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Possible causes of the recent rapid increase in the radial increment of silver fir in the Western Carpathians

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ABSTRACT

Silver fir is one of the most productive and ecologically valuable native European tree species, however, it has been experiencing decline which has periodically occurred over its natural range. This paper aims to investigate the recent climate–growth relationships of silver fir (*Abies alba* Mill.) and its temporal change along the course of its life. Long-term tree-ring databases, as well as records on climate, atmospheric SO_2, NO_3 and acid concentrations from four different regions in the Western Carpathians were used. The results provide clear evidence of significant increase of silver fir's radial increment over the entire Western Carpathian area since 1970–1980. The results indicated that the most probable factors behind the rapid recovery of tree radial increment were reductions in emissions of NO_3 and SO_2, alongside a significant increase in mean June, July and April temperatures.

1. Introduction

Silver fir (*Abies alba* Mill.) is among the most productive of the native European tree species (Korpeľ et al., 1982). In forestry, special attention is paid to silver fir for its silvicultural value but also because of a decline which has occurred periodically in Europe since about 1500 (Meyer, 1957; Cramer, 1984; Larsen, 1986). At first the decline was limited to the northern marginal populations in Saxony and Thuringia, however, over the last century it became a phenomenon endangering the persistence of local small populations and strongly reducing population sizes in areas with a more continuous occurrence over the whole central part of the species' range (Gömöry et al., 2004). Both natural phenomena and anthropogenic stress appeared to be contributing to the development of the dieback of the species. Larsen (1986) explained it as a process which was caused by insufficient genetic variation in the Central-European populations and implied a general lack of adaptability.

Atmospheric acidification became a serious issue in large parts of northern Europe in the 1970s, mainly in the Fennoscandia region due to slow weathering of soil and bedrock (Vestreng et al., 2007). In 1850, global sources of SO_2 emissions were split roughly evenly between those from open burning (for land clearing purposes) and from industrial activities. However, during the next 50 years this changed as anthropogenic SO_2 emissions increased by an order of magnitude, driven by increased use of coal (Smith et al., 2011). In the early 20th century, the growth of emissions was slowed by a global depression (Smith et al., 2011) and during the second half of the century, levels of atmospheric pollution in parts of central Europe were among the highest on the continent (Rydval and Wilson, 2012). Along the sulphur dioxide, nitrogen emission from combustion and agricultural activities has caused eutrophication of forest ecosystems in large part of the world (Aber et al., 1989; Galloway, 1995). However, while N deposition previously limited forest ecosystems, the ecosystems are now getting saturated with nitrogen (Aber et al., 1998). Forest growth has been observed to increase during the second half of the previous century, and it was attributed to higher N availability (Spiecker et al., 1996; Laubhann et al., 2009). However, some observations suggested that the growth increase after N addition is not sustainable as other factors become limiting (Nabuurs et al., 2007). Recently, there have been several observations that suggested the silver fir as well as Norway spruce growth recovery has been the result of the rapid SO_2

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emission reduction (Sakata and Suzuki, 2000; Elling et al., 2009; Hauck et al., 2012).

Atmospheric pollution can affect tree growth both directly and indirectly. Air pollution is known to cause direct injury to vegetative tissues and alter physiological pathways in plants (Jones et al., 1989). Indirect effects include soil acidification with a subsequent release of aluminium and heavy metal ions blocking enzyme activity (Longauer et al., 2004). Sulphur emissions also influence the level of acidification of soils and freshwater ecosystems (e.g. Stoddard et al., 1999).

Recently, the researches focus on the impact of tropospheric ozone and elevated CO_2 and nitrogen deposition (Paoletti et al., 2010; Serengil et al., 2011). In the Western Carpathians, some studies on the projections of climate change effects on forest growth and carbon balance in the Western Carpathians have appeared (Ďurský et al., 2006; Hlásny et al., 2011); there is however, a lack of empirical investigations of Carpathian tree species response to neither air pollution nor recent climate changes.

The aim of this study was to investigate the growth response of silver fir to climate variation over a longitudinal range of the Western Carpathians – Central and Central-Eastern Slovakia – and Low Beskids. In addition, the research focused on temporal changes to the climate–growth relationships over the last 30-year period as well as the change in absolute radial increment of silver fir. Recent climate change over the Western Carpathians, as well as SO_2 and NO_3 emission rates during the last 30 years, were analysed and related to temporal changes in the fir climate–growth relationship. The hypotheses that are to be answered by the study are as follows:

- Is there a change in radial growth of silver fir over the entire Western Carpathians after the peak of air pollution was reached in 1980?
- Is the reduction of atmospheric SO_2 and NO_x concentrations primary factor for the radial increment recovery, or it has been a combination of environmental factors such as emission reduction and recent climate change?

2. Material and methods

2.1. Study area

The research was conducted at four different regions throughout Slovakia (Table 1, Fig. 1) in 2011 and 2012. Sampling sites were selected to cover in particular the longitudinal range of the Western Carpathian Mountains because of differences in genetic variability of silver fir resulting from postglacial migration routes (Longauer, 2001; Longauer et al., 2003). Moreover, the regions represent the southern margin of silver fir distribution in the Western Carpathians (Fig. 1). The selection of sampling stands in each region was achieved using the following criteria: i) silver fir was dominant in the forest species mixture; ii) the stand had reached production maturity (at least 100 years according to Halaj et al. (1990)); iii) located at approximately similar altitudes; iv) subject to similar management measures over the past 50 years (due to the availability of reliable climatic data for such a period). Meeting the criteria, sampling sites were chosen from long-term research plots located in the selected regions for core sampling (Halaj and Petráš, 1998; Štefančík et al., 2012).

2.2. Tree ring data and mean chronology development

At each site 20 dominant trees were sampled; to ensure some uniformity and that sample trees could have recorded climatic interactions (rather than mainly management-related records), trees selected for coring were of similar age (but as old as possible), in a dominant position in the stand, without signs of damage, with a straight, untwisted stem, with a symmetric and completely intact crown. One wood core (core from bark to pith) per tree was taken using an increment borer.

The core samples were air-dried and mounted onto wooden slats and sanded using a vibration sander. The tree ring widths (TRW) were measured to the nearest 0.01 mm using WinDendro software (Regent Instruments Canada Inc., 2011). After visual cross-dating, the individual ring width series were subsequently cross-dated using standard procedures (Fritts, 1976; Cook and Kairiukstis, 1990) performed in the R environment (R Development Core Team, 2011) using the dplR-package (Bunn, 2008, 2010).

First, the mean tree ring width series for each site was calculated to investigate temporal changes in absolute radial increment during the lifetimes of the sampled trees. For further dendroclimatological analysis, the individual series were detrended and standardized.

In order to remove age-related biological trends, as well as signals caused by other factors than climate variation (e.g. competition), a smoothing spline was used. To select the smoothness of the spline, several settings of the spline were tested starting from the commonly used 50% frequency-response cut-off of 67% of the series length (Fritts, 1976; Cook and Kairiukstis, 1990), to the spline of 70% frequency-response of 10 years. The most reliable equation for removing non-climatic variability from the ring-width series was found to be the spline function with 70% frequency-response of 10 years (Table 2). Subsequently, ring-width indices (RWI) were calculated by dividing the observed tree-ring width by the value fitted using the spline function.

For the four sites, mean chronologies were developed by calculating the Tukey's biweight robust mean (Mosteller and Tukey, 1977) to remove outliers and extreme values (Fig. 2). To assess the signal strength in each chronology (Briffa, 1995), inter-tree correlation (Rbar) and expressed population signal (EPS) were calculated (Cook and Kairiukstis, 1990). Moreover, upper and lower 99% confidence intervals were calculated with 1000 bootstrap replicates.

2.3. Climate data

The ability to assess the response of a species growth pattern to climate variation accurately is also limited by the availability of long-term and high quality climate records in close proximity to the sample sites. Therefore, climatic data were sourced from the nearest meteorological stations of the Slovak Hydrometeorological Institute (SHMI) network (see Fig. 1). Since temperature in this region has been shown to be highly correlated with altitude (e.g. Dodson and Marks, 1997; Hlásny, 2007), mean monthly temperatures were interpolated using altitude as an independent variable. For the Polana and Vychod sites, the source of the closest temperature data was up to 5 km distant, for the Helpa area it was 20 km and for the Komarnik area 17 km. Since precipitation was far more variable than temperature, monthly precipitation amounts were simply averaged from three nearest climate stations. The stations which supplied precipitation data for the study were at a maximum distance of 5 km from the sample sites. Only the temperature and precipitation records for the 1961–2010 period were available and used in the study.

2.4. Sulphur dioxide and NO_x data

Investigations into two types of atmospheric pollutants were made in this study; SO_2 and NO_x emissions measured directly at source and atmospheric SO_2 and NO_3 concentrations. Emission data were obtained from the Slovak Hydrometeorological Institute (Burda et al., 2000; Čaracký et al., 2012). Data on atmospheric SO_2 and NO_3 concentrations were sourced from the European Monitoring and Evaluation Programme (EMEP). In addition, concentration of acid in precipitation (pH), also available from EMEP, was considered as well. Measurements of air quality in Europe have been carried out under the "Co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe" since October 1977 (Hjellbrekke and Fjaeraa, 2012). Slovakia has provided data on air pollution in different periods since 1978 to the present. Of the five measurement sites

Table 1
Selected site characteristics of the study areas and plots.

Locality	Altitude	Slope inclination (%)	Slope orientation	Age	No. cores	Parent rock	T_{year}	P_{year}
Komarnik	500	17	S	160	20	Flysch	6.5 °C	875
Vychod	780	22	W	160	20	Phylit	5.5 °C	845–945
Helpa	750	35	N	110	16	Quartzite, sandstone, slate	5.2 °C	900
Polana	760	18	N–W	150	20	Granodiorite	6.2 °C	780–830

Note: T_{year} – mean annual temperature averaged over the reference period (1961–1990); P_{year} – annual precipitation sum averaged over the reference period (1961–1990) (Lapin et al., 2002).