Palaeogeography, Palaeoclimatology, Palaeoecology 411 (2014) 155–166

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

The influence of volcanic eruptions on growth of central European lowland trees in NE-Germany during the last millennium

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ARTICLE INFO

Article history:
Received 6 February 2014
Received in revised form 14 June 2014
Accepted 17 June 2014
Available online 30 June 2014

Keywords:
Dendrochronology
Volcanic forcing
Tree-rings
Climate change
Pinus sylvestris L.
Quercus robur L.

ABSTRACT

Palaeoclimate proxies have shown links between climate changes and volcanic activity. However, not much is known about the impact of volcanic outbursts on growth of lowland trees. We investigate the effect of large volcanic eruptions on the growth rate of trees. The study is based on an unexplored comprehensive database with 1128 samples of long tree-ring width (TRW) chronologies of *Quercus robur* L. and *Pinus sylvestris* L., correlating with forest net primary production (NPP), originating from three different sites in eastern Germany (Greifswald, Eberswalde and Saxony). This study focuses on trees in rarely examined temperate zones where tree growth is less temperature limited. Growth relationships were compared against 52 large volcanic eruptions known for the last 1000 years. Dendrochronological methods revealed a predominantly negative (60.2%) effect of large volcanic eruptions on the tree-ring chronologies. Nevertheless, also positive (31.7%) and neutral (8.7%) tree growth reactions were detected. In the tree-ring width chronologies of *Q. robur* and *P. sylvestris*, we detected a negative influence on tree growth for up to four years after large eruptions. The chronologies of *Q. robur* revealed a stronger negative response (68.1%) than those of *P. sylvestris* (53%). However, at the Greifswald site both tree species (79% *Q. robur* and 73% *P. sylvestris*) show a negative response in tree growth after every volcanic eruption. Furthermore, the results suggest that volcanic aerosols originating from the Northern Hemisphere cause a greater reduction in tree growth than aerosols being emitted from Southern Hemisphere volcanoes, which might be related to the long distances between trees and volcanoes, as well as the global atmospheric circulation patterns. This study demonstrates that the effects of major volcanic eruptions are less clear in trees from central European lowlands than in trees growing at the altitudinal or latitudinal timberlines.

1. 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.

In history large volcanic eruptions have had more or less significant influences on the regional to global climate for one to several years. Through this impact they have been mentioned as a possible explanation for worldwide climate change or as inducers of climate turning points, such as the expiry of the Medieval Warm Period (MWP).

Large eruptions of volcanoes have strong impacts on the global climate (Schweingruber, 1996; Free and Robock, 1999; Crowley, 2000; Shindell et al., 2001; Battipaglia et al., 2007; Salzer and Hughes, 2007; Gao et al., 2008; Latif, 2009, Sigl et al., 2012) lowering the global temperature (Lacis and Sato, 1992; Minnis et al., 1993; Zielinski et al., 1994; Jones et al., 1995; McMormick et al., 1995; Press and Siever, 1995; Briffa et al., 1998a; Zielinski, 2000; Robertson et al., 2001; Shindell et al., 2003; Larsen et al., 2008; D'Arrigo et al., 2009) and increasing the diffuse light fraction for one to several years after the eruptions (Gu et al., 2003; Krakauer and Randerson, 2003). Volcanic aerosols can play an important role in disturbing the Earth's climate, for example by creating a dust veil, which reduces the transparency of the atmosphere. It has been argued that due to scattering by volcanic sulfur aerosol the more diffuse light fraction can be used more efficiently by forests (Roderick et al., 2001; Farquhar and Roderick, 2003; Gu et al., 2003; Robock, 2005). However, other observations suggest a growth decrease because of the cooler conditions following large eruptions (Smiley, 1958; Briffa et al., 1988b, 1998a,b; Scuderi, 1990; Jones and Bradley, 1992; Yamaguchi and Lawrence, 1993; Krakauer and Randerson, 2003; Battipaglia et al., 2007; Salzer and Hughes, 2007; Sheppard et al., 2009; Anchukaitis et al., 2012; Breitenmoser et al., 2012; McCarroll et al., 2013). After major historically recorded eruptions, such as those of Tambora in Indonesia (AD 1815) and Laki in Iceland (AD 1783), present day writers recorded severe late frosts and peculiar hazes in regions located far away from the volcanoes themselves (Grattan and Brayshay, 1995). Dendroclimatological studies have shown that the tree-rings of Irish bog oaks were unusually narrow after the eruptions of the volcanoes mentioned above (Baillie and

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http://dx.doi.org/10.1016/j.palaeo.2014.06.012
0031-0182/

Munro, 1988), while bristlecone pine growth rings of the same age in California showed signs of frost damage (LaMarche and Hirschboeck, 1984). These have been interpreted as the result of a cooler and/or wetter climate. However, in Turkey, experiencing a hot and dry climate in summer, the same climatic change gave rise to more, not less, favourable growing conditions and to broader tree-rings (Kuniholm et al., 1996). While the evidence linking tree-rings, climate and volcanic eruptions is impressive, it also suggests that in most cases the climate perturbation was short-lived, typically a decade or less (Lyons et al., 1990; Zielinski et al., 1994; Press and Siever, 1995; Robock and Fee, 1995; Free and Robock, 1999; Robertson et al., 2001; Shindell et al., 2001, 2003; Gu et al., 2003; Sheppard et al., 2009; Timmreck et al., 2009, 2010; Speer, 2010). The understanding of whether tree growth after volcanic eruptions increases or decreases in the same way worldwide is important for climate-vegetation models, especially global scale carbon balance models (Roderick et al., 2001). So far tree-ring studies indicated that around 80% of the investigated trees suffered significant growth reductions primarily due to unusually low temperatures after volcanic explosions during the growing season (e.g., Krakauer and Randerson, 2003). However, such studies have been based mainly on coniferous species from the high latitudes and altitudes. Coniferous 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. Due to a lack of studies in temperate zones (Gu et al., 2003; Krakauer and Randerson, 2003) there is still a need for understanding how trees grow after volcanic outbursts in temperate zones. After volcanic eruptions carbon balance models are indicating negative carbon balances for forested areas worldwide (Lucht et al., 2002). However, if trees would benefit rather than suffer after volcanic eruptions, more carbon than currently modelled would be bound by the forests (Kirschbaum, 2003, 2006).

The response of tree growth to volcanic forcing will be examined by using 1000-year ring-width chronologies constructed from *Pinus sylvestris* L. (Scots pine) and *Quercus robur* L. from a previously unexplored area in eastern Germany to add new insights to the controversial issue whether volcanic eruptions result in favourable or unfavourable conditions for tree growth (Fig. 1). We present new ring-width data from temperate lowland sites and compare them with previous studies, which only focused on extreme sites at the latitudinal and altitudinal limits of forest distribution (e.g. Jones et al., 1995; Briffa et al., 1998a, b; D'Arrigo et al., 1999; Jacoby et al., 1999; Gervais and MacDonald, 2001; Krakauer and Randerson, 2003; Salzer and Hughes, 2007; Larsen et al., 2008; Anchukaitis et al., 2012; Breitenmoser et al., 2012; Esper et al., 2013; McCarroll et al., 2013). 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.

Three different scenarios of tree responses were established: The first scenario (scenario I) states a neutral growth reaction of tree growth. The radiation balance of the atmosphere is not significantly influenced by increased aerosols after a volcanic eruption and thus no significant response of tree growth after volcanic activity is expected (Timmreck et al., 2009; Mann et al., 2012). According to the second scenario (scenario II), the changed radiation balance cools the atmosphere, leading to an increase in relative humidity and a reduction of tree growth. Visible signs on the trees would be a decrease in tree-ring width (Briffa et al., 1988a,b, 1998a,b; Scuderi, 1990; Jones and Bradley, 1992). The third scenario (scenario III), the increase in diffusive radiation, caused by volcanic ashes and aerosols in the atmosphere, enhances the photosynthetic rate (Kuniholm et al., 1996; Roderick et al., 2001; Farquhar and Roderick, 2003; Gu et al., 2003), resulting in an increased tree growth. In this case, we expect wider tree rings.

The aim of this work is to focus on volcanic eruptions as potential control parameters steering weather conditions temporarily and consequently tree growth. Extensive tree ring chronologies and the variability of atmospheric volcanic aerosol concentrations may play important roles in the dynamics of the global carbon cycle.

2. Material and methods

2.1. Study regions

The study material was collected at three different locations in eastern Germany (Fig. 1). The trees used for buildings in Greifswald and Eberswalde were felled in forests in the close surroundings of the two cities (Fig. 1a–b). 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, the samples of *Quercus robur* L. were collected on fertile soils in the areas of Dresden, Meißen and Torgau, and of *Pinus sylvestris* L. on rather sandy soils in the surroundings of Dresden/Kamenz and Görlitz (Fig. 1c).

In general, the study regions are all located within a temperate warm and humid climate, usually experiencing warm summer temperatures (Kottek et al., 2006). However, the three locations differ in regard to precipitation rates and temperatures. The region of Saxony is more continental with drier summers than Eberswalde and Greifswald. Hence, in Saxony water is likely to have a stronger limiting impact on tree growth than in Greifswald and Eberswalde and can lead to drought stress for the vegetation.

2.2. Database

A database of 1128 samples of long tree-ring chronologies of two different tree species (*Quercus robur* and *Pinus sylvestris*) covering more or less the last millennium was used (Table 1). In general, the tree-ring data pool is based on heterogenous archaeological material.

Moreover, a time series of annual mean Northern Hemisphere 550-nm optical depth from AD 1000 to identify eruption years was used. This time series was derived primarily from high-resolution ice core sulfate measurements calibrated against atmospheric observations after modern eruptions (Crowley, 2000) (http://www.ngdc.noaa.gov/paleo/pubs/crowley.html, 09/15/2013). Eruption years were defined as those that showed a peak in volcanic aerosol forcing.

Furthermore, additional volcanic eruption year dates from various sources were collected (LaMarche Jr. et al., 1984; Briffa et al., 1998a; Gervais and MacDonald, 2001; Gao et al., 2008; http://www.volcano.si.edu/, 09/08/2013). For the Southern Hemisphere sites, Southern Hemisphere volcanic-aerosol optical depths from the time series of Robertson et al. (2001), which extends back to 1500 CE and was also primarily derived from ice core records, were used.

Overall, 52 eruption years with a Volcanic Explosivity Index (VEI) of ≥ 4 for the period AD 1000–2000 (Fig. 3; Table 2) were obtained. The VEI is a general indicator of the explosive character of an eruption. It is a composite estimate of magnitude and/or intensity and/or destructiveness and/or (less frequently) dispersive power, violence, and energy release rate, depending on which data were available. Eruptions can be assigned a VEI on a scale of 0 to 8 (Newhall and Self, 1982). Subsequently, we will focus on large volcanic eruptions like Tambora 1815, Krakatau 1883 and Pinatubo 1991. Temperature, precipitation and Palmer Drought Severity Index (PDSI) data back to AD 1901 were extracted from the webpages of the Climate Research Unit (www.cru.uea.ac.uk, 09/08/2013) to characterise the climatic conditions of the regions of interest.

2.3. Standardisation

The tree-ring series were first checked for their crossdating qualities using TSAPWin software (Rinn, 2003) and COFECHA software (Holmes, 1983). In a first step, only highly correlating ring-width chronologies (a correlation of ≥ 0.59 with the master chronology) were selected for