

REACTION OF SILVER FIR (*ABIES ALBA*) GROWING OUTSIDE ITS NATURAL RANGE TO EXTREME WEATHER EVENTS AND A LONG-TERM INCREASE IN MARCH TEMPERATURE

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ABSTRACT

Silver fir trees grown outside their natural distributional range were intensively studied in terms of their adaptability to increased late winter temperature and extreme weather events. The main questions of the study are: what is the influence of March temperature increase on tree rings and is the further introduction of silver fir outside its natural range economically justified? A total of 268 cores of silver fir were obtained from 12 sites throughout north Poland, which were located outside its natural range. Next, standard dendrochronological and dendroclimatological methods were applied. The March temperature increase was investigated using the bootstrap running correlation option with a 25-year moving window. Response function analysis revealed that the studied trees were more sensitive to winter temperature than to precipitation. Hierarchical cluster analysis identified two distinct geographical regions of fir growth. The positive effect of high March temperature is observed in both regions. Trees from the northwestern Poland region recovered from an extreme cold period in the following year, whereas trees from northeastern Poland were more sensitive, and needed an additional year for recovery. The reason for the relatively fast growth recovery in northwestern Poland is the influence of the mild Atlantic and Baltic climates.

Keywords: dendroclimatology, dendroecology, tree rings, silver fir, *Abies alba*, climate change, north Poland.

INTRODUCTION

Silver fir (*Abies alba* Mill.) is found growing naturally in central and southern Europe (Figure 1). Its natural distribution is limited to mountain ranges and massifs, and its northeastern distribution limit runs across Poland, where the occurrence of silver fir is associated mainly with the Carpathian, the Sudetes and the Świętokrzyskie Mountains (Obidowicz *et al.* 2004). Fir growing outside its natural range in northwestern Poland is characterised by being in good condition and showing natural regeneration. Its occurrence depends mostly on anthropogenic factors, and local climate conditions, especially high annual precipitation totals and low temperatures (Robakowski *et al.* 2005). As a result of the significant increase of March temperature in Poland observed

since 1951 (Kozuchowski and Degirmendzić 2005), there is clearly a need for information about the impact of climate change on the ecology and growth of this species. A warming in the early

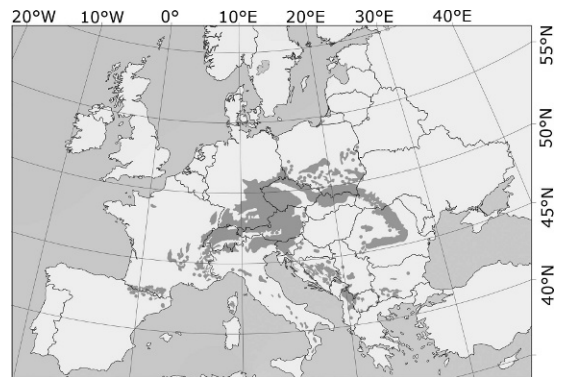


Figure 1. Distribution of *Abies alba* in Europe. [Courtesy of EUFORGEN, http://www.euforgen.org/distribution_maps.html].

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spring (February to April) by 1°C causes an advanced beginning of growing season of 7 days (Chmielewski and Rötzer 2000). Shortened cold periods during the winter, with warmer temperatures beginning earlier in the spring (Kožuchowski and Degirmendžić 2005) may affect fir growth.

Tree-ring widths in most cases reflect environmental conditions. Some factors such as frost or summer drought, may have an immediate effect on ring width, whereas other factors such as winter drought may have a delayed effect on ring widths, because the growing tissue is dormant during the winter months. The effect of different factors is seen as variation in ring size and structure, which change systematically, or vary slowly throughout the life of the tree (Fritts 1976). Previous dendrochronological studies of trees growing outside their natural distribution and sharing the same area of Poland with silver fir gave promising results in terms of climate-growth relationships and their changes over time (Koprowski 2012, 2013). For Norway spruce (*Picea abies*), a significant positive influence of high February and March temperatures was identified for most northern sites, along with a negative correlation with temperature of the previous and current growing season (Koprowski 2013). As expected, Norway spruce reacts positively to high rainfall during the growth season in the current and previous year (Koprowski 2013). European larch (*Larix decidua*) reacts to the temperature of the previous July, August and September. A strong negative correlation was particularly evident for larch from northeastern Poland, affecting both the earlywood and the total ring width (Koprowski 2012).

Tree-ring studies of non-native tree species have been conducted for different regions. Norway spruce growing outside its natural range in southern Italy, was compared with native silver fir. Battipaglia *et al.* (2009) found that *Abies alba* was more sensitive to precipitation than non-native *Picea abies*. The authors concluded that the reforestation programmes in the Mediterranean region should take into consideration the species that are better adapted to climate change. Such an approach should be taken into account especially when scenarios for global biodiversity suggest that Mediterranean ecosystems will experience a large

biodiversity loss (Sala *et al.* 2000). In some cases the introduction of non-native species creates problems important for local biodiversity. In the Czech Republic *Pinus strobus* suppresses native vegetation by forming dense monocultural stands and by depositing a thick layer of needle litter (Härtel and Hadincová 1998, after Mácová 2008). The growth of *Pinus strobus*, native to the eastern part of North America, was compared with that of *Pinus sylvestris*. No clear link was found between its dendroclimatological response and its invasive behaviour (Mácová 2008). The common European trees like *Picea abies* and *Pinus sylvestris* were also introduced to North American forests. Both of these species showed more differential responses to climatic variations in comparison with local *Pinus strobus* and *Pinus resinosa*, and this, together with other chronology parameters like signal-to-noise-ratio and mean sensitivity, suggest that they are more sensitive to local climate conditions (Kilgore and Telewski 2004).

Taking into account the uncertainties in the climate change projections and the impact of these changes on forests, four main questions are addressed in this paper:

1. How does temperature and precipitation affect the growth of fir outside its natural range?

In Poland, silver fir and European larch growing outside their natural ranges cover almost the same area in northern Poland, while Norway spruce grows outside its natural range in the northwestern part of Poland. Comparison of fir growth with other coniferous species might help to determine which species is better adapted to weather conditions outside its natural distribution. The latter is already sufficiently known for many natural stands (*e.g.* Rolland 1983; Feliksik 1990; Rolland *et al.* 1998; Koprowski and Gławenda 2007; Bijak 2010; Bronisz *et al.* 2010; Carrer *et al.* 2010; Dittmar *et al.* 2012; van der Maaten-Theunissen *et al.* 2013)

2. What is the influence of March temperature increase on tree rings?

The early onset of spring (Kožuchowski and Degirmendžić 2005) observed from 1951

onwards may influence patterns of tree growth in a way similar to that observed for changing June–July temperature in Alaska (D'Arrigo *et al.* 2008).

- Are the regional differences related to tree-growth different reactions to climate and extreme weather events?

The spatial distribution of increment patterns allows homogeneous regions to be recognised and generalisations about the climate requirements for non-native species in each area to be made. Fir from Alpine and Mediterranean areas shows different regional responses to most of the climate-related limiting factors along the latitudinal and longitudinal gradients (Carrer *et al.* 2010). Feliksik (1990) compared fir growth at different sites in Poland and stated that winter temperature was responsible for the high correlation between the sites.

- Is the further introduction of silver fir outside its natural range economically justified?

In terms of changing climate variables and unpredictable changes in environment, the question of introducing new species outside their natural range is still open. Increased biodiversity within plantations through an increase in the number of species (multi-species plantations) may be an attractive adaptation option, as they are more resilient, or less vulnerable, to climate change (Nabuurs *et al.* 2007).

MATERIAL AND METHODS

Material and Study Sites

A total of 268 cores of silver fir were taken from 12 sites (Figure 2) throughout north Poland at sites outside its natural distributional range. Two core samples were taken from each tree, one from the west and one from the east, using a Pressler borer, at a height of approximately 1.30 m above the ground. The cores were prepared for measurements using standard dendrochronological procedures (Zielski and Krąpiec 2004).

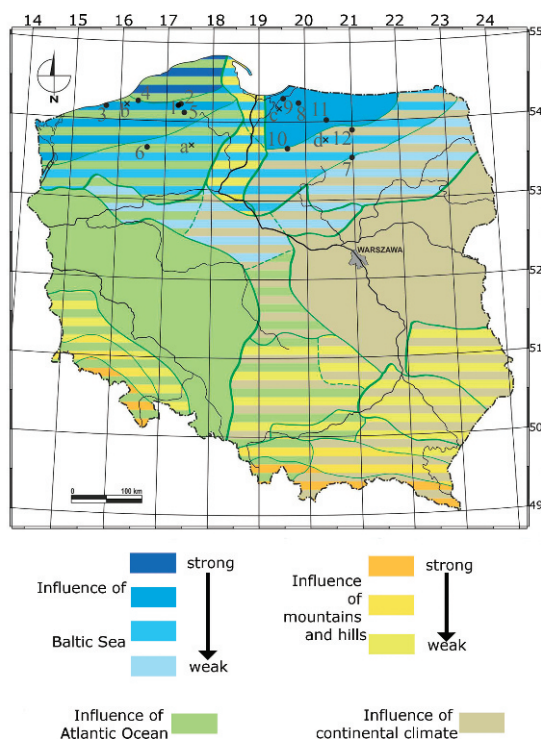


Figure 2. Map of locations of the research sites (●) and meteorological stations (×) with climatic regions in Poland (according to Okołowicz and Martyn 1984). Numbers of research sites and letters of meteorological stations correspond to those in Table 1.

Northeastern Poland is connected to the Lowland East-Baltic-Belarus region. From the south to the northeast, the dominance of the Atlantic climate decreases, while the effects of climatic parameters of the continental climate increase. This is expressed especially in decrease in the vegetation growth period and a greater amplitude in annual temperature. The Polish lowland (60%) belongs to the Middle-European Lowland, and has generally sub-Atlantic vegetation, with a predominantly oceanic climate. The mean annual precipitation is between 450–700 mm, and the mean annual temperature range is 7–9°C (Kondracki 2002).

Southern Poland is mostly uplands and mountains (Kondracki 2002). In northeastern Poland the mean annual temperature is 6.7°C, while in the southern part it is 8.4°C. The difference in temperature is clearly visible in January, when the minimum temperature under

the influence of the continental climate is -4.2°C ; by contrast, in the southern part it is -1.4°C (Woś 2010). Climate diagrams of the Meteorological Stations in Chojnice, Koszalin, Elbląg and Olsztyn are presented as Online Supplementary Figures S1a-d. Climate data were obtained from the European Climate Assessment & Dataset (ECA&D) project (Klein Tank *et al.* 2002).

Chronology Development

Basic tree-ring parameters were obtained from the measurement of ring widths to the nearest 0.01 mm using CooRecorder software combined with the related CDendro program (URL: <http://www.cybis.se>). Checks on cross-matching were carried out using COFECHA (Holmes 1983). Additionally, each sample was analysed by means of the skeleton plot method after Stokes and Smiley (1968). Both the skeleton plot method and the results from the COFECHA programme were used for evaluating and detecting narrow and wide rings (Grissino-Mayer 2001). The smoothing spline option of the dplR package (Bunn 2008) from R (R Development Core Team 2007) was used to detrend the temporal data series. The “n-year spline” at $2/3$ the wavelength of n years was used (after Cook *et al.* 1990). The effect of outliers was minimized using Tukey’s bi-weight robust method (Cook *et al.* 1990). A residual version of the chronology was built by pre-whitening after fitting an autoregressive model to the data using the Akaike Information Criterion (AIC) for variable selection (Bunn 2008). Additionally, the Expressed Population Signal (EPS) was calculated as a measure of the common signal in the chronology (Wigley *et al.* 1984). Hierarchical cluster analysis (Ward method) was used as implemented in the amap R package (Author: Lucas) to separate the tree-ring series from each site and to distinguish regions with similar increment patterns (Wilson and Hopfmueller 2001). The idea of hierarchical clustering (Ward method) is to maximize the between-group variance, while minimizing the within-group variance (Ward 1963). Pearson’s correlation coefficient was used as a measure of similarity. K-means clustering was then used to group the indices of tree-ring

series in selected years. At first, the number of clusters is given *a priori*. In this case two groups were chosen. Next, a current set of means (residual values of TRW) is minimized by assigning each observation to the closest cluster mean (Hastie *et al.* 2009, pp. 509–510).

Dendroclimatological Analysis

In order to investigate climate/growth relationships, the DendroCLIM 2002 software was applied (Biondi and Waikul 2004) using a bootstrap procedure to estimate the error. Climate data from May (previous year) to September (current year) served as independent variables and the regional residual chronologies were used as dependent variables with a common period of 1951–2009. For each region the climate data were taken from the nearest meteorological stations and mean values were counted as the arithmetic mean (Figure 2, Table 1). The March temperature increase was investigated using the bootstrap running correlation option with a 25-year moving window (package bootRes, Author: Zang). Figure 3 shows the linear trend for March temperature increase.

RESULTS

Tree-Ring Parameter Chronologies

The hierarchical cluster analysis identified two distinct regions of fir growth (Figure 4). The first region is characterised by a maritime climate. The second region is a mixture of Baltic climate and continental aspects. Among the selected sites, the oldest trees (130–140 years old) were found in the Bytów Forest Inspectorate at site 5, and the chronology for these trees covers the years 1890–2006 (region 1, Online Supplementary Table S1). Mean tree-ring widths varied from 1.12 mm (site 7) to 3.10 mm (site 6). The narrowest earlywood (EW) and latewood (LW) were found in trees from site 7, as was the narrowest overall tree-ring width (TRW). In contrast, the widest EW was noted in site 5 and LW in site 3 (Supplementary Table S2). The portion of the LW in the tree-ring widths (TRW) is comparable and varies from 48.5% (region 1) to 47.7% (region 2) (Table 2). The Rbar

Table 1. Location of the research sites. The sites (numbers) correspond to those in Figures 2 and 4 and meteorological stations (letters) to those in Figure 2. Ff = mesic forest, Fmf = mesic mixed forest.

Site number	Forest Inspectorate	Region	Latitude and Longitude		Forest site	Meteorological Station, Elevation, Latitude and Longitude, Time span of climate series
1	Osusznica 1	Region 1	54°06'49.5"N	17°22'33.3"E	Fmf	a. Chojnice, 172, 53°42'N, 17°33'E
2	Osusznica 2		54°06'42.7"N	17°23'09.7"E	Ff	Temperature and precipitation
3	Goscino		54°10'14.2"N	15°41'35.5"E	Ff	1951–2009
4	Karnieszewice		54°15'07.8"N	16°22'28.8"E	Fmf	b. Koszalin, 32, 54°12'N, 16°08'E
5	Bytów	Region 2	54°13'19.5"N	17°18'05.1"E	Fmf	Temperature and precipitation
6	Szczecinek		53°39'46"N	16°36'11"E	Ff	1951–2009
7	Szczytno		53°32'11.1"N	20°58'32.6"E	Ff	c. Elbląg, 38, 54°10'N, 19°26'E
8	Zaporowo		54°14'34.9"N	19°51'02.1"E	Ff	Temperature 1954–2005
9	Elbląg		54°17'56.5"N	19°31'02.4"E	Ff	Precipitation 1944–2004
10	Ilawa		53°39'46.8"N	19°36'03.5" E	Ff	d. Olsztyn, 133, 53°46'N, 20°25'E
11	Wichrowo		54°01'30.2"N	20°26'46.8"E	Fmf	Temperature and precipitation
12	Wiposwo		54°53'28.4" N	20°59'40.4"E	Ff	1951–2009

and EPS of TRW for sites varied from 0.295 to 0.571, and from 0.670 to 0.908, respectively (Supplementary Table S1). For 8 sites the EPS values for TRW were above the frequently applied threshold of 0.85 (Supplementary Table S1), indicating robust mean value functions (Wigley *et al.* 1984). Regional EPS is higher than 0.85 (Table 2) and seems to be more promising, suggesting that the sample size is adequate

(McCarroll and Loader 2004). Furthermore, the regional values of EPS for latewood and earlywood mean that the common signal in LW and EW is reliable for dendroclimatic study (Table 2). Taking each site separately, an EPS above 0.85 was found for both EW and LW at five sites (Supplementary Table S2). The mean sensitivity and first-order autocorrelation for TRW range from 0.258 to 0.358 and from 0.651 to 0.827,

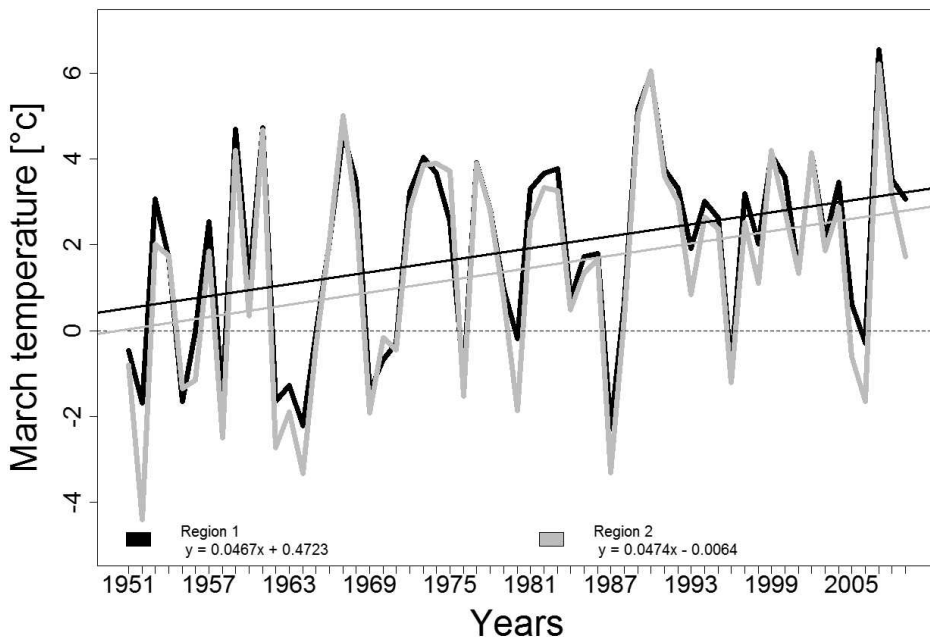


Figure 3. The increase of March temperature in both regions, which follow a positive linear trend.

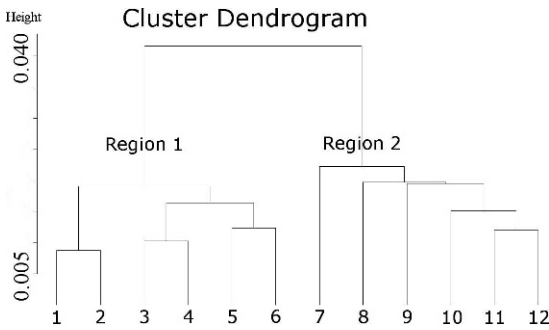


Figure 4. Dendrogram of the results of cluster analysis. Numbers of research sites correspond to those in Table 1.

respectively, giving information about year-to-year variation in raw data chronologies for each site.

Climate Effect

A negative effect of temperature of the previous year was found in region 1 for EW and relates to July, September and October temperature. A positive correlation was observed for TRW and LW from January to March in both regions. High temperature in May, on the other hand, had a general negative impact on EW in both regions (Figure 5a). The influence of temperature on tree-ring widths, latewood and earlywood is comparable. The cross-correlation between the responses of TRW, EW, LW and temperature varied for both regions from 0.69 ($p < 0.01$) to 0.98 ($p < 0.01$). The most homogeneous reaction is between TRW, EW, LW and temperature from January to March. In region 1, correlation is between 0.96 ($p < 0.05$) and 0.99 ($p < 0.05$) and in region 2 for

each parameter is 0.99 ($p < 0.05$). In total, 25% of the temperature correlations for all months were significant at $p < 0.05$. Precipitation had mixed effects on ring width. Low precipitation in the previous September and high precipitation in February, May and July increased tree growth (10% of all significant correlations for precipitation) (Figure 5b). In contrast to temperature, the correlation between growth-precipitation relationships is lower and varies from 0.49 ($p < 0.05$) to 0.97 ($p < 0.001$). The bootstrap running correlation with a 25-year moving window revealed the positive effect of high March temperature in both regions, especially for TRW and LW (Figure 6). The visual assessment and analysis of extreme ring widths using COFECHA revealed the occurrence of extremely narrow rings in 1929, 1940, 1956 and 2006. In these years, the residual values of the master dating series were below -2.0 in at least one region. Trees from region 1 recover in the following year, especially in 1941 and 1957. In contrast to region 1, trees from region 2 recover later. K-means clustering revealed that in region 2 only trees from site 9 recover in 1941 (Figure 7a). The growth of trees from region 2 in the years 1956–1958 is not so homogenous. Trees from sites 9, 10 and 11 need more time to recover and in 1958 still reveal narrow rings (Figure 7b).

DISCUSSION

Influence of Temperature and Precipitation and the Effect of Extreme Weather Conditions

The effect of temperature and precipitation on fir growth should be considered in two aspects:

Table 2. Descriptive statistics for arithmetic means in each region. TRW = tree-ring widths; EW = earlywood; LW = latewood; **Rbar.eff** = the effective signal calculated as $\text{rbar.bt}/(\text{rbar.wt} + (1-\text{rbar.wt})/c.\text{eff})$, where: **rbar.wt** is the mean of the correlations between series from the same tree over all trees, **rbar.bt** is the mean inter-series correlation between all series from different trees; **c.eff** = the effective number of cores; **EPS** = the expressed population signal.

	Series	Period	Mean measurement (mm)	Rbar effective	EPS
Region 1	TRW		2.68	0.316	0.956
	EW	133	1.30	0.265	0.944
	LW		1.38	0.251	0.940
Region 2	TRW		2.43	0.381	0.964
	EW	135	1.16	0.322	0.954
	LW		1.27	0.320	0.954

firstly in comparison within the same species from the natural distribution, and secondly, between European larch growing in the same area outside its natural range and Norway spruce introduced to northwestern Poland as a result of forest management. However, the species differ in terms of their ecological requirements, *i.e.* spruce relies more on water reserves than fir and larch (Larcher 2003). The studied trees grow in lowland areas, in contrast to the trees from natural distributions that are mostly from high altitude; Boratyński (1983) considered fir to be a species of mountainous areas. Previous findings emphasized that fir from outside its natural range in the lowlands is sensitive to winter temperature (Koprowski and Gławenda 2007; Bijak 2010). Winter temperature is also the most important limiting factor influencing distribution in both southern Poland and the western Ukraine (Feliksik 1990; Szychowska-Krąpiec 2010; Iszkuło *et al.* 2011). However, the opposite relationship between March temperature and fir growth was observed in the Świętokrzyskie Mountains. This may be caused by sudden temperature decreases during the relatively warm period (Bronisz *et al.* 2010). The present study identified that the effect of temperature is comparable between regional chronologies for TRW, EW and LW and the correlation coefficients being 0.88 ($p < 0.001$), 0.92 ($p < 0.001$) and 0.93 ($p < 0.001$), respectively. Except EW (region 1), significant bootstrap correlation values were observed for temperature from January to March (Figure 5a). Similar relationships are found for fir in southwestern Germany above 900 m a.s.l. (van der Maaten-Theunissen *et al.* 2013). From the eco-physiological point of view, the importance of temperature in late winter is related to photosynthetic activity, which in the case of fir, may be activated by relatively high temperature (Guehl 1985). It could stimulate carbohydrate storage and, as a result, the growth in the current year (Lebourgeois 2007).

In the current research, 13% of all significant correlations for TRW with precipitation for separate sites were significant at $p < 0.05$, whereas 20% of temperature correlations were significant at $p < 0.05$. The mean significant negative correlation coefficient for temperature is -0.30

and the significant positive value is 0.35, whereas for precipitation the correlation coefficients are -0.21 and 0.30 , respectively. The influence of temperature on EW and LW is higher than the effect of precipitation, *i.e.* for EW 8% of all correlations are significant for precipitation and 28% for temperature, whereas for LW they are 14% and 17%, respectively. In the Eastern Carpathian Mountains, temperature is less significantly correlated than precipitation (Bouriaud and Popa 2009). The limiting factors, on fir growth from low elevation in French Alpine sites, are winter frost and summer aridity (Desplanque *et al.* 1999), whereas at upper levels the weather conditions in the summer season are more important (Rolland 1983; Desplanque *et al.* 1999). Temperature in February was positively correlated with TRW at 92% of all sites and precipitation at 33%. From a regional perspective, there is a clear correlation between EW and precipitation from both regions (Figure 5b). The positive effects of high temperature and precipitation in February are associated with relatively warm air (low-pressure areas) (van der Maaten-Theunissen *et al.* 2013).

As expected, trees reacted positively to high rainfall in the current growing season, especially in May. A negative correlation with temperature and a positive correlation with precipitation during the growing season were observed in most of the studies (*e.g.* Bouriaud and Popa 2009; Carrer *et al.* 2010; van der Maaten-Theunissen *et al.* 2013).

Fir is highly sensitive to extremely low temperature (Jaworski and Zarzycki 1983). Response function analysis revealed that the studied trees were more sensitive to winter temperature than to precipitation. According to the weather records of the Institute of Meteorology and Water Management in Warsaw, the lowest temperature in Poland, below -40°C was noted in 1929 and 1940 and -35°C or below in 1956, 1963 and 1964, 2006 and 2012. As a result, narrow rings in 1929 and 2006 appeared in trees from region 2. In both regions, reductions in ring widths were observed in 1940 and 1956; however, differences can be seen in their recovery times. Trees from five sites from region 2 show narrow rings in 1941, whereas trees from region 1 have wider rings in 1941 (Figure 7a). In 1957 narrow rings are observed in trees

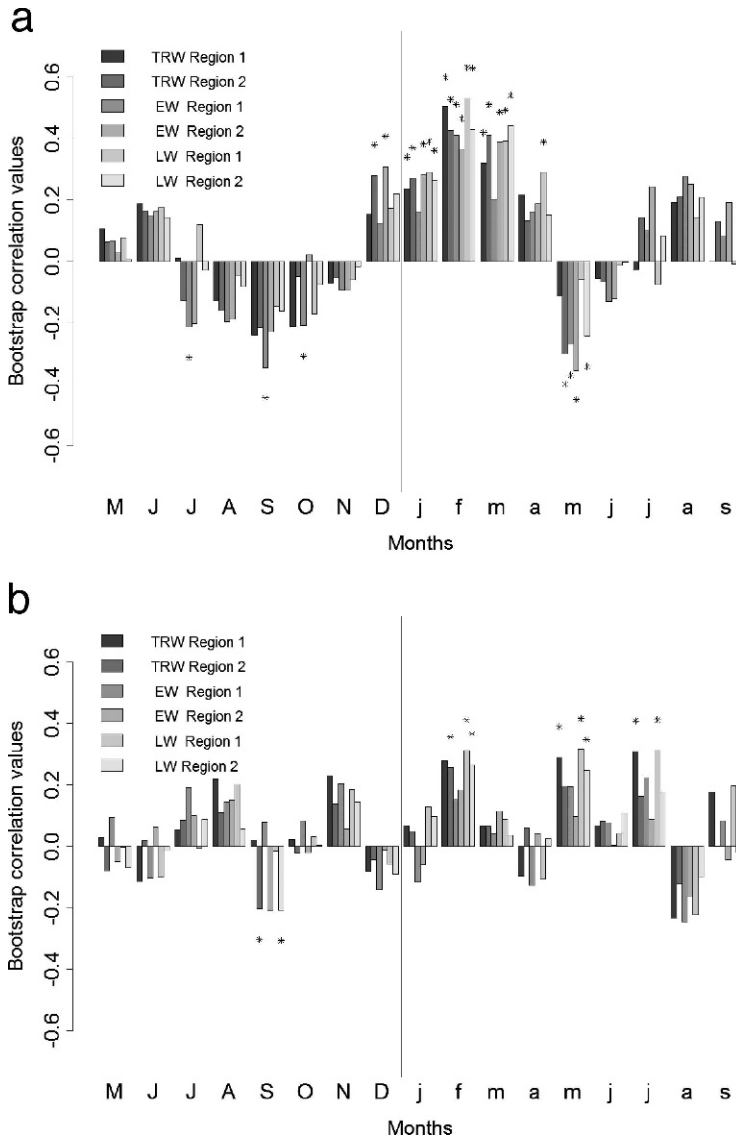


Figure 5. Relationships between growth and temperature (a) and between growth and precipitation (b) in each region. TRW = tree-ring width; EW = earlywood; LW = latewood. Asterisk (*) indicates significance at $p < 0.05$. Left side of each panel shows previous year, right side shows current year.

from sites 9, 10 and 11 (Figure 7b). A negative effect of cold winters in 1929, 1940 or 1956 was observed in southern Germany, but none of these instances initiated a long-lasting growth depression in these trees that were affected by SO_2 (Elling *et al.* 2009). In the present study it was shown that the extremely low temperature in region 2 may lead to a growth reduction lasting a year longer (1941, 1957) and after that, if narrow

rings appear, they were not extreme. Region 2 is situated in northeastern Poland, meaning that the trees are growing under the influence of the continental climate, with a decrease in the growth period, and a greater yearly temperature amplitude (Kondracki 2002). Sites 8 and 9, even though they are located in region 2, are also under the influence of the mild Baltic climate. From a regional point of view, the trees from region 1

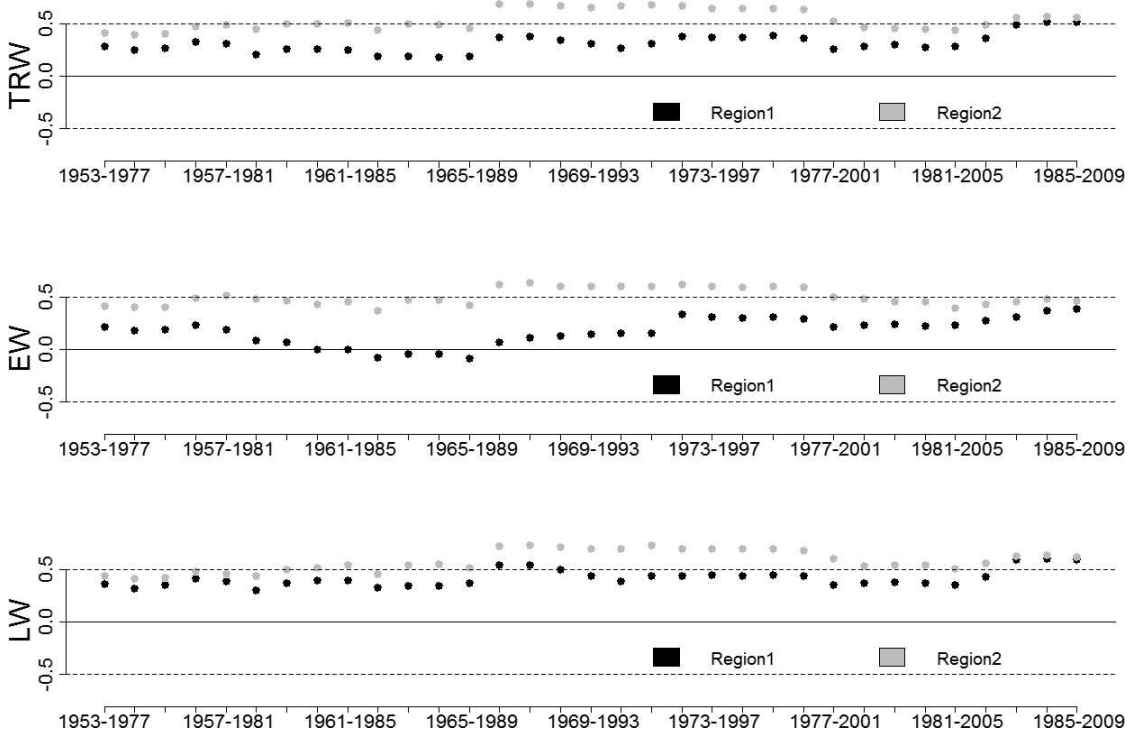


Figure 6. Change in influence of March temperature on tree-ring widths in sequential 25-year time intervals. TRW = tree-ring width; EW = earlywood; LW = latewood.

recover from the extreme cold period in the next year, whereas trees from region 2 are more sensitive, and need an extra year for recovery. Northeastern Poland has four frost-free months (Olsztyn Meteorological Station), whereas region 1 has five frost-free months (Supplementary Figures S1a–d). Elbląg, which is located within region 2, is more under the influence of the Baltic Sea. In region 2, the reason for the quicker recovery of trees from site 9 in 1941 and sites 7 and 8 in 1957 is the influence of the mild Atlantic and Baltic climates.

Silver fir is much more sensitive to severe frost than to drought. The analysis of extreme narrow rings discussed above confirms this assumption. In Germany the fir dieback in and after drought periods, *e.g.* 1976, was caused by an attack of parasitic fungi (Seitschek 1981), so in this case the reduction after the drought is a secondary effect (Elling *et al.* 2009).

In this research, fir dieback was not observed, the condition of the trees was good, and in most of the sites seedlings were very common. According

to Jaworski and Zarzycki (1983) mean January temperature below -4.5°C is a limiting factor. However, in region 2 lower temperatures, for instance in 1963 (-12.2°C in Olsztyn Meteorological Station), led to growth reduction, not to species dieback. This may be explained by wider ecological requirements than are observed in its natural range.

Effect of Increasing Temperature

The reaction to winter temperature seems to be a major factor that controls the spatial distribution of tree growth in lowland Poland, as was also observed in southern sites (Feliksik 1990). In the case of fir, winter temperature is the most crucial factor. There has been a significant increase of March temperature in Poland (Kozuchowski and Degirmendzić 2005) in recent years, and given the positive significant bootstrap correlation between March temperature and TRW, EW and LW, the changing climate might

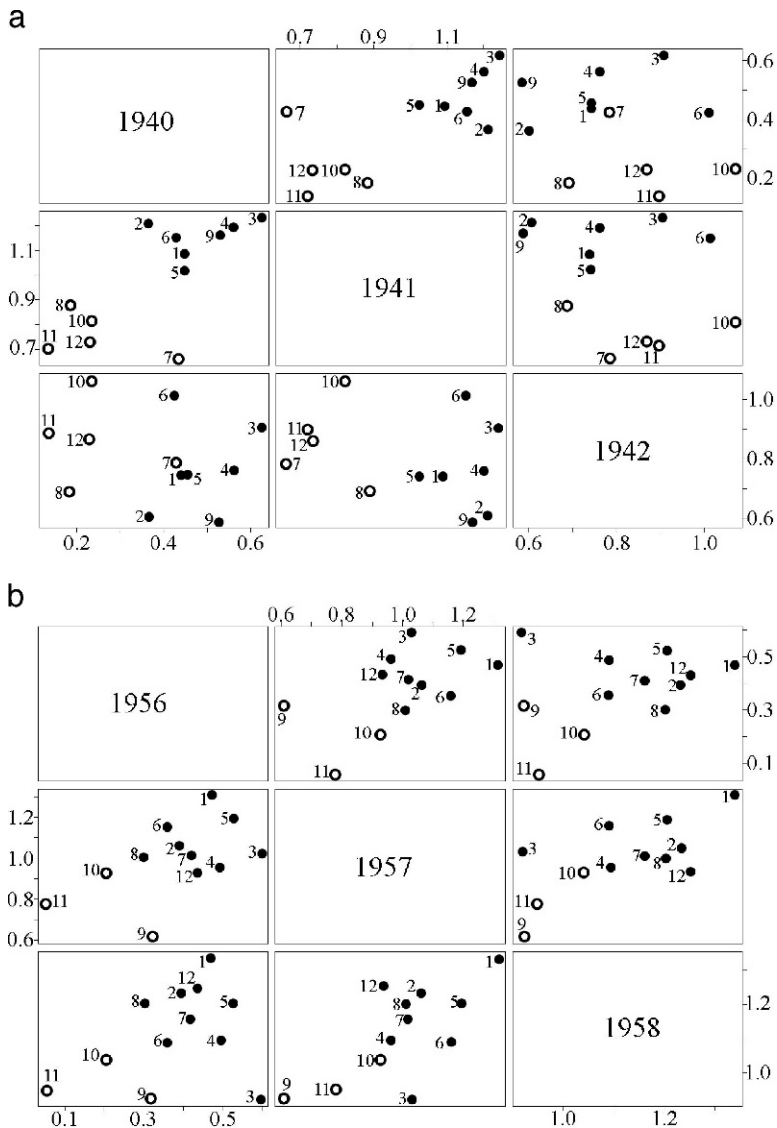


Figure 7. Diagram of results of k-means analysis for years 1940–1942 (a) and 1956–1958 (b). Circles and dots represent the sites and numbers correspond to those in Table 1. The sites were grouped on the basis of TRW indexed values. On each graph two groups of sites were identified, the first one by circles (○) and the second one by dots (●). In Figure 7a, the comparison between index values of TRW in 1940 and 1941 shows the narrow rings for trees from sites 7, 8, 10, 11, 12 in 1941 and in 1940, except at site 7. In Figure 7b, TRW indices for 1956 and 1957 from sites 9, 10 and 11 were grouped into one cluster that represents tree sites with narrow rings.

cause different seasonal reactions of tree growth to these temperature changes. The “divergence problem” has been observed in northern Alaskan forests where it is associated with increasing June–July mean temperatures (D’Arrigo *et al.* 2008). In fact, this is common for Northern Hemisphere trees, and different factors might be

involved, such as increasing atmospheric CO₂, higher levels of pollutant transport (*i.e.* nitrates or phosphates), other changes in soil chemistry, or increased UV-B levels (Briffa *et al.* 1998). The correlation observed here, using a 25-year moving window, revealed a positive, constant impact of late winter temperatures during the whole period

(Figure 6), especially in the case of TRW and LW. It is worthwhile to emphasize that for *Larix decidua* and *Picea abies* the same values vary about zero (Koprowski 2012, 2013). This is a result of fir sensitivity to low winter temperature.

The exclusion of 15 cold years from the meteorological data (mean temperature below -3°C from December to February at least in one station) and 15 rings from following years in region 1, and 19 rings from region 2, confirmed this assumption. In this case, the significant values of correlation between tree-ring width and winter temperatures on tree-ring widths were not observed in either region 1 or in region 2. The increase of March temperature may stimulate fir growth and natural regeneration of this species outside its natural range, and in areas adjacent to its distribution limits in lowland Poland.

CONCLUSIONS

The research presented here identifies that the observed recent increased March temperature has a positive effect on tree-ring widths. The presence of silver fir seedlings together with the observed lack of a negative response of tree growth to the increase in March temperature suggests that wider introduction of fir outside its natural distributional range may be beneficial. It is worth noting, however, that the further introduction of this species to northeastern Poland may not be as beneficial. Here, fir, which is more sensitive to sudden frost, may suffer because of the more continental climate. On the other hand, because of the uncertainties in the climate change projections and an incomplete understanding of tree responses to the changing climatic factors (Lindner *et al.* 2008), it is impossible to predict the final effect of changes on silver fir growth. One possible solution to ameliorate the impact of climate change on forests is to extend the surface area of the forest and to increase the biodiversity within plantations by increasing the number of species (multi-species plantations) (Nabuurs *et al.* 2007). The introduction of *Abies alba* to northwestern Poland, and to a lesser extent to northeastern Poland, may in the long-term be crucial for both forest management and the biodiversity of these areas.

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