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Influence of volcanic eruptions on tree growth in NE-Germany during the last Millennium

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Introduction

The availability of light energy, water and specific temperature are the essential parameters for plants to photosynthesize. Thus a change in these meteorological conditions results in an altered plant net primary production and eventually in a modified tree growth.

One main scientific topic worldwide is climate change and the reasons for it. To discuss the change in climate is not the task of this work rather to focus on one potential control parameter steering weather conditions and the impact on tree growth such as the consequences of volcanic eruptions. Large eruptions of volcanoes have strong impacts on the global climate (Battipaglia et al. 2007, Latif 2009, Schweingruber 1996, Gao et al. 2008), lowering the global temperature (Press & Siever 1995, Robertson et al. 2001) and increasing the diffuse light fraction for one to several years after the eruptions (Krakauer et al. 2003, Gu et al. 2003). It has been argued that due to scattering by volcanic sulfur aerosol the more diffuse light fraction can be used more efficiently by forests. However, other observations suggest a growth decrease because of the cooler conditions following large eruptions. Trees growing to the north of the temperate zone are mainly temperature-limited (*e.g.*, Esper et al. 2002) and therefore a reduction in ring width after large volcanic eruptions seems inevitable. Since tree growth in the temperate zone is less limited by temperature than by other climate parameters such as precipitation, we hypothesize that tree growth may not suffer from lower temperatures so much but profit from increased diffuse light and reduced water stress.

Our goal is to compare different tree species at various sites in eastern Germany to test whether tree growth suffered or profited from the globally changed conditions after large eruptions during the last millennium.

Material and Methods

Study area

The study material was collected at three different locations in eastern Germany (Fig. 1).

In general, the tree-ring data pool is based on heterogenous archaeological material from the three sites. The material of Greifswald and Eberswalde was collected in the direct surroundings of the two cities (part B in Fig. 2 (1-6)). In contrast, the data pool from Saxony comprises numerous site chronologies and originates from the foothills of the Erzgebirge, a mid range mountain chain in the South of Saxony. In Saxony, *Quercus robur* L. (part B in Fig. 2 (1)) was collected on fertile soils in the area of Dresden/Meißen/Torgau (Fig. 1) and *Pinus sylvestris* L. on rather sandy soils (part B in Fig. 2 (1)) in the surroundings of Dresden/Kamenz/Görlitz (Fig. 1).

Temperature and precipitation data back to 1901 were extracted from the webpages of the Climate Research Unit (http://www.cru.uea.ac.uk) to characterise the climatic conditions of the regions of interest.

In general, the study sites are all located within a temperate warm and humid climate, usually experiencing warm summer temperatures (Kottek et al. 2006).

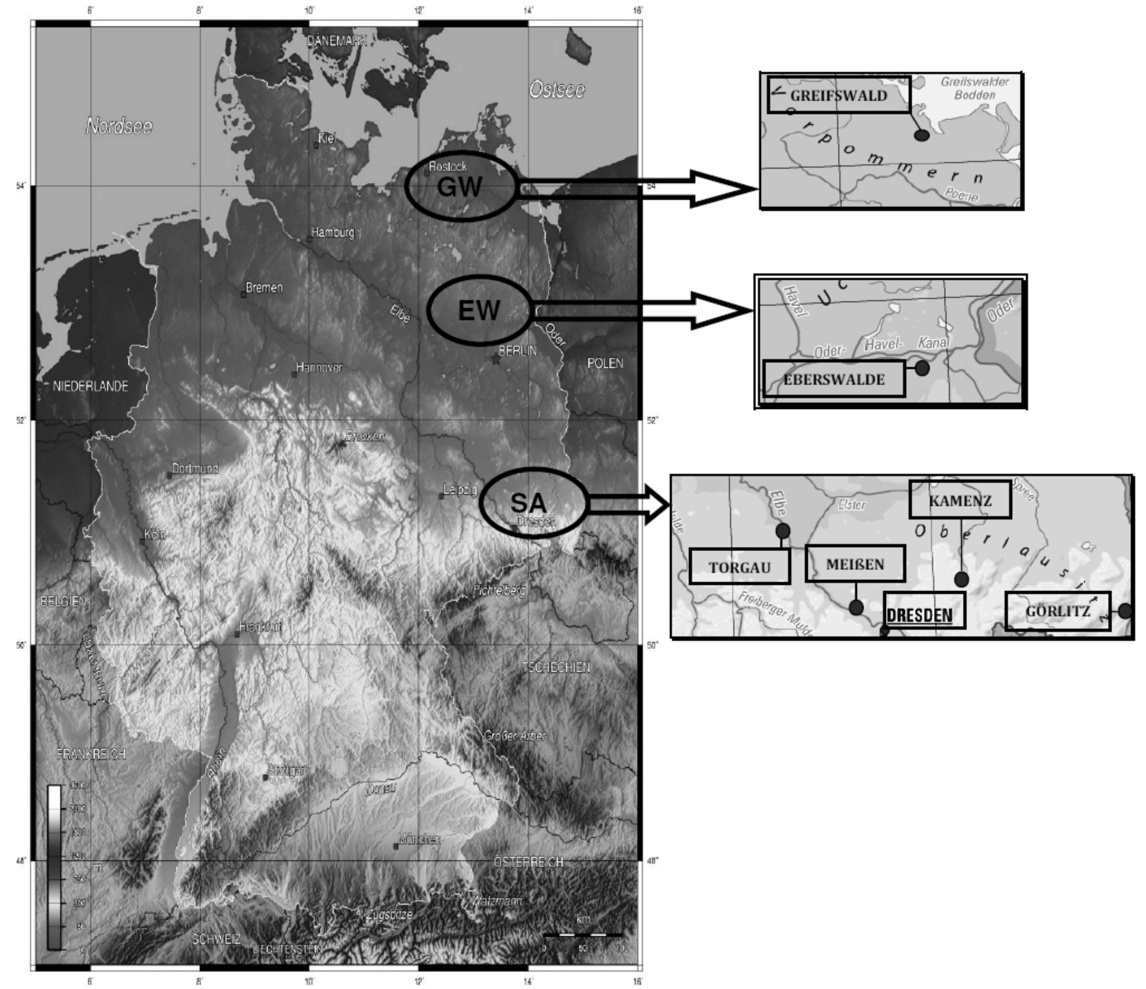


Figure 1: Location of the study sites (GW: Location Greifswald, EW: Location Eberswalde, SA: Location Saxony)

However, the three locations differ notably in regard to precipitation rates and temperatures. The site Saxony is more continental with drier summers than Greifswald and Eberswalde. The lower annual precipitation sum (precip/sum = 547mm) and the higher mean summer temperature (JJA = 18.1°C) in Saxony are characteristic for a more continental climate in comparison to Greifswald (precip/sum = 562mm, JJA = 16.74°C) and Eberswalde (precip/sum = 560mm, JJA = 17.67°C). Hence, in Saxony water is likely to be a more limiting factor to tree growth than in Greifswald and Eberswalde and can lead to drought stress for the vegetation. Eberswalde is also characterized by a continental influence but with a higher precipitation rate, therefore trees are likely to be less drought-stressed than in Saxony. Greifswald is the most maritime location characterized by balanced temperatures, relatively high amounts of precipitation and comparatively mild winters.

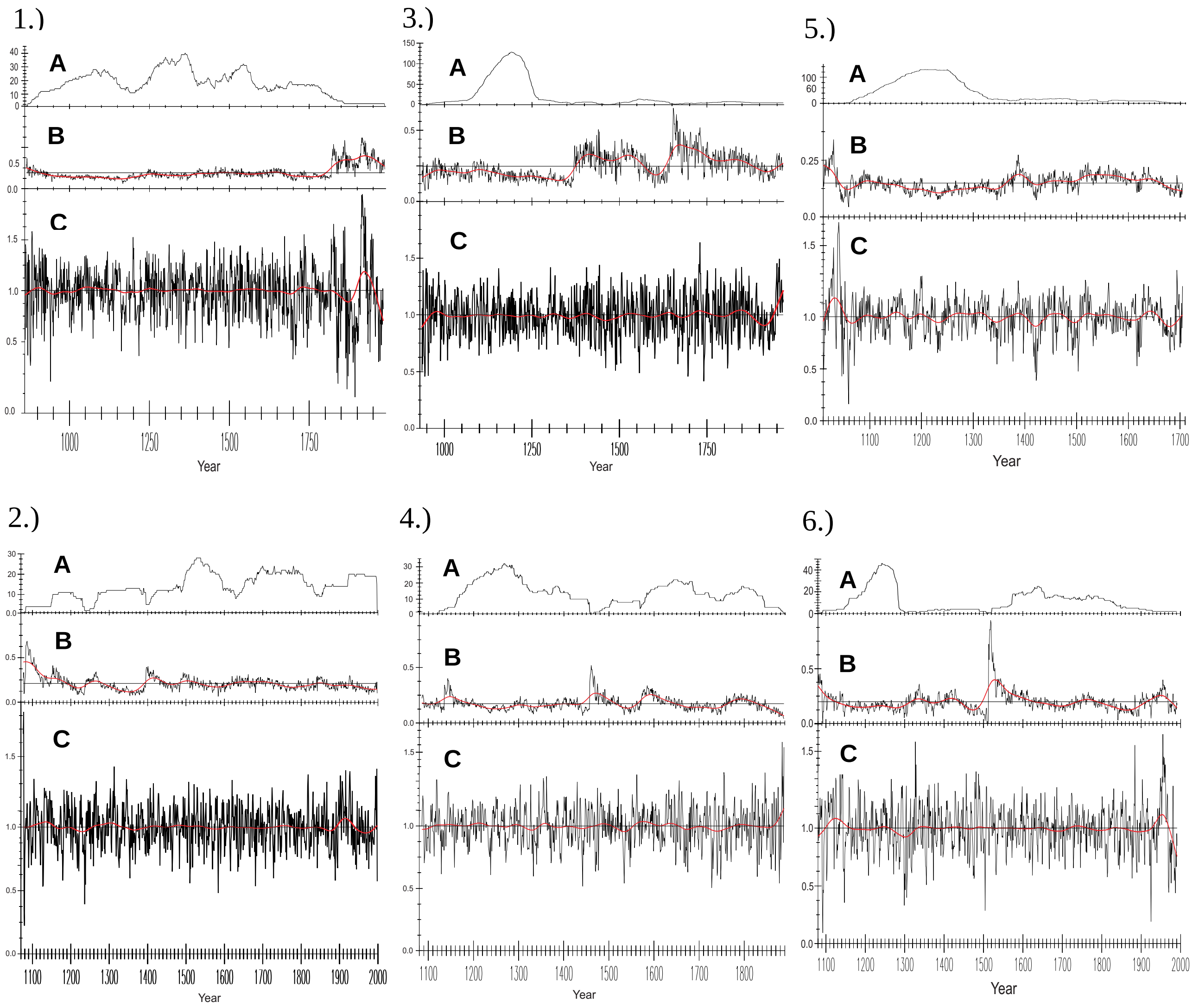


*Figure 2: (1-6): Overview of all sites and tree species with **A**: Number of samples; **B**: Raw ring width chronology; **C**: Standard Chronology ; a: Quercus from Saxony (QS) ; b: Pinus from Saxony (PS) ; c: Quercus from Greifswald (QG) ; d: Pinus from Greifswald (PG) ; e: Quercus from Eberswalde (QE) ; f: Pinus from Eberswalde (PE).*

We used a database of long tree-ring chronologies of two different tree species (*Quercus robur* L. and *Pinus sylvestris* L.) from three sites in eastern Germany (Fig. 2), covering more or less the last millennium (Tab. 1).

Table 1: Temporal intervals of the series of the two tree species from the three sites

	Sites		
Tree Species	Greifswald	Eberswalde	Saxony
Pinus sylvestris	1086-1888	1079-1991	1076-1998
Quercus robur	909-1968	1010-1705	782-1986

Besides, we used a time series of annual mean Northern Hemisphere 550-nm optical depth since 1000 CE (Crowley 2000) (http://www.ngdc.noaa.gov/paleo/pubs/crowley.html) to identify eruption years. This time series was derived primarily from high-resolution ice core sulfate measurements calibrated against atmospheric observations after modern eruptions. Eruption years were defined as years with a peak in volcanic aerosol forcing by using the volcanic explosivity index (VEI) (Newhall & Self 1982) The VEI uses geological evidence as a proxy for the measure of the power of the eruption and can range from 0 to 8 (Simkin & Siebert 1994). In this study we used strong volcanic eruptions with VEI of 4 or higher. Subsequently, we focused on large volcanic eruptions like Tambora 1815, Krakatau 1883 and Pinatubo 1991.

Furthermore, we collected additional volcanic eruption year dates from various sources (Gervais et al. 2001, Gao et al. 2008, Briffa et al. 1998a, LaMarche Jr. et al. 1984, http://www.volcano.si.edu/).

For the Southern Hemisphere sites, we used Southern Hemisphere volcanic-aerosol optical depths from the time series of Robertson et al. (2001). (http://www.ngdc.noaa.gov/paleo/pubs/robertson2001/robertson2001.html). This time series extends back to 1500 and was also primarily derived from ice core records. Overall, we obtained 49 eruption years (Fig. 3) for the period 1000-2000.

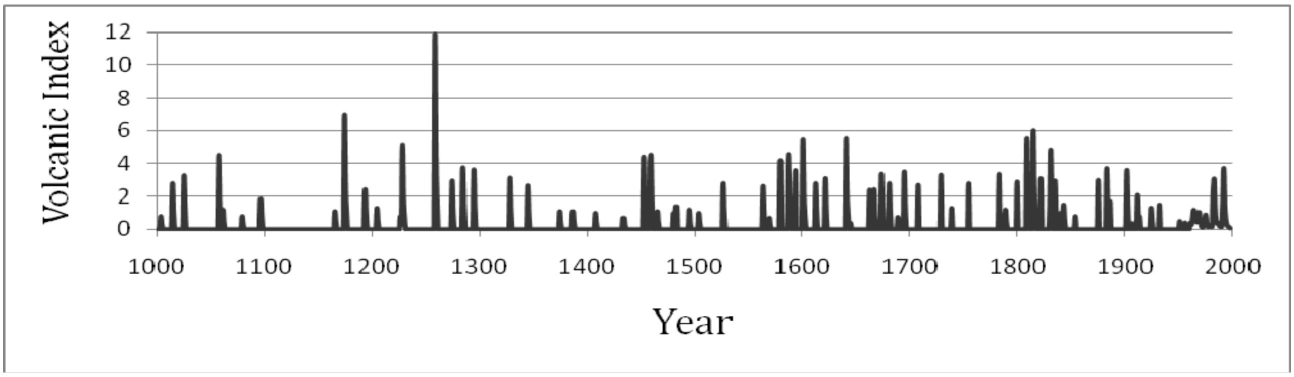


Figure 3: Overview of the 49 major volcanic eruptions derived from natural archives such as ice cores selected for comparison with tree rings for the period 1000-2000.

The tree-ring series were first checked for their crossdating qualities using TSAPWin (Rinn 2003) and COFECHA-software (Holmes 1983). In a first step, only highly correlating ring-width chronologies were selected for further detrending in ARSTAN (Cook 1985). The remaining ring-width series were standardized by fitting the Hugershoff growth curve model to the individual tree-ring series in order to remove biological growth trends as well as other low-frequency variations and to preserve all high-frequency signals (part C in Fig. 2 (1-6)). The detrended tree-ring series were examined individually for their reactions to large volcanic eruptions. The analysis was conducted by comparing boxplots (Fig. 5) focusing on growth trends of tree-ring series two years before and after the 45 strongest volcanic outbursts during the last 1000 years to test whether positive, negative or neutral tendencies within tree growth exist (Tab. 2). After the normal distribution of the data was determined the growth trends before and after each volcanic eruption were exposed to a Student’s t-test (with $p = 0.05$ (two-tailed) as the significance level) to examine if significant differences in tree growth after volcanic eruptions could be detected.

Additionally, we analyzed the overall response of the standardized site chronologies of the two tree species at the three sites five years before and after the volcanic eruption (Fig. 4).

Furthermore a pointer year analysis was conducted to detect the influence of volcanic eruptions on tree growth. This method investigates the reaction of trees to unusually favorable or unfavorable conditions via the formation of exceptionally wide or narrow tree rings (Schweingruber et al. 1990).

The pointer years were analyzed on the basis of the Cropper-method (Cropper 1979). That means that for the individual tree-ring width series indices are calculated through the ratio of each standard mean curve with a 13-year low-pass filter followed by a z-transformation of the index values in a 5-year moving window.

The pointer year analysis was repeated with the computer program WEISER developed by Gonzales (2001), which also analyzes the individual data series for pointer years.

Results and Discussion

Despite two delayed negative growth reactions (Quercus from Greifswald, QG (Fig. 4-c) and Pinus from Eberswalde, PE (Fig. 4-f)) an immediate negative signal of all tree species was clearly visible when analyzing the overall response of the standardized site chronologies five years before and after the volcanic eruptions (Fig. 4).

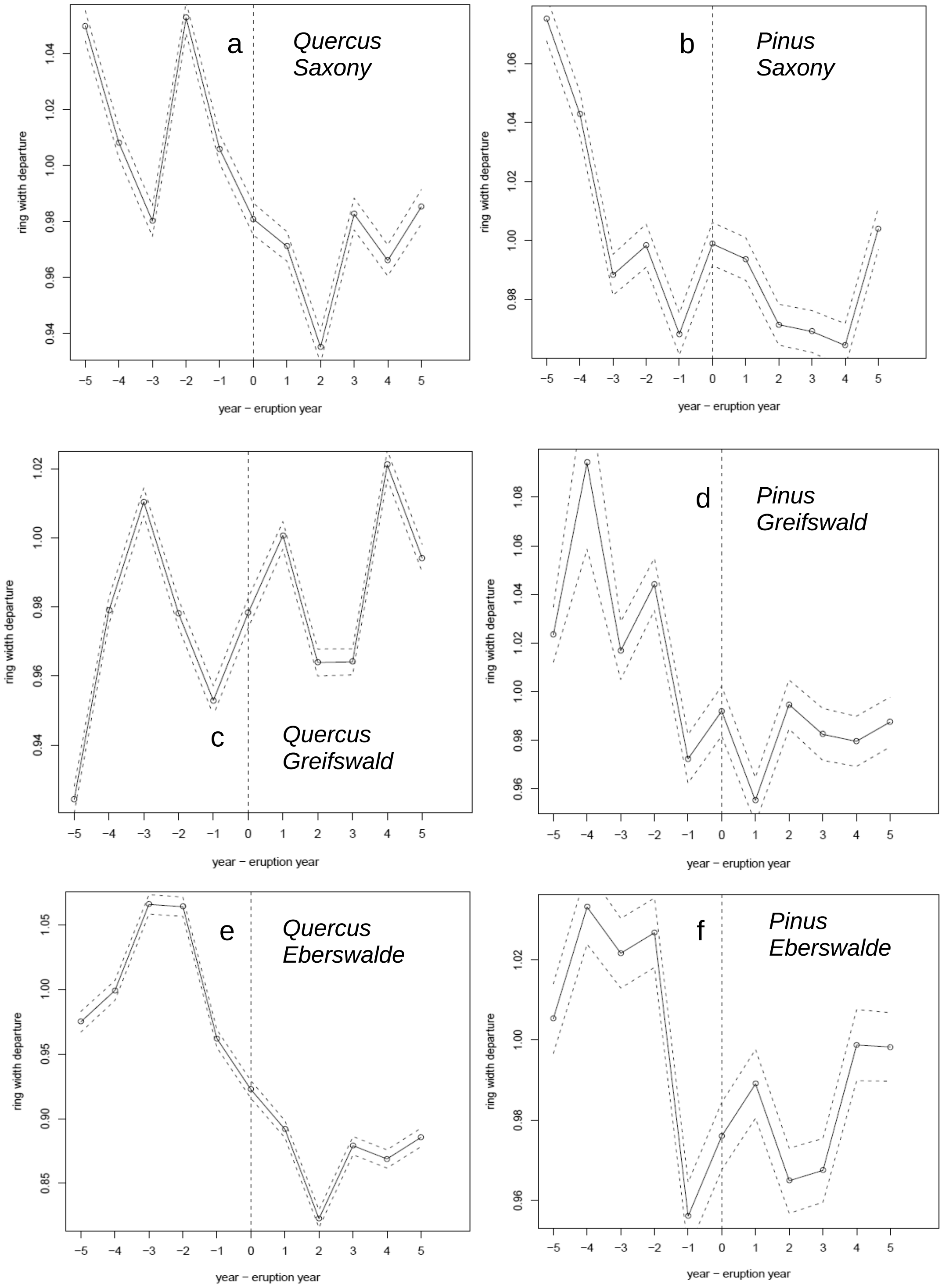


Figure 4 (a-f): Mean ring width departures before and after eruption years (0), separated by site and tree species. Tree–ring width departures are expressed in absolute values. Dashed blue lines show confidence intervals based on the variations across eruption years.

Most negative growth trends after the eruption lasted for two years except for *Pinus* from Greifswald (PG) and *Pinus* from Saxony (PS). At PG the negative trend lasted for one year (Fig. 4-d) and at PS it was even stronger and lasted for 4 years (Fig. 4-b). Generally, the growth rate decline within the five year interval after the eruption, compared to the five years before the eruption, except for QG (Fig. 4-c) and PE (Fig. 4-f) which increase at the fourth year after the eruption. Comparing all ring-width departures in Fig. 4, *Quercus* from Eberswalde (QE) (Fig. 4-e) shows the largest reduction.

The analysis of the individual reactions of the tree-ring series to large volcanic eruptions two years before and after the 49 strongest volcanic outbursts during the last 1000 years (e.g. Fig. 5) displays three different growth trends (negative, positive and neutral) as seen in table 2.

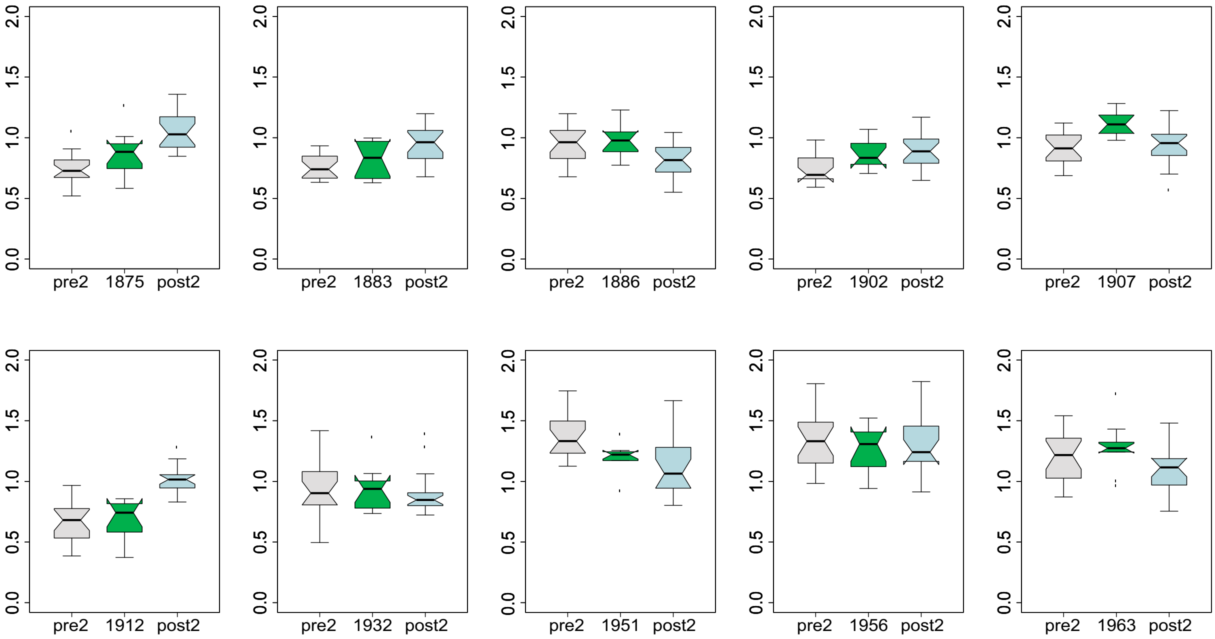


Figure 5: Example for boxplots analyzing the growth trends of standardized tree-ring series two years before and after volcanic outbursts during the period 1875-1963 for the site Quercus Greifswald. X-axis displays the year of eruption, two years before (pre2) and two years after (post2) a large volcanic eruption. Y-axis shows growth reactions of the standardized tree-rings series.

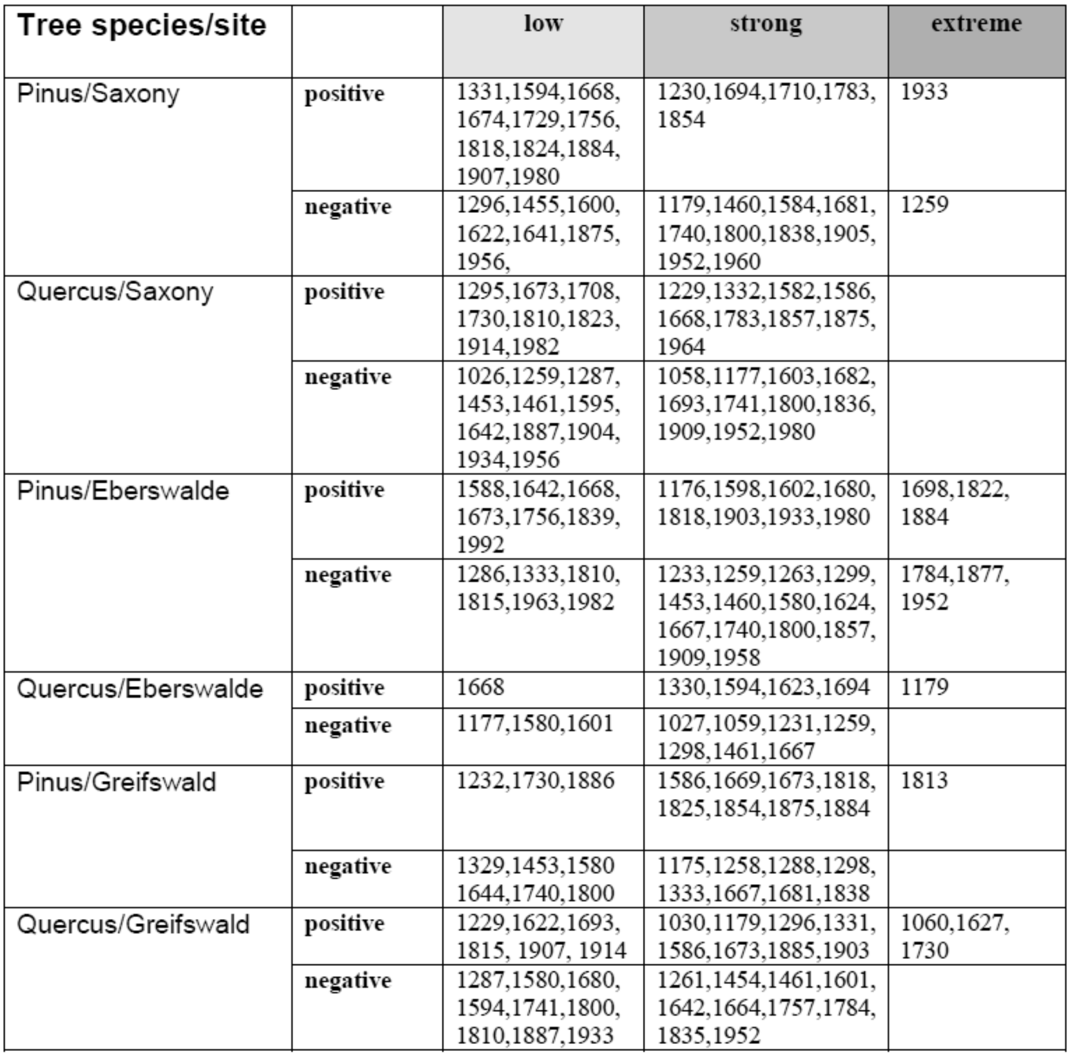
Through this analysis out of 225 possible cases 118 negative, 100 positive and 7 neutral growth trends after the volcanic outbursts were revealed. Thus, the impact of volcanic eruptions appeared to have a rather more negative influence and confirm the previous analysis (Fig. 4). When comparing both tree species *Q. robur* shows a tendency to more negative reactions than *P. sylvestris* which at Greifswald and Saxony displays mainly positive reactions as shown in table 2.

Table 2: Numbers of positive, negative and neutral tree-growth trends 2 years after each volcanic outburst sorted by tree and site. In brackets are the significant results. 46.5% of the P. sylvestris and 39.21% of the Q. robur results are significant (EW – Eberswalde, GW – Greifswald, SA - Saxony).

Growth-trend	Quercus EW (QE)	Quercus GW (QG)	Quercus SA (QS)	Pinus EW (PE)	Pinus GW (PG)	Pinus SA (PS)
positive	6 (2)	18 (8)	16 (2)	20 (10)	18 (4)	22 (11)
neutral	2	0	3	0	0	2
negative	13 (8)	24 (11)	25 (9)	22 (10)	15 (7)	19 (12)

By comparing all tree species at the three sites a relationship of 60% negative significant growth reactions and 40% positive reactions after the eruptions is shown. Slightly different results but with the same tendency are revealed by comparing the tree species at each site. QE, QS as well as PE and PS display 80% negative growth trends for *Quercus* and 50% for *Pinus.* In Greifswald, the growth trends are somewhat different, that is, with 58% and 64% negative growth response for QG and PG, respectively, only in Greifswald both tree species show a clearly negative response in tree growth after volcanic eruptions.

Table 3: Overview of the pointer years separated for tree species, locations and severity of the pointer years (low-1 standard deviation, strong-1.5* standard deviation, extreme-2* standard deviation)*



Tree species/site		**low**	**strong**	**extreme**
Pinus/Saxony	**positive**	1331,1594,1668, 1674,1729,1756, 1818,1824,1884, 1907,1980	1230,1694,1710,1783, 1854	1933
	negative	1296,1455,1600, 1622,1641,1875, 1956,	1179,1460,1584,1681, 1740,1800,1838,1905, 1952,1960	1259
Quercus/Saxony	**positive**	1295,1673,1708, 1730,1810,1823, 1914,1982	1229,1332,1582,1586, 1668,1783,1857,1875, 1964	
	negative	1026,1259,1287, 1453,1461,1595, 1642,1887,1904, 1934,1956	1058,1177,1603,1682, 1693,1741,1800,1836, 1909,1952,1980	
Pinus/Eberswalde	**positive**	1588,1642,1668, 1673,1756,1839, 1992	1176,1598,1602,1680, 1818,1903,1933,1980	1698,1822, 1884
	negative	1286,1333,1810, 1815,1963,1982	1233,1259,1263,1299, 1453,1460,1580,1624, 1667,1740,1800,1857, 1909,1958	1784,1877, 1952
Quercus/Eberswalde	**positive**	1668	1330,1594,1623,1694	1179
	negative	1177,1580,1601	1027,1059,1231,1259, 1298,1461,1667	
Pinus/Greifswald	**positive**	1232,1730,1886	1586,1669,1673,1818, 1825,1854,1875,1884	1813
	negative	1329,1453,1580 1644,1740,1800	1175,1258,1288,1298, 1333,1667,1681,1838	
Quercus/Greifswald	**positive**	1229,1622,1693, 1815, 1907, 1914	1030,1179,1296,1331, 1586,1673,1885,1903	1060,1627, 1730
	negative	1287,1580,1680, 1594,1741,1800, 1810,1887,1933	1261,1454,1461,1601, 1642,1664,1757,1784, 1835,1952	

The following pointer year analysis also confirmed the results of the previous analyses. The analysis identified 191 pointer years of which 106 were negative and 85 were positive pointer years. Common negative pointer years at all sites and of both tree species are 1258, 1453, 1663, 1739, 1800, 1951, 1956 and positive pointer years are 1586, 1667, 1673, 1822 and 1912.

For the eruption years 1229, 1815 and 1854 both tree species have similar patterns in growth reactions. In Greifswald and Saxony, both tree species show positive (low and strong pointer years) growth reactions after the eruptions. In contrast, trends to negative tree growth are suggested for *Q. robur* and *P. sylvestris* in Eberswalde (strong pointer years).

In the eruption year 1783 the two tree species in Greifswald show negative pointer years and in Saxony positive pointer years. Furthermore, in eruption year 1835 two negative and in 1854 two positive pointer years for Greifswald and Saxony are highlighted (Tab.3). However, we did not identify any extreme pointer years common to all three sites and the two tree species.

Dendrochronological analyses are a useful approach to distinguish the degree of growth reduction in *Q. robur* and *P. sylvestris* in eastern Germany due to volcanic eruptions. This work is a study on the effects of strong volcanic eruptions resulting in growth response on the local scale. This is an opportunity to explore the process and causal relationships between climatic changes and the response of the vegetation. Tree growth is limited by different factors, depending on the species and on the specific site conditions (Fritts 1976, Briffa et al. 1990, Briffa & Jones 1994, Mann et al. 1998, Hughes 2002).

Two hypotheses were considered in this study:

The first hypothesis dealt with the change in the radiation balance thereby cooling the atmosphere and leading to temporarily lower temperatures and a reduction of tree growth. Presumably a decrease in temperatures and an increase in relative humidity would lead to higher stomatal conductance and a possible decrease in photosynthetic rates. Ultimately, this will lead to a reduction of d13C and d18O values in the organic matter (Battipaglia et al. 2007, Krakauer et al. 2003). However, in this study no isotope data were analyzed, and thus, no stomatal conductance could be investigated to evaluate the impact of volcanic eruptions on net primary production. Visible signs would be decreasing tree-ring widths (Briffa et al.1988a, b, 1998a, b; Scuderi 1990; Jones & Bradley 1992). The hypothesis of a significant reduction in ring width following eruptions could be confirmed in this study. Comparable to results for tree species in southern Italy (Battipaglia et al. 2007) and northern forests (Krakauer et al. 2003) *Q. robur* showed in 70% of all cases and *P. sylvestris* in 54% negative growth trends at all three sites.

The second hypothesis, that is, enhanced photosynthetic rates and thus tree growth due to more diffusive light caused by volcanic ashes and aerosols in the atmosphere (Gu *et al.* 2003) could not be verified. Only a small proportion (30% of *Q. robur* and 46% of *P. sylvestris)* of the tree species analyzed showed positive growth trends. In these cases wider tree rings could be expected, with increased d13C values, and hardly changed or slightly lower d18O values, as a result of higher relative humidity and stomatal conductance, as suggested previously by Battipaglia et al. 2007.

However, a clear relationship between eruption magnitude, location of the volcanoes and tree-ring responses was not found. Not all large volcanic eruptions resulted in reduced tree growth in eastern Germany (Gervais et al. 2001).

In conclusion, volcanic eruptions seem to have a more negative influence on tree growth of *Q. robur* and *P. sylvestris* in eastern Germany, although the signal is not as clear and strong as has been found in previous studies (e.g., Briffa et al. 1998a). We identified more negative growth trends for *Q. robur* in comparison to *P. sylvestris*. The site Greifswald showed the most negative trends by comparing the growth trends of the trees from all three sites with each other. Volcanic eruptions of the northern hemisphere seem to have a more negative influence on tree growth of *Q. robur* and *P. sylvestris* in eastern Germany than volcanic eruptions of the southern hemisphere, although the signal is not as clear and strong as has been identified in previous studies for trees growing in more northern latitudes with comparatively longer negative growth trends of 10-20 years (e.g., Scuderi 1990, Shiyatov 1996, Briffa et al. 1998a, Jacoby et al. 1999, Gervais et al. 2001, Krakauer et al. 2003). In this study, negative growth trends of the trees lasted from 1-4 years.

For a comprehensive confirmation of the current results further investigations of other plant physiological parameters such as wood anatomical properties and stable carbon and oxygen isotopes of *Q. robur* and *P. sylvestris* and other tree species would be desirable.

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