



Deviations of treeline Norway spruce radial growth from summer temperatures in East-Central Europe

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ABSTRACT

While some cold regions show evidence of recent decoupling of tree-ring growth from observed temperature rise, i.e. restricted growth increase, similar evidence from other regions is missing. Increasing or diminishing regional coherency in tree growth has also been observed over recent decades. The temporal and spatial extent of the abovementioned processes are poorly known and their drivers are not well understood. Pollution and changing climate have often been discussed as a cause of divergent or convergent growth patterns and deviations of growth from driving climatic variable. We compiled climatic records and robust tree-ring chronologies of treeline *Picea abies* covering 1920–2010 for four regions in East-Central Europe (Czech Republic, Poland, Slovakia, 50°N, 15–20°E) which experienced differing acid pollution loads. The divergence of these chronologies from Jun-Jul temperatures was compared with temperature and pollution trends. We found a period of low intra-regional growth coherency in the 1950s reflecting warmer, less temperature-limiting conditions and land use change. Highly coherent growth in the 1930s, 1970s and 1980s was related to the strong environmental growth-limiting signals of short growing seasons and high acid pollution loads. In all regions, we identified periods with higher (1940–1960s) and lower (1970–1980s) growth than expected based on temperature. In the high-frequency domain, the effect of pollution on growth departure from temperature was limited and detectable exclusively in regions that were most impacted by pollution. In the low-frequency domain, the departures of growth from temperature were caused by combined effects of the changing seasonal window of tree growth sensitivity to climate and pollution load. These results highlight the need to recognize non-stationary noise in the relationship between temperature and tree growth.

1. Introduction

Mountain forests are crucial carbon sinks (Kurz et al., 2007), making it vital to understand their growth dynamics. Production of stem biomass in mountain forests is primarily affected by competition, disturbance and environmental constraints (Pretzsch et al., 2014). The latter includes climatic variables, among them temperature, which has been showing an almost uniformly increasing trend over recent decades (IPCC, 2014). In the temperate zone of Europe, growth responses of mountain forests to increasing temperature have been predominantly positive in terms of radial growth (Leal et al., 2007; Hartl-Meier et al.,

2014), with some exceptions from the lower part of the montane forest zone (Ponocná et al., 2016). The strongest positive responses have been reported from treelines (Rolland et al., 1998; Oberhuber, 2004; Tremel et al., 2015a). However, growth divergence (i.e. decoupling of growth curves from temperature trends) has been observed across many temperate and boreal forests (Wilson et al., 2007; D'Arrigo et al., 2008), even for temperature-limited trees close to their upper or northern limits (D'Arrigo et al., 2004; Wilmking et al., 2005; Galván et al., 2015). Since there is also evidence that trees in some cold regions do not display signatures of growth divergence (e.g. treelines in the Alps, Büntgen et al., 2008), the degree to which trees are decoupled from

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climatic forcing, and the spatial and temporal extent of this phenomenon, remains unknown.

In temperature-limited environments, a weakening of the link between radial growth and temperature has been observed in several regions of Canada and Alaska (D'Arrigo et al., 2004; Wilmking et al., 2004), Siberia (Jacoby et al., 2000), Northern Europe (Schneider et al., 2014 for maximum wood density), the Pyrenees (Galván et al., 2015) and Central Europe (Wilson and Elling, 2004). The observed divergence has been attributed to, for instance, the intervention of other climatic limiting factors such as drought in Canadian and Alaskan treeline areas (Barber et al., 2000; Lloyd and Fastie, 2002). In montane forests of Central Europe, divergence has been ascribed to the effect of sulfur and nitrogen air pollution (Wilson and Elling, 2004; Godek et al., 2009; Rydval and Wilson, 2012). It has been suggested that divergence in other areas, particularly boreal forests (D'Arrigo et al., 2008; Stine and Huybers, 2014), has been due to the effect of “dimming” (i.e. decrease in incident solar radiation due to increasing concentration of aerosols in the atmosphere). However, Büntgen et al. (2008) argued that no divergence appears in high-elevation tree-ring chronologies from the Alps, with most treeline chronologies tracking both high and low-frequency temperature variations well.

In our region of interest – Central Europe – growth divergence has been observed not only in mountain but also in lowland tree-ring chronologies. This includes oak chronologies since the 1980s (Dobrovolný et al., 2016; Prokop et al., 2016) and also some silver fir chronologies (Wilson and Elling, 2004; Büntgen et al., 2011). Although pollution has been suggested as a probable cause for fir, the sudden decrease in climate sensitivity of oak remains unresolved.

In contrast to observed growth divergence from climatic trends, another general pattern related to changing climatic conditions has recently emerged – increasing convergence of growth patterns within regions (Shestakova et al., 2016). Under increasing environmental stress (e.g. increasing drought severity and/or frequency) tree growth coherency increases as well (Shestakova et al., 2016; Tumaier and Treml, 2017). Based on this pattern, assuming that growth of treeline trees is limited by temperature (Körner, 2012), their growth coherency should decrease if they are subjected to warming, which may be accompanied by a decrease in strength of the temperature signal in treeline tree-ring chronologies. On the other hand, pollution, as a stressor, could become a driver of convergence in growth patterns.

In this study, we hypothesized that the possible decoupling of tree growth from temperature forcing will be proportional to the pollution load or the degree of warming. We also hypothesized that decoupling will be more obvious in low-frequency variability than in the high-frequency components of time series. This is because the influence of previously negligible or absent variables affecting growth (i.e. pollution, extension of the growing season) are thought to gradually shift the prevailing climate response (D'Arrigo et al., 2008). To test these hypotheses, we built representative tree-ring chronologies, similar in terms of age and site representation, for four treeline areas with a differing air pollution load.

2. Material and methods

2.1. Geographic setting

The focal area for our study is the mountainous area of East-Central Europe (i.e. the region situated at 50° N latitude and between 15° and 20° E longitude, Fig. 1). The study region comprises crystalline areas of the Krkonoše Mts. (KRK), the Jeseníky Mts. (JES), both belonging to the Bohemian Massif, and flysch, crystalline and limestone massifs of the Carpathians (Babia Góra Mts. - BAB, Nízké Tatry Mts. - NT) with elevations ranging from 1491 to 2056 m a.s.l. Norway spruce (*Picea abies* L. Karst.) dominates montane forests up to the timberline. Prostrate dwarf pine (*Pinus mugo*) is also widespread in the treeline ecotone except at JES. The climate is cold (mean treeline growing season

temperature is 6.7 °C, (Kaöpar and Treml, 2016) and humid, with annual precipitation totals ranging from 1200 mm in JES to 1500 and 1800 mm on the summits of BAB and KRK, respectively (Kwiatkowski, 1982; Migala, 2005). Soils of the montane forests are mostly podzols, dystric cambisols, and rankers (Tomášek, 1995; Granec and Šurina, 1999).

The lower limit of the alpine treeline ecotone (i.e. so-called timberline) increases toward the east from 1240 m a.s.l. in KRK to 1320 m a.s.l. in JES, ca. 1370 m a.s.l. in BAB and 1410 m a.s.l. in NT, with maximum timberline positions about 100 m higher than the above-mentioned mean values (Treml and Migoń 2015, Czajka et al. 2015a). Since the second half of the 20th century, treeline ecotones have been gradually advancing upwards as a consequence of land-use change and warming (Czajka et al., 2015b; Treml et al., 2016). During the 1970s and 1980s, forests in the study area were affected by acid pollution resulting in growth suppression and increased mortality (Sander et al., 1995; Rydval and Wilson, 2012). The major pollution sources were situated in the boundary region of Germany, Poland and the Czech Republic, which was reflected in a pronounced gradient in reaction to pollution from the western (strongest response) to the eastern part of the study area.

2.2. Sampling and sample processing

Increment cores from co-dominant or dominant *P. abies* growing at timberline were collected in KRK, JES, BAB, NT between 2010 and 2012 (Table 1). Each region was represented by two to three sites located on different slope aspects. Mean tree height was about 10 m. All sites were without visible recent human intervention (e.g., no evidence of recent logging or grazing). Two cores per tree were taken at breast height (approx. 1.3 m above the ground) perpendicular to the slope. Cores were prepared using standard dendrochronological methods (Stokes and Smiley, 1996). Core samples were mounted on wooden supports and sanded, and tree-ring width (TRW) was measured to the nearest 0.01 mm with a TimeTable measuring stage (Vienna Institute for Archaeological Science). The minimum sample depth for tree-ring chronologies was 40 trees. Tree-ring chronologies were assembled based on similar age structures among the sites, because differences in age structure might produce differences in growth trends (Carrer and Urbinati, 2004; Nehrbass-Ahles et al., 2014). In most regions, the originally extensive sample sets (~60–70 trees) were thus reduced by removing certain age cohorts of trees.

Each TRW growth curve contains an age trend, which should be removed through tree-ring standardization (Cook and Pederson, 2011) prior to the extraction of environmental information. We performed standardization procedures that retain medium to low-frequency variability in growth (i.e. variability on the order of several decades). Since standardization approaches differ in their sensitivity to the age structure of samples (Helama et al., 2004) and in their ability to mitigate the so-called end effect (Melvin and Briffa, 2008), we employed two different standardization procedures. First, we performed individual-based detrending using splines with a 66% variability cut-off at 90 years (i.e. approximate mean series length at each site) (Treml et al., 2012) and signal-free standard chronologies (“SPLINE”) were created (Melvin and Briffa, 2008). Such chronologies preserve medium-frequency growth variability and are free of end effects (Melvin and Briffa, 2008). These chronologies were created using CRUST software (Melvin and Briffa, 2014). Second, basal area increment chronologies (BAI) were constructed by converting tree-ring widths to ring areas (Biondi and Qeadan, 2008). BAI transformation was performed in R (package ‘dplR’) using the BAIin function. Although pith offset was not accounted for, we only used tree-ring cores that reached the pith or those with a very limited estimated number of missing rings to the pith (three missing rings at maximum). BAI chronologies are good at preserving low- to medium-frequency growth variability (Biondi and Qeadan, 2008; Hartl-Meier et al., 2014), however, they fail to track

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