors, in order to better understand the link between extreme climate events and anomalous tree growth (Neuwirth et al. 2004). These Cropper values were calculated for the period 1901-1996, and individual years were considered as positive or negative pointer years, if the normalized Cropper-value exceeded a threshold of $Z_i = \pm 1000$, respectively. For selected pointer years exhibited by most sampled trees, climate data of the associated years were selected to search for extreme climatic events or disturbances possibly leading to the recorded anomalous tree growth. The long-term monthly means were subtracted from the extracted climate data of the extreme years and the resulting residuals were plotted over a 24-month window starting from January of the previous year and ending in December of the current year (Heinrich et al. 2008).

Results

Chronology characteristics

For both chronologies, important statistical parameters such as the mean EPS values, which constantly stay above 0.85, the chronology replications, the mean series inter-correlations, and the mean segment lengths (MSL) are summarised in table 2.

Table 2: Summary statistics for the oak chronologies in W and NE Germany. MSL: mean segment length (years); AGR: mean radial increment (mm yr^{-1}); Rbar: inter-series correlation and EPS: expressed population signal (calculated for the max. common period).

Site name	Western region	Northeastern region
	Holzmaar	Carpin
Chronology length	2004-1822	2009-1703
No. of trees	16	14
MSL (years)	174	272
AGR (mm year^{-1})	1.5	1.19
Rbar	0.63	0.67
EPS	0.92	0.94

The site chronology in W Germany covers the period 1822-2004, while at the site in NE Germany, the chronology covers the period from 1701 to 2009 (Fig. 3). The western chronology shows a marginally higher mean radial increment (AGR) of 1.5 mm yr^{-1} than the northeastern with 1.3 mm yr^{-1} , and also the values of Rbar are similar ranging from 0.6 (NE Germany) to 0.7 (W Germany). The mean Rbar and EPS values of more than 0.6 and 0.85, respectively, suggest that the chronologies are robust estimates of annual growth changes and that they are suitable for further dendroclimatic research.

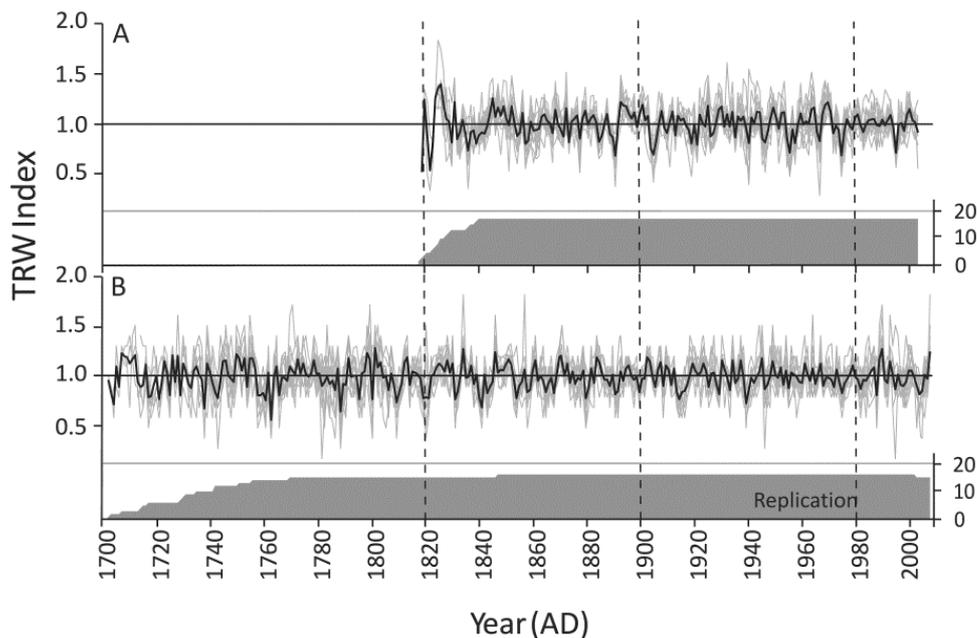


Figure 3: Plots of tree-ring (TRW) indices for W Germany (A) and NE Germany (B). Grey graphs represent indices of individual trees and the black graphs are the respective means. The grey-hatched graphs indicate the number of trees sampled through time.

Climate-growth relationships

Correlations with precipitation are mainly positive which indicates that the availability of water during spring and summer has a positive effect on the growth of oaks at both sites. At the site in NE Germany, annual tree-ring growth is significantly positive correlated to February ($r = 0.32$) and June ($r = 0.34$) precipitation sums and to seasonal precipitation sums during the early growing season (April to June) of the current year as well as to the summer precipitation sums of the previous year (July to September). The western oak chronology exhibits a significant positive correlation with June precipitation ($r = 0.33$). The correlation is stronger for the seasonal variables April to June and May to September suggesting cumulative effects of single months which lead to notably higher correlations with seasonal precipitation sums, whereas no significant correlations for the previous vegetation period exist (Fig. 4A).

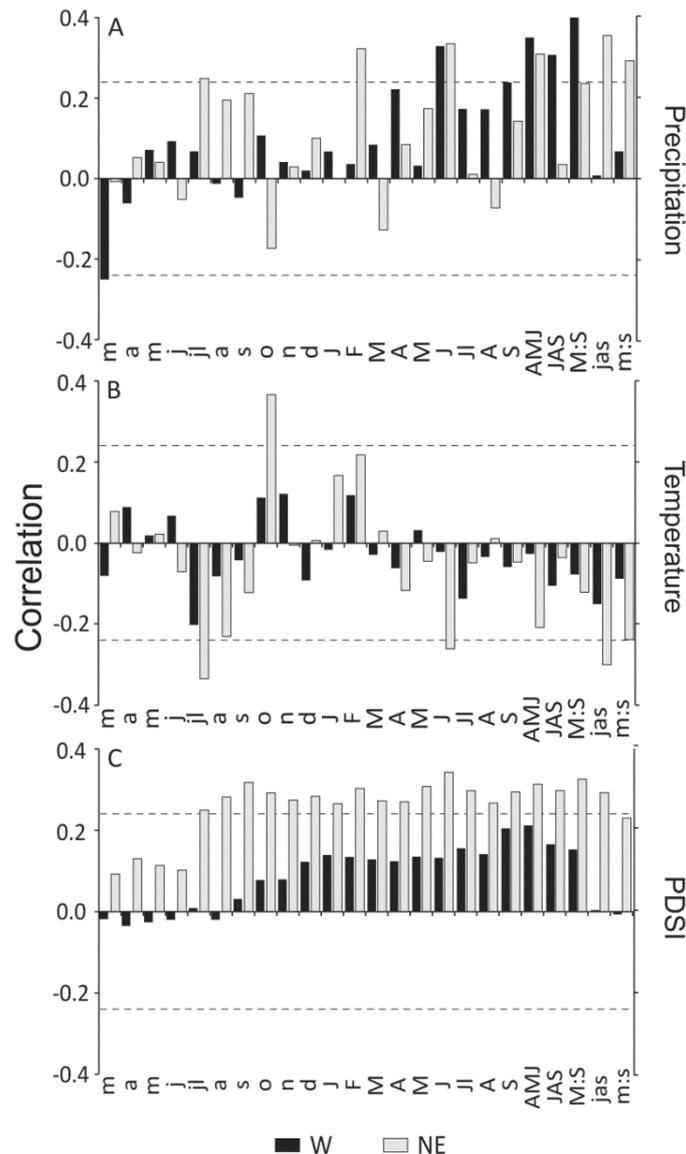


Figure 4: Climate-growth relationships of mean indexed chronologies with mean monthly precipitation (A), temperature (B) and scPDSI (C) (1901-2002), expressed by the coefficient of correlation. The black lines represent the 99% significance levels. Seasonal means are averaged for April to June (AMJ), July to September (JAS) and May to September (M:S) of the previous (small letters) and current (capital letters) year.

At both sites, correlations with temperature are mostly negative for both the current and previous summer month, however, significant values are only indicated for the site in NE Germany where correlations are negative for mean June temperatures ($r = -0.26$) of the current year and for the seasonal mean summer temperatures of July to September of the previous year. Significant positive correlations are only indicated for mean October temperatures ($r = 0.37$) of the previous year for the site in NE Germany (Fig. 4B).

At both sites correlations with scPDSI are positive, however, they are only significant for tree-ring indices from NE Germany. For tree-ring indices from NE Germany, strongest correlations are discernible for the mean June scPDSI ($r = 0.34$) of the current year, the mean September scPDSI of the previous year ($r = 0.31$) and for the seasonal mean summer scPDSI of May to September of the current year (Fig. 4C).

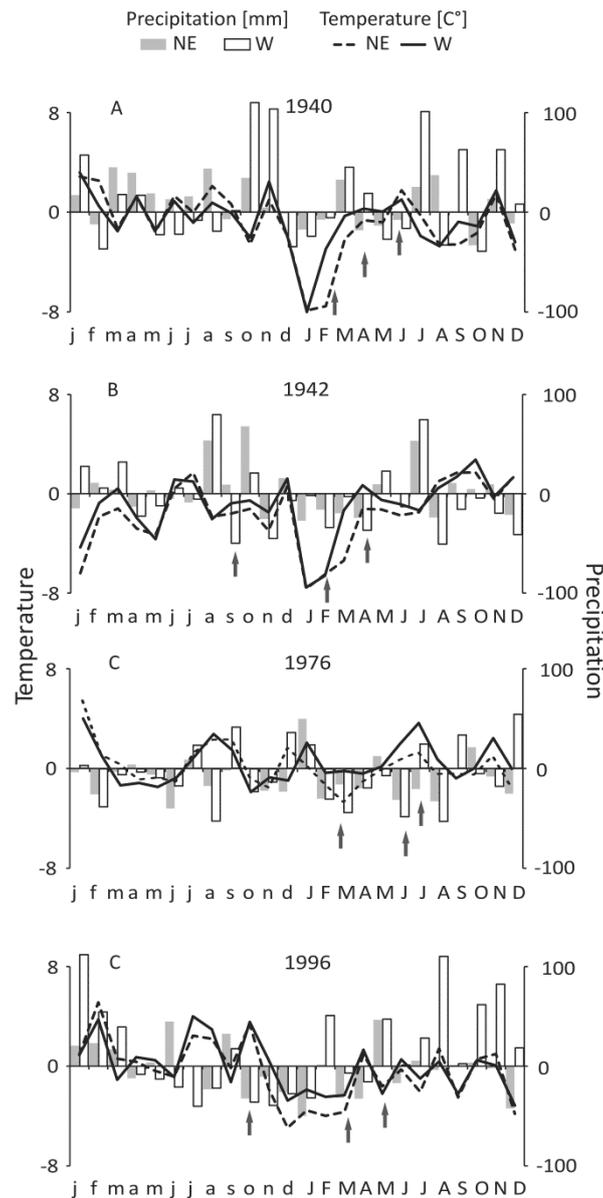


Figure 5: Representative negative pointer years detected only for site NE Germany (A), site W Germany (B), and for both sites (C). Values of temperature and precipitation were plotted as deviations from the long-term averages; small/capital letters mark the climate variables of the previous/current year before/during the pointer year (january to december/ January to December). Arrows indicate months of significant influence.

With the Cropper method 18 years of extreme growth anomalies were detected for the period 1901 to 1996. Oaks growing at the NE Germany site show more growth anomalies. At the NE Germany site, twelve pointer years were detected, six positive and six negative pointer years. At the W Germany site, eight pointer years were identified, two positive and six negative pointer years. In 1976 and 1996 only, both site chronologies exhibit significant negative pointer years simultaneously, but no common positive pointer years were found.

In order to compare growth anomalies in common and different pointer years, which may be induced by the same or dissimilar extreme climatic events at both sites, pointer years were compared to precipitation and temperature anomalies. Four negative tree-ring index pointer years, that is, 1940, 1942, 1976 and 1996 were selected for comparison (Fig. 5).

The year 1940 is a pointer year only at the NE Germany site, 1942 only at the W Germany site and 1976 as well as 1996 at both sites. The year 1940, the pointer year only found in NE Germany, is characterized by precipitation deficits in December of the previous year and January to March of the current year, and by temperatures much below average between December of the previous year and March of the current year. Interestingly, at the W Germany site only precipitations sums in November and December of the previous year were well above average. The year 1942, the pointer year only found in W Germany, is similar to 1940. However, monthly temperatures are not only below average between December of the previous year and March of the current year but also during most months of the previous year. Furthermore, monthly precipitation sums are mainly below average during the previous and current year, and only in August of the previous year and July of the current year can positive deviations from the long-term mean be found. Common negative pointer years found at both sites are indicated for the years 1976 and 1996. In 1976, the extreme negative growth reaction likely is the result of below-average precipitation during the growing season. In the same year the temperature was below-average in spring and high above-average from June to September. The year 1996 is characterised by above-average temperatures in July to October of the previous year, below-average temperatures between December of the previous year to March of the current year and markedly below-average precipitation sums from April of the previous year to April of the current year.

Discussion and Conclusion

At the site in NE Germany, precipitation of the previous late summer to autumn is more limiting for tree growth than at the site in W Germany, which indicates the importance of photosynthetic products obtained in the previous year for the tree growth of the current year. It is known that oak trees initiate their earlywood formation, just before photosynthetic activity starts, by remobilising stored reserves (Pilcher 1995). Less rainfall during times of carbohydrate storage in autumn has been reported to reduce the amount of reserves for the following year (García-González & Eckstein 2003; Michelot et al. 2012). Consequently, autumn precipitation may be important in determining the onset of the following growing season and the amount of earlywood formed with reserves from last year, particularly in drier environments such as the NE Germany site. Oaks growing at the site in NE Germany also show a positive correlation with February precipitation which suggests that early tree growth is likely to profit from higher soil moisture contents. Above-average snow accumulation in winter may also lead to a surplus of soil water (Kelly et al. 2002; van der Werf et al. 2007), positively influencing tree growth.

The highest correlations between oak growth and precipitation were found for the seasonal means (April to June and May to September). Both sites seem to be water-limited during summer, especially in June, which is supported by similar results from other studies (Menzel 2000; Rötzer et al. 2004). The importance of spring to summer water balance during the year of ring formation has been reported in several investigations (van der Werf et al. 2007; Čufar et al. 2008; Friedrichs et al. 2009). Water potential limitations within the root-to-leave system can induce stomata closure, and hence lead to radial growth decreases (Bréda et al. 1993; Bréda et al. 2006; Zweifel et al. 2006).

The correlations between tree growth and temperature values of the current vegetation period are generally low. The only significant correlation is exhibited for June, which negatively effects oak growing at the site in NE Germany. This negative correlation underlines the drier environmental character of the northeastern site where hot and dry conditions lead to limited growth in summer. Significant negative correlations were also found between tree growth and July to September temperatures of the previous year. The influence of hot conditions on oak growth patterns has been previously reported, especially with regard to the importance of vapour pressure deficits (Lövdahl & Odin 1992), and thus to decreasing photosynthetic rates (Lebourgeois et al. 2004). Furthermore, high air temperatures, which are associated often with low precipitation, have been reported to lead to significant inverse correlation signals in oak (Fritts 1976; Bednarz & Ptak 1990;

Pederson et al., 2004). These findings corroborate our results of mainly negative correlations between tree growth and temperature.

The correlation patterns between tree growth and scPDSI revealed significant correlations for most months at the site in NE Germany but no significant correlations for the site in W Germany, indicating disagreement in the growth responses at the two study sites in regard to drought conditions. It seems that at the site in NE Germany the stronger drought signal is a combination of generally lower amounts of precipitation, that is, approximately 800 mm versus 600 mm per year in W and NE Germany, respectively, and sandy soils with lower water holding capacities in NE Germany (Ruseckas 2006). These results suggest site-specific responses to differing soil moisture availability, which may be interpreted in terms of different soil texture and locally varying rainfall sums in particular (García-Suárez et al. 2009). These findings are also comparable to results reported by Wazny (1990) and Paltineanu et al. (2007) emphasising the influence of the soil conditions.

The pointer year analysis has helped to identify several years characterised by extreme positive or negative growth. Tree growth during the two common negative pointer years (1976 and 1996) was probably influenced by the same macroclimatic extremes occurring simultaneously at both sites. Likewise, previous studies have also shown that the negative pointer year 1976 was mainly linked to limiting hydrological conditions during the growing season throughout Europe (Kelly et al. 1989; Lévy et al. 1992; Briffa et al. 1998). Such studies found that deficient water balances negatively influenced annual growth as a result of low precipitation and high temperatures, which was also found in our study, in particular for the site in NE Germany. At the two sites in W and NE Germany, tree-ring growth in 1996 was extremely limited by below-average temperatures during late winter of the previous year to spring of the current and below-average precipitation during most of the previous year. Likewise, Lebourgeois et al. (2004) and Michelot et al. (2012) have shown that extreme hydroclimatic conditions especially at the end of the previous growing season as well as winter and current spring are likely to induce extreme growth. The only two pointer years found at both sites (1976 and 1996) seem to be only partly due to the same limiting factors but also due to different site-specific factors.

In contrast, extremely cold winter to spring temperatures occurred at both sites in 1940 and 1942 but 1940 is a pointer year only at the site in W Germany and 1942 only at the site in NE Germany. Frost effects have also been recorded by Tyree & Cochard (1996). Their results suggest that frozen soil may prevent oaks from absorbing soil water during the early part of the season and thus delay growth. In comparison, common negative pointer years due to such very cold winter-to-spring conditions were not identified in our study. It seems likely, that at our two study sites site-specific conditions were favourable enough to buffer such prolonged cold conditions at one site in 1940 and then at the other site in 1942. For example, in 1940, such a year with cold winter-to-spring conditions only the site in NE Germany exhibits a pointer year. The difference between the sites is that only W Germany received above-average precipitation in October and November of the previous year, which might have been sufficient to somehow prevent negative pointer years in the western trees.

Furthermore, it needs to be stated that the formation of pointer years may also depend on various other environmental conditions, and pointer years may then be more difficult to explain. Both climatic and non-climatic impacts are crucial and therefore, incidences of defoliating insects should not be neglected (Weidner et al. 2010). According to Gieger and Thomas (2005), severe attacks of defoliating insects or pathogenic fungi can affect the drought tolerance, influence the development of fine roots, lead to a reduction in carbohydrate reserves, and finally weaken the general frost hardiness of oaks (Hartmann & Blank, 1992; Thomas et al., 2002).

The comparison of the climatic responses of both oak stands has allowed us to better understand how tree growth is functioning in W and NE Germany. Overall, the comparison of the climate-growth relationships at the two sites suggests that tree growth at Lake Großer Fürstenseer See (TERENO Northeast) in NE Germany is more sensitive to climate variations, in particular to

hydrological changes. However, extensive sampling of old living trees and archaeological material is needed to extend the local tree-ring chronology especially at Lake Großer Fürstenseer See. The combination of such a new multi-centennial chronology with varved lake sediment layers of Lake Großer Fürstenseer See will facilitate reconstructions of the regional landscape evolution and lake level dynamics. It will help to answer two important questions, that is, are the groundwater and lake level losses of up to 5 m happening within the last 30 years unique (Germer et al. 2011) and what are the absolute groundwater and lake level minima and maxima during the Holocene.

Acknowledgments

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