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Response of Growth to Climate within Oaks of the World Heritage Site of Prussian Gardens

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Abstract: *Trees constitute the basis for structure and convey the particular impression of most historic gardens and parks. In the World Heritage property 'Palaces and Parks of Potsdam and Berlin' (Germany) oaks are among the most abundant tree species and can be seen as key species. Questions about exact age, extent and time of environmental influences and impact of extreme weather events still remain unanswered. Against this background, this study tries to get answers about the reaction of these oaks to climatic conditions at three sites, and about the link between vitality and tree-ring growth with a dendrochronological approach. A correlation analyzes and moving correlations gave insight in climate-growth relationships and their stability. Growth reactions were also evaluated in single years by pointer year analyses and superposed epoch analyses (SEA).*

The oak trees show declining growth trends which can be interpreted as typical sign of the old stage of trees and that are not necessarily linked to changing climatic conditions. However, our results highlight the significance of adequate precipitation sums in previous year's July and September and from current May to July for xylogenesis. This result is confirmed by the correlation analyzes to ground-water table and a drought index as well as by the pointer year analyses and the SEA. The climate-growth correlations show instability in many months of previous and current year over recent decades. The results of the present study show strong site-specific drought sensitivity for Quercus – that is strongly correlated with soil moisture conditions and precipitation.

Keywords: *climate change, historic gardens, dendrochronology, quercus, super posed epoch analyses (SEA), drought stress, world heritage site Park Sanssouci*

1. INTRODUCTION

Woody species area dominant design element of historic parks and gardens. Planting scheme, species composition, and plant management provide fundamental insight into history and style of historic green spaces (Turner, 2005). Variances in size, habitus, leaf shape, color, bloom, and fruit were key features of creative planting composition and planting design (Stagoll et al., 2012). The World Heritage property 'Palaces and Parks of Potsdam and Berlin' in Germany may serve as an outstanding example for the manifold use of trees with ages reaching back from the late 17thto the early 20th centuries. Species' composition and planting design of the parks were determined during the stage of establishment and have to be maintained and cultivated based on historical specifications (ICOMOS, 1982;Heilmeyer et al., 2010; Rohde, 2014).

Over recent decades, the problem of declining vitality and growth rates of trees has been widely observed in many regions throughout Europe (Bontemps et al., 2012; Altman et al., 2013; Gillner et al., 2013; Denman et al., 2014; Hlásnyet al., 2014).Climate change associated with generally higher temperatures, changing precipitation sums, and a higher frequency of weather extremes such as heavy rains and heat waves has to be considered as a main driver for this process (Allen et al., 2010; Martínez-Vilalta et al., 2011; Camarero et al., 2015).

From a general point of view, it is worth to study the degree of species ability to adapt or resist to the changing environmental conditions. From a historical point of view, additional research on tree species in parks and gardens regarding cultural, design, and age-related aspects is needed (Turner, 2005; Stagoll et al., 2012). Although a number of dendrochronological studies in cultural heritage research exist, results are mostly published in local languages and literature and not available for the international research community (Čufar, 2007).

At the end of the 18th century, garden design aimed to use different age stages, sizes, and planting formations of trees for landscape gardening. In consequence, existing old-aged trees were integrated in the landscape gardens (Wimmer, 2014). In contrast to pioneer tree species, existing adult climax tree species such as *Quercusrobur*L. and *Quercuspetraea*(Matt.) Liebl. Were more frequently preferred and integrated into processes of planning and realization of parks (Sckell, 1825). Adult giant trees were highly appreciated as examples for robustness and longevity and for their picturesque appearance (Pückler-Muskau, 1834). In garden conservation, species composition is predetermined by design and leads to detailed plans (ICOMOS, 1982). Maintaining the historic authenticity, replanting can only be done according to the historic decisions. Past growth behavior allows conclusions to be drawn about potential long-term growth behavior that enables an assessment of future oak developments. The long-lasting life span of the trees implies the ability to adapt to changing environmental conditions involving pest dynamics, weather extremes, and past climatic variations.In dendrochronological studies oak species showed complacent growth patterns, indicating a lower climatic sensitivity compared with beech (Beck, 2011; Meinardus and Bräuning, 2011; Mérian et al., 2011; Michelot et al., 2012; Mette et al., 2013).In conjunction with the comparable stable climate-growth relationships over recent decades and the lower impact of drought years on radial growth (Scharnweber et al., 2013;Gillner et al., 2014), oak may better adapted under climate change than beech (Mette et al., 2013; Scharnweber et al., 2013). However, research also found oak decline throughout European regions (Drobyshev et al., 2008; Filippo et al., 2010;Benito-Garzón et al., 2013; Helama et al., 2014;Hlásny et al., 2014), which is also confirmed by the decreasing crown vitality found at many sites in the Palaces and Parks of Potsdam and Berlin.

In this study weinvestigatedthe extent of climatic influence on tree growth at the example of *Quercus* species using a dendrochronological approach. Since time-series of tree rings can be considered as natural archives telling us about life history of trees (Schweingruber, 1996), this study is also meant to obtain insight in parks' histories. We answer the following research questions: i) Are low vitality patterns of crown structure also indicated in tree-ring growth? ii) How do trees react to climatic conditions? iii) Are pointer-years climate-induced and do dry years have a significant impact on oaks' growth? iv) Provide time-series of oak insights into park history?

2. MATERIALS AND METHODS

2.1. Study Sites

The study was conducted in three sites located in parks of Potsdam and Berlin within the geographical region of the North German Plain (Figure 1). The study sites (52°24"N 13°02"E; 52°26"N 13°08"E) are in close proximity to one another (maximum distance 8.2 km) and elevation levels shows only little variation with minima of 31 m a.s.l. (Sanssouci) to maxima of 83 m a.s.l. (Ruinenberg).

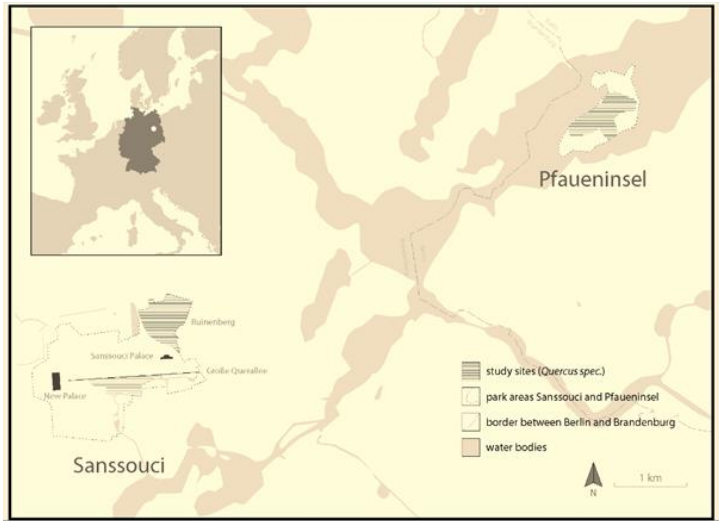

Figure1. *Study sites*

Sandy soils are dominating with low to extremely low water-retaining capacity and high to extremely high permeability at all study sites (Table 1) (LBGR, 2015). In Sanssouci, the mean groundwater table is maximal 1.5m near the surface with a mean value of about 1.2 m near the surface. At all other sites the groundwater table lies more than 3.0 m below surface (LBGR, 2015).

For the period 1961–1990, means of precipitation sums and air temperature sat site Potsdam Telegraphenberg (52°38’12.87"N 13°06’22.22"E, 81 m a..s.l) are 589.8 mm and 8.7 °C (DWD, 2016). The mean annual climatic conditions of the study region are indicated in Figure 2. In the last 25 years, mean air temperature rose significantly, in particular in spring and summer by +2.2 K and +1.5 K, respectively (Prochnow et al., 2015). Strongest change in climate can be observed for April with a rise in mean air temperature of +2.6 K, a decline in relative air humidity by −7.1 %, and a decline in precipitation by 28.0 mm (Prochnow et al. 2015).

Table1. *Data of location and site conditions of the three study sites*

	Pfaueninsel	**Ruinenberg**	**Sanssouci**
Establishment as a park area [year(s)]	1793	1748-1841	1744-1873
Elevation above mean sea level [m a.s.l.]	30 - 66	69-83	31-35
Total area of the park [ha]	64	22	285
Coordinates	52°26′ N 13°07′ E	53°09′ N 12°88′ E	53°09′ N 12°88′ E
Risk of erosion due to wind (LBGR, 2015)	none	very high	very high
Field capacity in the effective root zone(LBGR, 2015)[Vol.%]	very low < 6.0	low < 14.0	low < 14.0
Permeability of the soil to water (LBGR, 2015) [cm/d]	extremely high >300	no data available	very high < 300
Sorption capacity in effective root zone without organic upper layer (LBGR, 2015) [mmol/z/100g]	minor < 82	minor < 82	mean 82-164
Humus content (in % organic content)	minor 1-2	very minor 1	mean 2-4 %

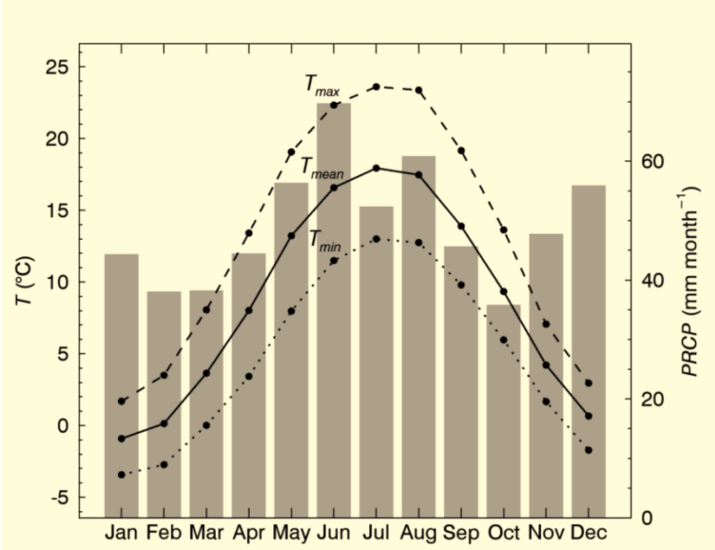

Figure2. *Mean climatic conditions for the period 1961 to 1990 at the meteorological station Potsdam Telegraphenberg (52°38’12.87"N 13°06’22.22"E, 81 a.m.s.l). T_{max} (dashed): Mean monthly daily maximum air*

temperature (T), T_{mean} (solid): monthly mean T, T_{min} (dotted): monthly mean daily minimum T, PRCP (grey bars): mean monthly sum of precipitation.

2.2. Sample Collection

Adult treesof *Q. robur* and *Q. petraea*represent the main fraction of species composition on the chosen forested clumps. Further tree species mainly consist of *Fagus sylvatica*, *Q. rubra*, *Fraxinus excelsior*, and species belonging to the genus *Tilia***.**

Since hybridization is commonly observed at the three sites, a clear discrimination between both species remains uncertain (DupoueyandBadeau, 1993), and we decided to refer our study only to *Quercus*spec.

Only trees in dominant position (Kraft 1 and 2)were chosen for sampling (Kraft, 1884). The trees were assigned to their crown vitality classes according to their branching pattern in the upper third of the crown (Roloff, 1999). Diameter at breast height (DBH) and tree heights were measured (Table 2). From each tree we collected a minimum number of two increment cores at breast height.

2.3. Chronology

Incrementcores were glued ontowooden mounts, and polished to ensure optimal visibility of growth ringsapplying a standard procedure (Stokes and Smiley, 1968;Bräker, 2002). TSAP-Win™ was used for measuring tree-ring width (Rinn, 2012).

Software TSAP-Win™ and COFECHA were used for cross-dating the time-series from a minimum number of five trees (Holmes, 1983). First-order autocorrelation, mean sensitivity, standard deviation, and average ring width were calculated for these cross-dated chronologies from 1893 to 2015. The biological age trend inherent to the raw time-serieswas removed with ARSTAN (Cook and Holmes, 1986; Holmes et al., 1986). (To do this, in a first step a negative exponential, in some cases a straight line, and in a second step a smoothing spline of 60 years with a 50 % frequency response were applied (Lebourgeois et al., 2004).

According to the recommended Expressed Population Signal (EPS) threshold of 0.85 (Wigley et al., 1984), the chronologies met a satisfactory signal strength within the period from 1893 to 2015 (Table 2).

2.4. Climatological and Hydrological Data

Monthly data from the meteorological station at Potsdam Telegraphenberg (52°23'N 13°04'E, 81 a.m.s.l) for air temperature and precipitation from 1893 to 2015, and monthly data of cloudiness and sun sum from 1893 to 1944 were used to calculate correlation analyses with residual chronologies (DWD, 2016).To investigate the impact of drought, the self-calibrating Palmer Drought Severity Index (scPDSI; Wells et al., 2004; van der Schrier et al., 2006) was used. This index uses temperature and precipitation data to estimate relative dryness. Groundwater table influence on growth for the trees was determined using monthly data of the depth of the groundwater table covering the period from 1989 to 2014 for the Sanssoucipark(SPSG, 2016).

Bootstrapped correlation coefficients were computed between monthly climatic data, groundwater data, and residual chronologies with DENDROCLIM2002software for a climatic window from previous year's July to current year's August (BiondiandWaikul, 2004). The significance level was calculated on bootstrap resamples to obtain the 95 % quantile limits. Year-to-year moving correlations (50 years base length)were calculated to provide information about possible shifts in climate-growth relationships up to the year 1893 (BiondiandWaikul, 2004).

Moving intervals were calculated with daily minimum, mean, and maximum temperatures, precipitation sums, maximum precipitations, and scPDSI. The time-series of sun sum and cloudiness from 1893 to 1944, and groundwater table from 1989 to 2014 had not adequate length to perform moving correlations.

Pointer years were calculated based on the approach by Neuwirth et al. (2004) over the period 1893 to 2015 (Neuwirth et al., 2004, 2007).

The significance of growth deviationswas tested by superposed epoch analyses (SEA)to a) the tendriest years considering the months from March to July b) the tenwettest years considering the months from March to July c) the ten coldest winters considering the mean temperatures from December to February, and d) years with late-frost events below a daily minimum T < -2.0 °C from May to July (Orwigand Abrams, 1997).The driest and wettest years were selected on the base of precipitation sums. To determine the coldest winters, mean air temperatures from December to February were used. Significant departures of mean ring width index (RWI) were detected for the three pre-event years, the event years, and the three post-event-years by software package dplR (Bunn, 2008).

3. RESULTS

3.1. Tree Growth and Chronology Statistics

Sanssouci oaks are oldest dating back to 1677. Since the chronologies are robust with a replication of at least four trees, the reliable part of the chronology starts 1707 (Table 2). The youngest oaks at Pfaueninsel show the highest average growth rates of 1.99 mm/a, whereas the oldest oaks at Sanssouci show the lowest average growth rates of 1.14 mm/a. Lowest mean sensitivity of the residual chronologies of 0.17 was also found for the Sanssouci trees, highest values of 0.23 occurred at Pfaueninsel. A first-order autocorrelation of 0.42 for the oaks of the Ruinenberg site indicates a lower influence of previous year's growth on radial growth of the current year, compared to 0.58 for the oaks of Sanssouci site.

The higher sensitivity of the Pfaueninsel and Ruinenberg oaks and the more complacent growth at Sanssoucican also be visually detected in the growth patterns of the chronologies (Figure 3). Although a declining growth trend is observed for the chronologies of Pfaueninsel and Ruinenberg over the recent three decades, average growth rates are still higher at Sanssouci, where growth shows no trend.

Table2. *Tree-ring chronology statistics and growth parameters at study sites*

	Pfaueninsel	***Ruinenberg***	***Sanssouci***
No. of trees	37	18	21
Diameter at breast height (DBH, cm)	73.55 ± *17.59*	89.62 ± *16.91*	85.17 ± *21.99*
Tree height (m)	24.10 ± *4.48*	25.25 ± *5.86*	25.91 ± *5.33*
Overall time span ^{a}	1865–2015	1834–2015	1707–2015
Average growth rate (AGR, mm) ^{b}	1.99 ± *0.70*	1.60 ± *0.52*	1.14 ± *0.28*
Mean sensitivity (MS) ^{c}	0.23	0.20	0.17
First-order autocorrelation (AC(1)) ^{b}	0.52	0.42	0.58
Expressed population signal (EPS) ^{c}	0.95	0.94	0.88

^{a} up to four trees

^{b} calculated from raw chronologies over the period 1893 to 2015

^{c}calculated from residual chronologies over the period 1893 to 2015

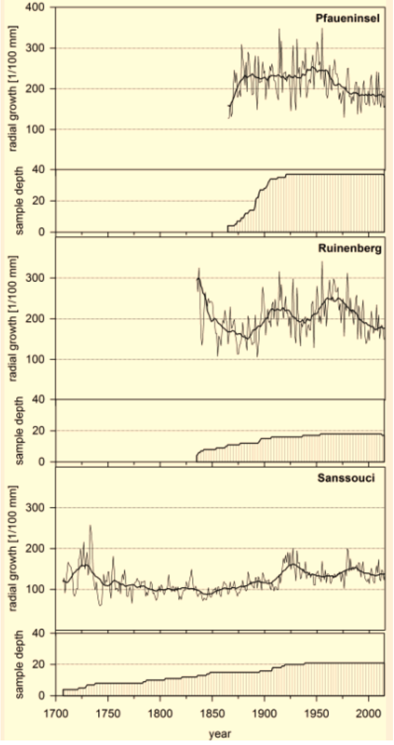

Figure3. *Raw tree-ring chronologies (light grey lines) and cubic smoothing splines (21 years, black lines). The sample depths are indicated in the panels below each chronology*

3.2. Relationships of Tree-Ring Growth and Environmental Variables

The results of the bootstrapped correlations for each chronology with monthly minimum, mean, and maximum temperatures, precipitation sum, daily maximum precipitation per month, groundwater level, scPDSI, cloudiness, and sun sum are shown in Figures4 to6.

Consistent significant positive correlations of mean minimum temperatures and radial growth exist for the previous October for each of the tree chronologies (Fig 4). Correlation analyses of radial growth and mean maximum temperatures only reveals negative significant correlations (Figure4). High temperatures in previous July and current June negatively impact radial growth rates at all sites.

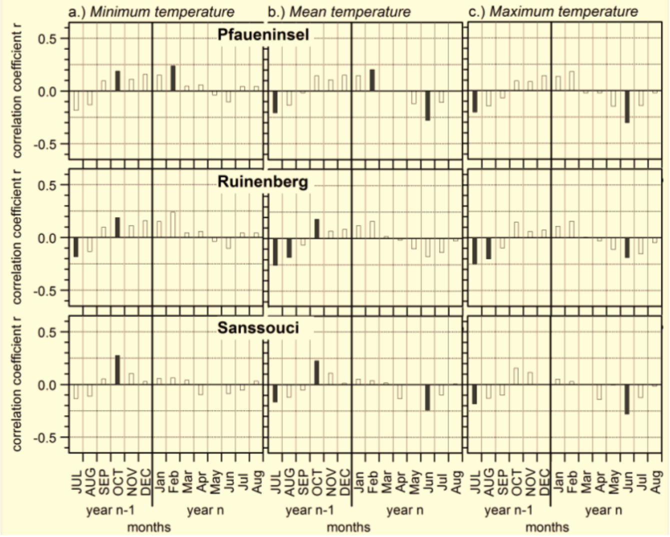

Figure4. *Correlation coefficients of mean monthly minimum (a), mean (b), and maximum temperature (c) and residual chronologies. Pearson's correlation coefficients with significance level of 95 % are marked in grey (BiondiandWaikul, 2004). Correlations were calculated for the period 1893 to 2015 from July of the previous year to August of the current year.*

Hydroclimatic variables including precipitation and groundwater level showed partly positive correlations with oak radial growth (Fig. 5). High precipitation sums in previous July and current May and June consistently increase growth rates. In addition, significant correlations were also observed with previous September and December, and current February and July for the Pfaueninsel and Ruinenberg oaks. Results of maximum daily precipitation sums and radial growth show lower correlation coefficients, and significant correlations are restricted to fewer months compared to those with precipitation sums. Except for previous July at Pfaueninsel, a high groundwater level is positively correlated with all chronologies and mainly shows significant relationships in current year's months from March to August.

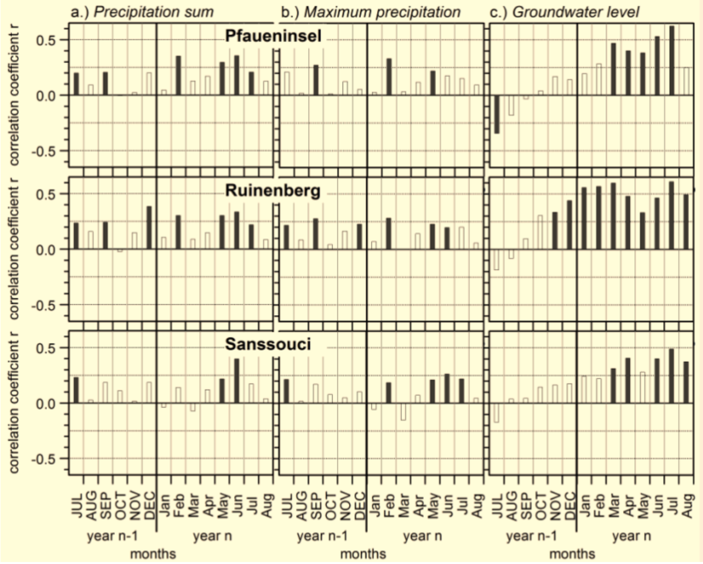

Figure5. *Correlation coefficients of the monthly precipitation sum (a), maximum daily precipitation sum (b), and mean monthly groundwater level (c) and residual chronologies. Pearson's correlation coefficients with*

significance level of 95 % are marked in grey (BiondiandWaikul, 2004). Correlations with precipitation were calculated for the period 1893 to 2015, and with groundwater level for the period 1989 to 2014 from July of the previous year to August of the current year.

The growth stimulating influence of high precipitation sums and high groundwater levels is also reflected in the significant positive correlations of radial growth and scPDSI from April to July (Figure 6). A high cloud cover results in a low sunshine hours and viceversa. These relationships can also be found in the correlation analyses of both parameters to tree growth, significant positive correlations with cloudiness correspond to negative correlations with sunshine duration.

Comparing the results of correlation analyses for the three chronologies, a higher number of significant correlations were found for the Pfaueninsel and Ruinenbergchronologies which also show higher correlation coefficients compared to the Sanssouci oaks.

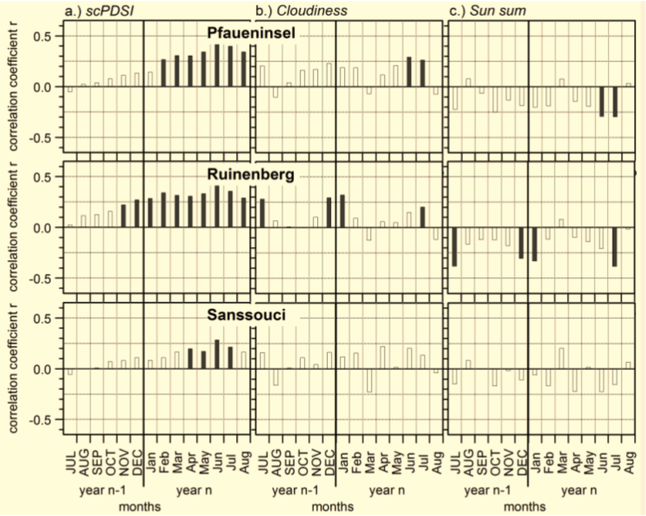

Figure6. *Correlation coefficients of the mean monthly scPDSI (a), cloudiness (b), and sun sum (c) and residual chronologies. Pearson's correlation coefficients with significance level of 95 % are marked in grey (BiondiandWaikul, 2004). Correlations were calculated for the period 1893 to 2015 with scPDSI and for the period 1893 to 1944 with cloudiness and sun sum from July of the previous year to August of the current year.*

Table3. *Stability of climate-growth relationships from 1893 to 2015 for daily minimum, mean, maximum temperatures; precipitation sum, maximum precipitation, and scPDSI.Only significant correlations existing over the last or first ten years of moving intervals to 2015 are indicated.*

	JUL	AUG	SEP	OCT	NOV	DEC	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
					Minimum temperature									
Pfaueninsel		N+++		P++			P---	P---						
Ruinenberg	N±	N+++		P+			P---	P---						
Sanssouci		N+++		P+	P---									
					Mean temperature									
Pfaueninsel	N--	N+++		P+++			P---	P---				N±		
Ruinenberg	N--	N+++		P+			P---	P---						
Sanssouci	N±	N+++		P±	P---					N--		N±		
					Maximum temperature									
Pfaueninsel	N--	N+++		P+++			P--	P---				N±		
Ruinenberg	N--	N+++		P+				P---				N±		
Sanssouci	N-	N+++								N---		N+		
					Precipitation sum									
Pfaueninsel	P---		P±			P++		P+++			P--	P++	P---	
Ruinenberg	P---		P++			P±		P++			P--	P++	P---	
Sanssouci	P-		P+			P+++				P---	P--	P+++	P---	
					Maximum precipitation									
Pfaueninsel	P-		P-					P++			P±	P+++	P---	
Ruinenberg	P±		P±		P++	P++		P+			P-	P+++	P---	
Sanssouci	P±							P+++	P---		P±	P+++	P---	
					scPDSI									
Pfaueninsel								P++	P+++	P++	P++	P++	P+	P+++
Ruinenberg			P+++	P+++	P++	P++	P+	P+	P++	P+	P±	P±	P±	P±
Sanssouci										P--	P--	P-	P--	

+	Increasing correlation (0.06 < 0.10)	-	Decreasing correlation (0.06 < 0,10)
++	Increasing correlation (0.11 < 0.20)	--	Decreasing correlation (0.11< 0.20)
+++	Strong increasing correlation (> 0.20)	---	Strong decreasing correlation(> 0.20)
±	Stable correlation (−0,05 ≤ 0 ≥ 0,05)	P	Positive correlation
underlined	Significant correlation, not existing for the whole period from 1893 to 2015	N	Negative correlation

Climate-growth responses showed considerable variations from 1893 to 2015 (Table 3). Correlations of radial growth and temperatures in previous August and October show a consistent strong increase, in contrast to a decrease in current January and February. Negative correlations with previous August temperatures strengthen for each of the three oak chronologies indicated by a shift in correlation coefficients of more than 0.20. Another remarkable correlation increase can be observed for the Pfaueninsel and the Ruinenbergchronologies with temperatures in previous October. Except for temperatures in previous November and current April,Sanssouci trees showed a higher stability in terms of correlations in most months.

The relationships of precipitation sums and radial growth showed a decreasing correlation with previous July rainfall and increasing correlations with previous September and previous December precipitation for all chronologies. Interesting aspects were foundin current year's months from May to July. For each of the three chronologies the influence of precipitation (precipitation sum and maximum precipitation) in current July drops to a nonsignificant level. In contrast to this decreasing trend, an increasing to strongly increasing correlation between precipitation and radial growth in current June was found, indicating a focusing of precipitation influence from three months to one central month.

Moving correlations with scPDSI showeddistinct differences among the three oak chronologies. Oaks at the Pfaueninsel show increasing correlation in current year's months from February to August. For Ruinenbergtrees,increasing correlations to scPDSI are restricted from previous September to current April, whereas from May to August stable correlations exist. For the Sanssoucitrees significant correlations only exist from April to July of the current year, with decreasing correlations coefficients.

3.3. Pointer Years and Effects of Climatic Anomalieson Radial Growth

The chronologies show a comparable number of pointer years, ranging from 33 years for the Ruinenberg site to 37 years for the Pfaueninselsite (Figure7). Except for the Pfaueninsel site with a higher number of positive pointer years, a higher number of negative pointer yearscan be found.At each site, the number of extreme positive pointer years doubles that of the extreme negative pointer years. All three chronologies simultaneously respondedin eight yearswith pointer years (positive or negative pointer years).

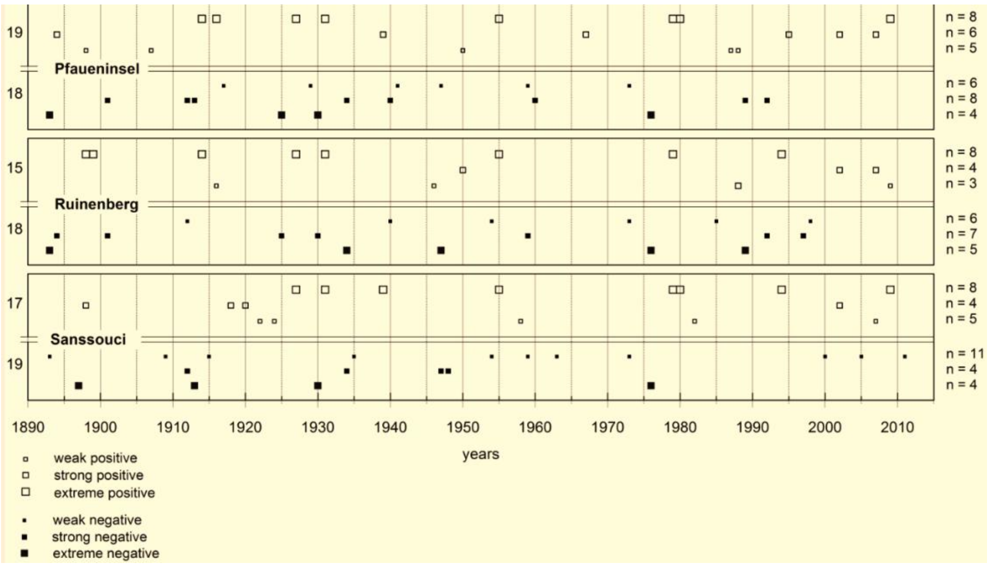

Figure7. *Pointer years from 1893 to 2015. Positive pointer years are marked with white squares and negative pointer years in black squares. On the left y axis the number of pointer years (negative and positive) for each site is indicated. On the right y axis the amounts of the extreme, strong, and weak pointer years are given.*

In the ten years with driest conditions during March to July, significant growth reductions occurred at all sites (Figure8). Each chronology responds with significant above-average radial growth rates in the pooled wettest years (Figure8). Significant growth reductions can be found in the second year pre-dating wet events and in the third year post-dating wet events (Figure 8). Late frost and winter frost events did not cause any significant growth reduction.

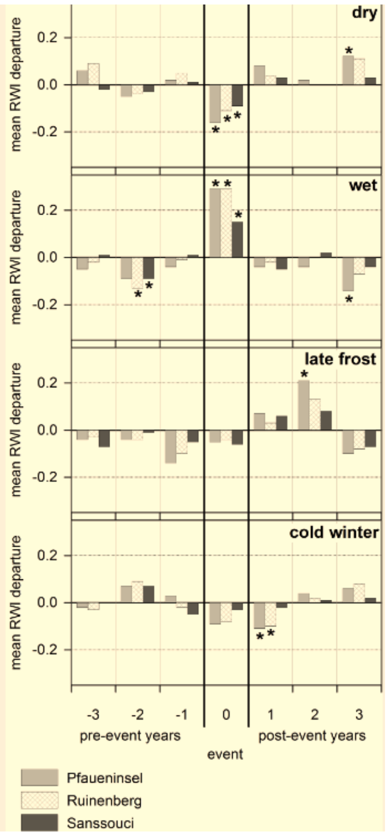

Figure8. *Mean ring-width index (RWI) for the climatic anomalies considered for the superposed epoch analyses. Asterisks mark columns with significant differences at* $p < 0.05$.

4. DISCUSSION

4.1. Chronologies and Age Structure

Age distribution and vitality classes of trees enable a clear assignment into the maturity stage of most trees of the Pfaueninsel and Ruinenberg site, whereas eleven trees of the Sanssouci site are older than 200 years and four of these are even older than 300 years. From a historical perspective this means that oldest trees of the Sanssouci chronology were not planted during the establishment of the historic park site after 1744, but these trees were integrated into the design.None of the trees of the Ruinenberg is older than 191 years and from 1825 to 1835 high growth rates of more than 2.5 mm per year can be found which is characteristic of juvenile growth.After the defeat of Prussia in the battle of Jena–Auerstedt 1806, reparations had to be paid and significant contributions were rendered by timber. Tree felling for timber production is also documented for the Ruinenberg site with a following resprouting from stumps (Wacker, 2014). A high plasticity of radial growth was also observedin adult trees of *Q. petraea* of a coppiced forest inCzech Republic confirming the ability of oak to react to traumatic events even in old stage (Altman et al., 2013).

Since 1998, a decreasing vitality and a declining trend of the crown index calculated bydifferent aspects as mean defoliation, openness, mortality, etc. biotic damages has been observedin the German federal state of Brandenburg (Forst Brandenburg, 2016). This general trend cannot be detected in the tree-ring series.

For fifteen stands of *Fagus sylvatica* in France located in different climatic regions, an increasing mean sensitivity under decreasing maximum extractable soil water was found (Lebourgeois et al., 2005). Generally, *Q. petraea* shows lower mean sensitivity compared to other native tree species such as *F. sylvatica* or *Pinussylvestris* (Michelot et al., 2012), but also for *Q. petraea*a water-status depending mean sensitivity was detected (Gillner et al., 2013). The more balanced water supply of the Sanssouci site with an average groundwater level of 1.2 m below surface results in more complacent growth reactions, involving lower values of mean sensitivity and a higher first-order autocorrelation(cf.Table 1 and 2).Even in years with pronounced and long dry periods, e.g. in 1992, 2003 or 2006, the groundwater table never dropped below 1.5 m below surface. This implies a possibility for an adequate capillary uplift capacity supporting also an adequate water supply for the trees. For the site of Pfaueninsel, permeability of the soil to water is extremely high and alsofield capacity in the effective root zone shows lowest values among the three sites with a subsequently higher mean sensitivity (cf. Table 2).

4.2. Climate and Tree Growth

High growth rates of oak can be caused byhigh temperatures in previous autumn, low temperatures in previous July and August and in current June (cf. Figure4). These results are confirmed by several studies focusing on climatic effects of oaks (Lebourgeois et al., 2004; Drobyshev et al., 2008; García-Suárez et al., 2009; Netsvetov et al., 2017).

Carbon reserves are essential for the formation of new earlywood in spring before leaf unfolding. Hence, unfavorable climatic conditions in summer and autumn months of the previous year may deplete carbon reserves (Michelot et al., 2012; Sala et al., 2012). Mild temperatures and sufficient precipitation in previous year'sautumn foster root growth and storage of carbohydrates of sessile oak (Barbaroux and Bréda, 2002; Lebourgeois et al., 2004). Favorable climatic conditions lead to a higher root biomass, resulting in an advantageous starting position for promoting radial growth in the subsequent vegetation period (Lebourgeois et al., 2004). This is consistent with the significant positive correlations of radial growth with precipitation sums in previous September as well as for minimum temperatures in previous October (cf. Figures4 and 5).

For each chronology, an increasing trend of the negative correlation with previous year's August and of the positive correlation with previous October between radial growth and temperatures was found. Based on the presumption that root growth will be promoted by increasing temperatures in autumn and photosynthesis will be limited by early stomata closure and early leaf fall in August, higher temperatures during recent decades will impact radial growth in both an adverse and a beneficial manner.

Tree-ring data from Continental Europe show a high sensitivity of oak trees to low winter temperatures (Denman et al., 2014; Netsvetov et al., 2017). In winter, sunny and warm conditions during the day and low temperatures during the night can cause frost cracks,causing damages to phloem and necrosis (Denman et al., 2014). Although, investigated trees donot showsignificant growth reductions in years following lowest winter temperatures, chronologies of Pfaueninsel and Ruinenberg show significant growth declines in the first year post-dating strong winter frosts. In summary, correlations with winter temperature indicate that risen winter temperatures prevent negative impacts on tissues of bark and roots. Since thin bark structures and near-surface parts of the crown are particularly predisposed to frost damages,especially young trees react sensitively to winter frost (Krahl-Urban, 1955;Chaarand Colin, 1999). Over recent decades, positivecorrelations to February temperatures dropped to non-significant levels,underlying the improvement of winter hardiness with increasing age. A different picture can be found for precipitation in previous December and current February, indicating reinforcing correlations over recent decades which may give anindication of the increasing significance of winter precipitation for soil water reserves under accelerating drought in spring.

For radial growth the current vegetation period from May to July plays the main role(Lebourgeois et al., 2004; Drobyshev et al., 2008; Gillner et al., 2013; Kern et al., 2013; Čufar et al., 2014; Netsvetov et al., 2017). Although correlation analysis for precipitation and radial growth donot show highest coefficients during this period, those of scPDSI and groundwater level show highest correlation coefficients from May to July with maximum values in current June at each site. It must be mentioned that the time-series for groundwater table refer to the Sanssouci site and groundwater tablesat both other sites lie more than 3.0 m below surface. Thus, a capillary water transport from groundwater to tree roots can be excluded for the Pfaueninsel and the Ruinenberg sites. It can thus be assumed that groundwater table values serve as a proxy for soil moisture, though this remains a hypothesis in the absence of adequate soil moisture data at the studied sites.

Our results are consistent with thosefor oaks in eastern Mecklenburg-Vorpommern, northeastern Germany, with comparable climatic and soil conditions (Scharnweber et al., 2011). Climate-growth analyses for sunshine duration and cloudiness for the Pfaueninsel and Ruinenberg sitesare in line with correlations with precipitation and temperatures (cf. Figures 4 to 6):A high sun sum during summer months leads to higher air temperatures, lower precipitation sums, and consequently high values of vapor-pressure deficits with a limited supply of water for the trees(Figure 6). Theseevidences –in particularly the strong correlation to groundwater table – point out the importance of soil water supply as the main driver for radial growth for the chosen historic park sites. Genus *Quercus* is generally well adapted to dry conditions and has several mechanism and strategies, including osmotic and elastic adjustments, specifications in root system, and wood anatomy to tolerate edaphic and atmospheric drought (Haavik et al., 2015). An adequate soil water content in combination with above-average precipitation sums lead to high rates of photosynthesis (C-source) and consequently contribute to the building up of carbon reserves for ahigh radial growth rate (Sala et al., 2012). Conversely, longer periods of drought in May, June, and July lead to early closure of stomata, restricted photosynthesis, and low reserves for radial growth (Sala et al., 2012).

Long-term trends of climatic variables show strongest alterations for April, with a rise in mean air temperature and sunshine duration and a decline in relative air humidity and precipitation (Prochnow et al. 2015). These climatic trends and the results of moving correlation analysis give evidence of a shift of climate growth relationships. Radial growth is mainly limited by water supply, andsoil moisture reserves in spring are strongly determined by preceding month's precipitation sums and soil moisture conditions. The increasing correlation withscPDSI at the Ruinenberg site and Pfaueninsel sitesin many of the previous and current year's months support this hypothesis. For a comparable oakstand in Mecklenburg-Vorpommern the temporal stability of correlations indicates also an increasing importance of current June scPDSI(Scharnweber et al., 2011). Evaluating to what extent shifts in climate-growth relations lead to oak decline, low tree vitality, and low growth rates is not yet clear. Bauwe et al. (2015) used modeled weather data from the regional climate model WETTREG2010 and partial least squares regression on the basis of climatic variables and tree-ring series to assess future growth trends. For the drier north-eastern German regions they assume growth reductions for *Q. robur* (Bauwe et al., 2015).

4.3. Pointer Years and Superposed Epoch Analyses

The negative pointer years 1901, 1913, 1925, 1930, 1934, 1947, 1948, 1954, 1976, 1992 and the positive pointer years 1914, 1916, 1927, 1931, 1950, 1955, 1979, 1980, 1988, and 2002 coincide with those found at regional level in Germany (cf. Figure7) (Scharnweber et al., 2011; 2013). Broadly speaking, below average rainfall and above average temperatures seem to trigger negative pointer years and contrary conditions lead to positive ones. A detailed description and grouping of the climatic conditions forcing pointer years is given by Neuwirth et al. (2007). Also for most years not corresponding with the pointer years for oaks at the regional level, climatic conditions at regional scale give strong evidence for the growth anomalies. For example, in the negative pointer years 1893, 1912, and 1989,precipitation sums from March to Julywere only 57 to 78 % of the long-time average. Drought is the key limiting factor for oak's radial growth at the historic park sites. This statement is also underlined by the results of the SEA using the ten driest and ten wettest years during April to June during 1893 to 2015. Impact of these anomalies on radial growth is restricted to the current year's growth rates, and neither for humidity nor for drought an impact on radial growth in the first post-event year could be detected (Figure8).

The less prominent role of temperatures for the formation of pointer years can be described by the positive pointer year 2007. Although temperatures from March to June were 28 % above average, a positive pointer year was found, since also precipitation sums were up to 57 % above long-term means. Besides climatic conditions the role of mast years, defoliation caused e.g. by late-frost or insect attacks, or water loggings can cause pointer years (Schweingruber, 1996). Late frost events with temperatures below -2°C may have caused negative pointer years in 1935 and 1941. Actually, the role of late-frost and winter frost for growth of oaks cannotbe significantly proven as the results for the SEA show (Figure8).

5. CONCLUSION

Old oaks of the World Heritage property 'Palaces and Parks of Potsdam and Berlin' reaching back several decades to centuries provide a distinctive element of vegetation and design in the parks and gardens. Although decreasing vitality and growth rates can be observed, oak trees will continue to be an option of park design also under envisaged future climatic conditions.

Increasing temperatures alone are not causing growth decline and significant lower growth rates. However, in combination with low precipitation rates leading to low soil water reserves,high temperatures have a significant impact on the growth rates. The fact that oldest trees were able to resist very different climatic extremes over more than 300 yearscan be taken as evidence for the high adaptive potential of oak trees. Declining growth trends of the trees cannot be considered as a sign for changing climatic conditions alone. Furthermore, declining growth trends are also a typical sign for the old stage of the trees. Climate-growth correlations indicate a shift in climate-growth relations over recent years. Under increasing drought, oak trees may respond with lower growth. However, significant effects in post-drought years were not found, indicating a high internal buffer capacity of the oak trees.

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