Long-term increase of March temperature has no negative impact on tree rings of European larch (*Larix decidua*) in lowland Poland

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Abstract European larch trees grown outside their natural range were intensively studied in terms of their adaptability to increased late winter temperature. A total of 264 cores of larch were taken from 12 sites throughout northern Poland at sites outside of its natural range. Clustering of de-trended chronologies reveal that research sites are grouped geographically. The mean ring widths, however, are similar amongst the four regions. In total, 21 % of the single correlations for all months for tree-ring widths were significant at the 5 % error level. For earlywood and latewood, the figures are 18 and 19 %, respectively. A generally positive precipitation effect was found, however, no significant negative effect was observed. Temperature had mixed effects on ring width. Higher temperatures in late winter and early spring increased ring width in region 2. High summer temperatures in both the previous and the current year, on the other hand, generally had a negative impact on tree-ring width during the growing season. On most of the sites, the observed long-term trend for increasing temperatures in March had no significant negative influence on tree growth. The visual condition of European larch together with the lack of any negative response of tree rings to observed March temperature increase suggest that it may be beneficial to introduce this species into new areas.

Keywords Dendrochronology · Dendroclimatology · European larch · *Larix decidua* · Tree rings · Environmental change

Introduction

The changes in climate have been well documented recently. At a global scale, warming and widespread changes in land use have been established (Solomon et al. 2007). A significant increase in March temperature has been shown in Poland (Kozuchowski and Degirmendžić 2005), and in addition, other factors related to vegetation have been changed. For example, there has been a change in the vegetational thermal season towards beginning of, or shortened cold periods during the winter, with warmer temperatures beginning earlier in the spring (Kozuchowski and Degirmendžić 2005). The temperature during the last days of winter and the beginning of spring is crucial for cambial activity. The dendroclimatological research in northern Poland using Scots pine (*Pinus sylvestris*) emphasised that February and March air temperature is the most important factor limiting pine growth (Zielski et al. 2010). February and March air temperature also plays an important role in the Małopolska Region (Lesser Poland) (Szychowska-Krąpiec 2010), Lower Silesia, and the Sudety mountains (Feliksik and Wilczyński 2000; Wilczyński and Skrzyszewski 2002). The impact of temperature during February and March is so important that long-term chronologies are used to reconstruct the climate in the area of North (Koprowski et al. 2012) and South Poland (Szychowska-Krąpiec 2010). For Norway spruce growing within its natural range in the south-eastern part of Poland, March temperature seems to be one of the most important factors in determining tree growth (Koprowski and Zielski

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2006). Silver fir growing in northern Poland is also sensitive to thermal conditions in March (Koprowski and Gławenda 2007; Bijak 2010). However, fir from the Świętokrzyskie Mountains shows the reverse, a negative relationship between growth and March temperature (Bronisz et al. 2010).

The impact of higher temperatures in March on the growth and health status of larch is still insufficiently understood. Because larch is one of the most important tree species in Polish forests, there is clearly a need for knowledge about the impact of climate change on the ecology and growth of this species. As a fast-growing tree, it can also be a potential plant for biomass production in Poland (Igliński et al. 2011).

The present work therefore has four major aims:

1. To identify the climate parameters that affect the growth of larch outside its natural range and to compare these patterns to those found for trees within its natural range. The latter is already sufficiently known for many natural stands (Büntgen et al. 2007; Danek and Danek 2011; Frank and Esper 2005; Carrer and Urbinati 2004, 2006; Kirdyanov et al. 2008).
2. To identify homogenous regions that are similar in growth pattern. The spatial distribution of increment patterns allows homogenous regions to be recognised and generalisations about the climate requirements for non-native species in each area to be made. This strategy was also applied for spruce and gave promising results (Koprowski 2012) and such differences also have implications for historical dating strategies.
3. To investigate how climate–growth relationships change over the time. D’Arrigo et al. (2008) linked this change to anthropogenic factors while Schweingruber (1996) pointed to general changes in environmental conditions. The early onset of spring (Kozuchowski and Degirmendžić 2005) may influence patterns of tree growth in a similar way to those observed for changing June–July temperature in Alaska (D’Arrigo et al. 2008).
4. The study of trees outside the natural range might help to decide how larch reacts after introduction and possibly how it reacts to climate change. Furthermore, it may help answer the question, ‘is the further introduction of European larch outside its natural range economically justified?’ Interestingly the ages of Polish larches reveal that most were planted outside their natural range at the end of nineteenth and at the beginning of twentieth century. Therefore, the data presented span at least 80 years and allow for a detailed comparison of tree growth and weather conditions.

Materials and methods

Materials

A total of 264 cores of European larch were taken from 12 sites (Fig. 1) throughout North Poland at sites outside or at the border of its natural range. The sites belong to the Polish lowland and have sub-Atlantic vegetation with a predominantly oceanic climate. The mean yearly precipitation ranges between 450 and 700 mm, and the mean yearly temperature range is 7–9 °C. By comparison, the natural range has a more continental climate with pronounced temperature differences between summer and winter.

Chronology development

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 ground. The cores were prepared for measurement using standard dendrochronological procedures (Zielski and Krąpiec 2004). 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 (<http://www.cybis.se>). Checks on cross-matching were carried out using COFECHA (Grissino-Mayer 2001). In addition, each sample was analysed by means of the skeleton plot method (Schweingruber 1996). Both the skeleton plot method and the results from the COFECHA programme were used for evaluating and detecting narrow and wide rings. De-trending of the chronology was done with the dplR software (Bunn 2008) using the smoothing spline option, which reflects trends in the chronology better than other options. The ‘*n*-year spline’ was fixed at 2/3 the wavelength of *n* years (Cook et al. 1990). The residual version of the chronology was built by pre-whitening, performed by fitting an autoregressive model to the data with AIC model selection (Bunn 2008).

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 maximise the between-group variance, while minimising the within-group variance (Ward 1963). Pearson’s correlation coefficient was used as a measure of similarity. The March temperature increase was investigated using the bootstrap running correlation option with a 25 year shifting window (package bootRes, Author: Zang).

Fig. 1 Locations of the research sites (filled circle) and meteorological stations (x) 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

Dendroclimatological analysis

Mean monthly temperature and total monthly precipitation for selected meteorological stations in Poland came from the European Climate Assessment and Dataset (ECA&D) project (Klein Tank et al. 2002). For each research site, the climate data were taken from the nearest meteorological station, or mean values were counted for stations at a similar distance from the research site (Fig. 1; Table 1).

Figure 2 shows the linear trend for March temperature increase.

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 residual chronologies for each site were used as dependent variables.

Table 1 Locations of the research sites

Site number	Forest inspectorate	Region	Geographical position		Forest site	Meteorological station, elevation (m.a.s.l.), geographical position
1	Barlinek	Region 1	φ N 52°58'01.8"	λ E 15°15'21.7"	Ff	a. Poznań, 88, φ N 52°25', λ E 16°49'
2	Łopuchówko		φ N 52°32'58.3"	λ E 17°07'42.8"	Fmf	b. Gorzów Wielkopolski, 72, φ N 52°45', λ E 15°16'
3	Sieradz		φ N 51°36'44.5"	λ E 8°48'36"	Ff	c. Wieluń, 195, φ N51°31', λ E18°35'
4	Tuchola	Region 3	φ N 53°33'22'	λ E 17°51'44"	Fmf	d. Chojnice, 172, φ N 53°42', λ E 17°33'
5	Golub Dobrzyń		φ N 53°11'50.8"	λ E 19°11' 50.0"	Ff	e. Toruń, 69, φ N 53°01', λ E 18°34'
6	Młynary	Region 4	φ N 54°09'7"	λ E 19°41'17.9"	Ff	f. Elbląg, 38, φ N54°10', λ E19°26'
7	Dobrocin		φ N 53°55'12.1"	λ E 19°50'41.7"	Ff	g. Olsztyn, 133, φ N53°46', λ E20°25'
8	Szczytno		φ N 53°32'11.1"	λ E 20°58'32.6"	Ff	h. Suwałki, 184, φ N54°08', λ E22°57'
9	Maskulińskie	Region 4	φ N 53°36'57"	λ E 21°32'34"	Ff	
10	Srokowo		φ N 54°17'20.3"	λ E 21°28'50.4"	Ff	
11	Szczebra		φ N 54°00'06.2"	λ E 22°51'56.3"	Ff	
12	Suwałki		φ N 54°19'38.2"	λ E 22°54' 58.3"	Ff	

The sites (numbers) correspond to those in Figs. 1 and 3 and meteorological stations (letters) to those in Fig. 1

Ff fresh forest, Fmf fresh mixed forest

Fig. 2 The increase in March temperature in each region

Results

Tree-ring parameter chronologies

The longest chronology for the selected regions was derived from region 1 and covers the years 1814–2009 (Table 2), the oldest trees grow in a natural reserve in the Łopuchówko forest inspectorate. The average tree-ring width varies between regions, ranging from 1.57 mm to 1.93 mm (Table 2). The portion of the latewood (LW) in the whole tree-ring width (TRW) is comparable and varies from 33 % (region 4) to 38 % (region 1). The R_{bar} and EPS of TRW varied from 0.512 to 0.766, and from 0.904 to 0.969, respectively (Table 2) and were above the frequently applied threshold of 0.85, indicating robust mean value functions (Wigley et al. 1984) and such EPS values suggest the sample size is adequate (McCarroll and Loader 2004). Furthermore, the values of EPS for latewood and

earlywood suggest that the common signal in LW and EW is reliable for dendroclimatic study.

The hierarchical cluster analysis identified four distinct regions of larch in the basis of tree-ring widths (Fig. 3; Table 1). The first and second region are characterised by a maritime climate (sites 1–3). The third region is a mixture of continental, Atlantic, and Baltic climate aspects. The fourth region in northeastern Poland is under the influence of the Baltic Sea (sites 6, 7, and 10) and mixture of continental and Baltic climate aspects (sites 8, 9, 11, and 12).

Climate response

The effect of temperature of the previous year on tree-ring widths, latewood and earlywood in the current year is comparable (Fig. 4). The cross-correlation between the responses of TRW, EW, LW and the temperature in the previous year varied from 0.99 ($p < 0.001$) to 0.41

Table 2 Descriptive statistics for arithmetic means in each region

	Series	Period	Mean measurement (mm)	Rbar effective	EPS
Region 1					
TRW	34	1814–2009	1.57	0.730	0.957
EW			1.01	0.706	0.951
LW			0.56	0.674	0.944
Region 2					
TRW			1.69	0.632	0.943
EW	20	1898–2009	1.08	0.598	0.934
LW			0.61	0.602	0.935
Region 3					
TRW			1.93	0.512	0.904
EW	27	1863–2009	1.27	0.494	0.897
LW			0.66	0.435	0.873
Region 4					
TRW			1.90	0.766	0.969
EW	121	1832–2006	1.27	0.743	0.965
LW			0.63	0.668	0.951

TRW tree-ring widths, EW earlywood, LW latewood, *rbar.eff* the effective signal calculated as $rbar.bt / (rbar.wt + (1 - rbar.wt) / c.eff)$, where *rbar.wt* the mean of the correlations between series from the same tree over all trees, *rbar.bt* the mean inter-series correlation between all series from different trees, *c.eff* the effective number of cores, *eps* the expressed population signal

Fig. 3 Dendrogram of the results of cluster analysis. Numbers of research sites and letters of meteorological stations correspond to those in Table 1

($p < 0.5$). The difference is between response of LW and EW. The latewood is less sensitive to increased temperature in the previous October (Fig. 4). TRW and EW react negatively to high temperature in the previous July, August, and September. The reaction on temperature in the current growth season is less homogenous (Fig. 4). The highest correlation is between regions 2 and 4 for TRW and EW, 0.784 ($p < 0.05$) and 0.768 ($p < 0.05$), respectively. For LW, it is between region 2 and 3 (0.841, $p < 0.005$).

The relationship between tree growth and precipitation varies between the regions (Fig. 4). In the previous years, the highest correlation is between regions 1 and 3 for TRW (0.699, $p < 0.1$), EW (0.778, $p < 0.05$), and LW (0.596, $p < 0.5$). The reaction to the monthly sum of precipitation in the current year is more comparable between regions; the highest values of correlation for TRW (0.798, $p < 0.01$) and LW (0.896, $p < 0.005$) are between region 1

and 2. In EW a similar reaction was found between region 2 and 4 (0.723, $p < 0.05$). The differences between TRW, EW, and LW from the same region are not great, however the correlation between EW and LW is lower (0.493).

Effect of March temperature

The positive effect of high March temperature is observed in region 2 for TRW and LW (Fig. 4). The lowest correlation is noted for region 1 (Fig. 4). The bootstrap running correlation with a 25 year shifting window revealed a decreasing impact of late winter temperatures, especially for TRW and EW in region 3, where the highest impact was observed for the years 1963–1989 (Fig. 5). In the last 20 years, the influence of March temperature on tree-ring widths and earlywood is stable and does not reveal a positive or negative effect. For latewood (LW), the influence of March temperature is slightly negative, especially for the period 1977–2001, reaching minimum values for the years 1981–2005. After this period, the correlation increases, but does not reach positive values (Fig. 5).

Discussion

Tree rings, earlywood, latewood and climate effect

The influence of climate on European larch tree rings growing outside their natural range differs from other coniferous species. There is a clear negative response to the temperature of the previous summer on TRW, and EW. The observed significant positive influence of March

Fig. 4 Climate/growth relationships in each region. *TRW* tree-ring widths, *EW* earlywood, *LW* latewood

temperature in region 2 is not so clearly visible in other regions (Fig. 4). Thermal conditions of the current year are most important in July for latewood (LW). In contrast to the Puławy (Poland) experimental plot (Oleksyn and Fritts 1991), the inverse relationship between the temperature in the previous year is not surprising. Vitas and Žeimavičius (2010) analysing pointer years revealed that the growth pattern of European larch is similar to that in Norway spruce, and this research supports that observation in some areas. The visible similarity is between the inverse response to the previous summer temperature; however, the impact of winter is not so clear. Spruce is more sensitive to low temperatures in February and March (Koprowski 2012) while the larch is more resistant. The studies from southern Poland (Danek 2009) and from Puławy (Oleksyn and Fritts 1991), in central part of eastern Poland, confirm that late winter temperature is not a crucial factor in determining the tree-ring width in larch. The latewood width (LW) of larch trees growing outside their natural range was more dependent on September temperature than on other summer months (Fig. 4). In southern Poland, the effect of current summer temperature was significant (Danek 2009). Because European larch grows naturally in mountainous regions, most of the research is from this area.

Trees from the Italian Alps (2,000–2,200 m above sea level) of similar age distribution (Carrer and Urbinati 2004) revealed that high maximum March and April temperatures have a negative effect on tree growth, in contrast to the observed positive response in June and July. In the Tatra mountains (1,450 m a.s.l.), a significant influence of temperature was found in May (Büntgen et al. 2007) and in the European Alps, in May to July (Frank and Esper 2005). The positive effect of increased precipitation is visible in the vegetation season of both the previous and the current years. However, the significance of particular months varies between the regions. There is a clear difference between the reaction of LW and EW in the current summer. Latewood is more sensitive to the amount of rainfall in summer months. Trees from other parts of Poland react more clearly to precipitation in the current growing season (Oleksyn and Fritts 1991; Danek 2009). In the Alps and Tatra mountains, the higher mean values of yearly rainfall at 1,186–1,288 mm and 849 mm respectively, mean that precipitation is not the limiting factor to growth (Büntgen et al. 2007; Carrer and Urbinati 2004), while in central and northern Poland, the mean yearly precipitation levels vary between 550 mm in the central region to 650 mm in the north (Kirschenstein and Baranowski 2005).

Fig. 5 Change in influence of March temperature on tree-ring widths in sequential 25-year time intervals. *TRW* tree-ring widths, *EW* earlywood, *LW* latewood

Effect of increasing temperature

Most studies on the effect of increasing temperatures focus mainly the problems of climate reconstruction, and the possible implication of this phenomenon on the processes of calibration and verification (D'Arrigo et al. 2008). The long-term temperature increase during February and particularly March in Poland (Kozuchowski and Degirmendzić 2005) reflects the changing climate in Europe and might cause different seasonal reactions of tree growth to temperature. D'Arrigo et al. (2008) called this phenomenon the “divergence problem”. It was observed in northern Alaskan forests where it was associated with June–July mean temperatures (D'Arrigo et al. 2008). The effect of climate change is clearly observed in regions where temperature is a limiting factor. This condition is found amongst trees growing in the European Alps (Theurillat and Guisan 2001). In this environment, larch will increase its radial growth with an increase in mean annual temperature of 2 °C and a slight increase in precipitation (Keller et al. 1997). This study extends the existing knowledge. At first, the trees grew only in the lowland, but later, forest management activities extended this range. The March temperature increase has had no impact on TRW and EW in the period 1982–2006. The width of the earlywood

which accounts for between 72 and 77 % of TRW is not dependent on March temperature, as shown by the moving window between 1950 and 1982 and from 1970 to 2008, where the bootstrap correlation coefficient varies from -0.2 to $+0.2$ (except for the period 1981–2005 in region 4) (Fig. 5). LW was reduced in region 1 between 1963 and 2009. When the bootstrap correlation coefficient is below 0 in the period 1977–2009, the width of LW makes up less than 30 % of TRW (Fig. 5).

Should the European larch be introduced more widely outside its natural range?

The uncertainties in the climate change projections are often emphasised. The impact of these changes on forests remains uncertain because of an incomplete understanding of tree responses to the changing climatic factors (Lindner et al. 2008). The coniferous forests expand beyond the limits of their natural range because of forest management (Spiecker 2003). The palynological study of species distribution clearly shows no anthropogenic influenced tree migration in response to changing climate during the Holocene. A good example of this is Norway spruce, where pollen studies reveal that during the Preboreal period spruce

had re-distribution expanded in association with the warming climate (Latałowa and van der Knaap 2006). Currently, the climate change scenario (Lindner et al. 2008) and the ecological oriented approach of forest management does not favour coniferous forests, which have been introduced on sites naturally dominated by broadleaved trees (Spiecker 2003). On the other hand, in Germany, two different climate change scenarios were tested, and coniferous species (spruce and pine) showed more positive responses than beech and oak. The scenarios differ in precipitation level, both of them represented the increase of temperature of about +3 K (Lasch et al. 2002). On the basis of these findings, it is difficult to clearly decide about the introduction of coniferous trees outside their natural range.

Conclusions

In terms of changing climate variables and unpredictable changes in environment, the question of introducing new species outside their natural range is still open. One of the solutions in terms of undermining the impact of climate change on forests is increasing surface area of the forest. However, this may lead to an increase in the sensitivity of forests to changes in precipitation and high temperatures. One way to counteract this is to increase biodiversity within plantations through an increase in the number of species (multi-species plantations) (Nabuurs et al. 2007). The research presented here identifies that the observed recent increased March temperature has no significant, negative effect on tree-ring widths. However, the present visual condition of European larch together with the lack of negative response to tree growth observed with the increase in March temperature suggests that wider distribution of larch outside its natural range may be beneficial.

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