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ORIGINAL RESEARCH ARTICLE

Climate signal in the radial growth of selected coniferous species from the Forest Experimental Station in Rogów

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Abstract. I present dendroclimatological analysis of coniferous tree species growing under the same environmental conditions in the WULS-SGGW Forest Experimental Station in Rogów (51°49' N, 19°53' E, ca. 190 m a.s.l). The study focuses on silver fir, European larch, Scots pine and Douglas fir. For each species, tree-ring width and annual sensitivity chronologies were developed for the period 1931–2010. Analysed species show considerable similarity of their radial increment course (GLK up to 67%, the t-value of 3,5–9,5). The relationship obtained for of the influence of climate conditions on radial growth of these species is typical of the relationships reported from other locations in lowland Poland. Late winter and early spring temperature, especially during February-March, is the main factor affecting tree-ring formation. The general relationship demonstrates that this seasonal thermal limitation operates at an inter-regional and interspecific level in determining the growth of coniferous tree species in Poland. Whereas, the dependence of these species on precipitation is much less significant.

Key words: dendroclimatology, Scots pine, silver fir, European larch, Douglas fir, central Poland

1. Introduction

The growth of trees, including increase of their diameter, is a complex process. The structure, density and above all the width of a tree-ring are the result of mutual interaction of many different, sometimes contradictory factors and relationships between the environment and a plant (Schweingruber 1996; Zielski, Krąpiec 2004). Both natural forces and human activity have influence on cambium activity and, what comes with it, on tree growth. Dynamics of weather conditions, characterised by significant monthly and annual fluctuations is an important factor that shapes the radial growth of a tree (Fritts 1976; Schweingruber 1996). Trees response to factors influencing their growth can be observed in short-term increment reaction. The discrepancies in this process between particular species result from different sensitivity to climatic factor, which is also modelled by age, genes, site characteristics and different random incidents (Fritts 1976; Schweingruber 1996; Wilczyński 2010).

Knowledge about impact of natural environment on the functioning of trees is one of the main requirements of proper forest management. This is because of the basic role that habitat, especially climatic conditions, plays in the formation of growth of particular species. Recently observed climate changes cause changes in relations between tree growth and factors shaping it. These effects can be also observed in growth trends of particular species, which has direct influence on the production capacity of forest ecosystems (Spiecker et al. 1996; Jaworski 2003a, b). As Chmura et al. (2010) report, changing environmental conditions not only cause changes in plant communities, but also in forestry and the business related with it. These issues show that research on the influence of climate conditions on tree growth is gaining importance and its results should be used in practice.

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Studies on the impact of climate conditions on radial growth of forest trees began in Poland in the middle of XXth century (Zielski, Krąpiec 2004) and so far most of the native species along with the selected introduced ones were analysed. Research focused mainly on Scots pine – the most popular forest tree species in Poland. The influence of weather conditions on tree-ring widths for this species was researched by Feliksik and Wilczyński (1996), Zielski (1997), Wilczyński (1999), Wilczyński et al. (2001) and Cedro (2001, 2004). Dendroclimatology of European larch was studied by Feliksik (1992), Feliksik and Wilczyński (1998b), Danek (2009) and Koprowski (2012). As for fir, studies were conducted by Feliksik (1990), Koprowski and Gławenda (2007), Bijak (2010) and Bronisz et al. (2010). Douglas fir is the most widely recognised introduced tree species in terms of dendroclimatological investigations (Feliksik, Wilczyński 2004, 2008, 2009).

Because of the different genes, reactions to environmental factors, including climate parameters, can be different for particular species, therefore comparative studies on dendroclimatological reaction are valuable (Opała 2009). Previous Polish works in this area contained, inter alia, analysis of the impact of climate conditions on growth of pine, fir and beech in Świętokrzyski National Park (Feliksik et al. 2000) and in Ojcowski National Park (Opała 2009), spruce, pine and larch at Pogórze Wilamowickie (Wilamowickie Foothills) (Feliksik, Wilczyński 1998a), and fir and larch in Zagnańsk Forest District (Wilczyński, Wertz 2012). Comparison of ‘climate – growth’ relationships for both native and introduced species was carried out for Scots pine, different spruces and Douglas fir in Pomorze (Pomerania) by Feliksik and Wilczyński (2009), for Scots pine, Douglas fir and oaks in Pomorze Zachodnie (Western Pomerania) by Cedro (2004), and for red and pedunculate oaks in Rogów by Bijak et al. (2012a, b).

The objective of this study was to recognise the radial growth pattern of the selected coniferous species (fir, larch, pine and Douglas fir) growing under the same environmental conditions in the Forest Experimental Station in Rogów, and to compare relationship between their radial growth and environmental factors.

2. Material and methods

The research material was collected in autumn 2010 in the area of Forest Experimental Station (FES) in Rogów (51°49' N, 19°53' E, ca 190 m a.s.l). Study site was located at the eastern outskirts of Wzniesienia Łódzkie (Łódzkie Hills) a region, which is a part of Wzniesienia Południowomazowieckie (Południowomazowieckie Hills) (Kondracki 2000). According to nature-forest zoning by Trampler et al. (1990), FES in Rogów is located at the northern edge of Kraina Małopolska (Małopolska Land), in Łódzko-Opoczyński District of Sieradzko-Łódzki mesoregion. Bedrock consists mostly of glacial formations made of clays and sands, where fertile, but acid luvisols had been formed. Ground water level is very low, often too low for trees roots. Vegetation period lasts 205-215 days on average. Average annual precipitation is 591 mm, of which less than 65% falls during the vegetation period. Average annual temperature is 7,5°C. January is the coldest month with average monthly temperature equal to -2,7°C, while July is the hottest one (17,6°C).

In the experimental stands of FES in Rogów, we selected one stand for silver fir (*Abies alba* Mill.), European larch (*Larix decidua* Mill.) and Scots pine (*Pinus sylvestris* L.). In the Arboretum, one site for Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) was chosen. The investigated stands were about 60-65 (larch, pine) and 70-80 (fir, Douglas fir) years old. Studied species grew on a fresh deciduous forest and fresh mixed deciduous forest habitats. 15 healthy and dominating individuals with correctly formed crown were selected at each site. One increment core per tree was taken from diameter at breast height. After drying the samples and grinding their surface with the purpose to increase the contrast between particular rings, the collected cores were scanned (1200 DPI resolution) with an EPSON Expression 10000XL scanner. Tree-ring widths were measured with an accuracy of 0,01 mm using the graphic files in CooRecorder (www.cybis.se). Next, material was cross-dated (particular years were assigned to respective annual rings) and measurement accuracy was checked in CDdendro software (www.cybis.se). Similarity of developed chronologies was assessed (*t*-value, GLK coefficient; Cook, Briffa 1990). Sequences of the least similarity to the others, thereby enabling addition of noise to the so-called ‘common signal’, were excluded from further analysis.

In order to eliminate influence of trees age and to examine interannual variability in diameter growth dynamics, we developed series of incremental indices based on tree-ring widths. Indices emphasise short-term incremental reaction for particular species. Value of annual sensitivity (c_i) for each analysed tree was calculated using the following formula (Fritts 1976; Cook, Briffa 1990; Wilczyński 2010):

$$c_i = 2\,\frac{x_i - x_{i\text{-}1}}{x_i + x_{i\text{-}1}}$$

where x_i and x_{i-1} stands for tree-ring width in the following two years.

Uniformity of developed sensitivity chronologies, indicating their representativeness and part of 'common signal' expressed by species chronologies, was assessed with EPS index (Expressed Population Signal; Wigley et al. 1984). Threshold of EPS = 0,85 was taken as a minimum value indicating usefulness of a chronology in dendroclimatological analysis (Mäkinen, Vanninen 1999; Wilczyński 2010). Similarity of incremental reaction between investigated species was also rated. GLK coefficient and *t*-values were taken as its measures. Gleichläufigkeit coefficient (GLK) describes similarity of two tree-ring width sequences in a qualitative way. Its value equals the share of cases of incremental reactions of the same character (raise or drop of ring's width in interannual scale) in a common period for both chronologies. The latter index is a quantitative indicator for similarity of two chronologies and is calculated analogously as Student's test statistics (Cook, Briffa 1990; Zielski, Krąpiec 2004).

The influence of climate conditions on radial increment of analysed species was investigated based on the so-called response function, which is a multiple regression and correlation model that connects increment index (dependent variable) with climate parameters (explaining variable) (Fritts 1976; Briffa, Cook 1990). Calculations were carried out in DendroClim2002 (Biondi, Waikul 2004). Series of annual sensitivity were taken as an input data as well as average, minimal and maximal monthly temperature and monthly precipitation for the period from July in the year preceding ring formation to September in the year of current increment (16 months). Hence the defined temporal range of climate data enables assessment of the relationship between radial growth and climatic factors also in vegetation period and time just prior to the winter dormancy period (Fritts 1976). Dendroclimatological analysis was carried out for years 1953–2010, common interval for all analysed species (58 years). Climate data came from meteorological station located in FES in Rogów and maintained by the Department of Forest Silviculture WULS-SGGW.

3. Results

Chronologies elaborated for analysed coniferous trees growing in the area of FES in Rogów cover the period of 1931–2010. The longest sequences of tree-ring parameters were specified for Douglas fir, while the shortest ones for European larch (Table 1). Transformation of tree-ring width series into sensitivity sequences reduced the influence of mid- and long-term variability, while short-term variability related mostly to climate factor was enhanced. Significant variability of increment indexes in particular years (Fig. 1) illustrates that particular trees show individual response to environmental factors pressure. However, EPS values received for species chronologies show congenial response within the species (Table 1). The highest uniformity of radial increment pattern can be observed for pine and Douglas fir (EPS>0,92), the lowest one for fir (EPS=0,88). Both the average values EPS and values calculated in 30 years period exceeded threshold values 0,85, which confirms usefulness of compiled annual sensitivity chronologies for dendroclimatological analysis.

Both *t*-values and GLK coefficient indicates some interspecific similarity in the radial growth of analysed coniferous species in FES Rogów (Fig. 1; Table 2). In the case of raw tree-ring width chronologies, the *t*-value varied from 3,5 to 9,5. Fir chronologies were the least similar to other species sequences, while Scots pine and Douglas fir series resemble other species the most. GFK coefficient analysis gave similar result. According to this criterion, Scots pine was the most similar to other species (Table 2). In the case of annual sensitivity series, the *t*-values were lower than that in raw chronologies (on average 2/3-times lower). Values of GLK coefficient for indexed chronologies were almost equal to those for raw chronologies, while that of *t*-values amounted to about half of them (Table 2). This shows similar qualitative character of studied species reactions to interannual changes of climate conditions.

The most important role in the formation of the tree ring of the studied coniferous species growing in the area of FES in Rogów should be assigned to thermal conditions. The role of precipitations in this process was much smaller. For all species, except larch, thermal conditions in winter and early spring had the biggest influence on the formation of annual growth ring. This was observed for both mean temperature (Fig. 2) as well as extreme conditions – average minimum (Fig. 3) and maximum (Fig. 4) temperature. Significant

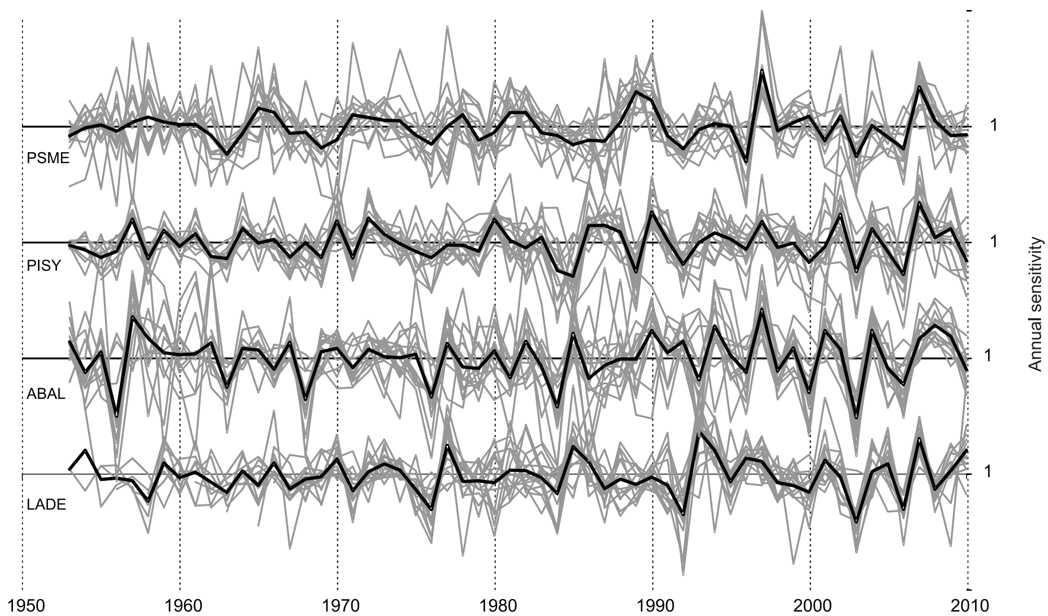

Figure 1. Series of annual sensitivity of analysed coniferous species from Rogów FES – individual trees (grey) and average for a species (black):
ABAL – Abies alba, LADE – Larix decidua, PISY – Pinus sylvestris, PSME – Pseudotsuga menziesii

Table 1. Basic descriptive features of chronologies of analysed coniferous species from Rogów FES

Species	Number of trees	Time span	Chronology median length	mTRW (SD) [mm]	r_{bar}^{*}	EPS*
ABAL	15	1939–2010	66	2,26 (1,33)	0,331	0,881
LADE	15	1953–2010	53	3,12 (1,85)	0,412	0,913
PISY	15	1946–2010	58	2,13 (1,12)	0,467	0,929
PSME	14	1931–2010	70	3,66 (1,68)	0,466	0,924

mTRW (SD) – mean tree-ring width with standard deviation in parenthesis;
r_{bar} and EPS – values given for series of increment indices
Species abbreviations as in Figure 1

Table 2. Similarity (*t*-values – left bottom part, GLK coefficient – right upper part) of raw and index chronologies of analysed species

	Tree-ring width chronology				Indexed chronology				
	ABAL	LADE	PISY	PSME		ABAL	LADE	PISY	PSME
ABAL	x	53%	67%	58%	ABAL	x	61%	66%	58%
LADE	3,5	x	67%	54%	LADE	2,9	x	66%	57%
PISY	3,9	9,5	x	67%	PISY	2,9	2,0 x	x	63%
PSME	6,9	5,4	8,8	x	PSME	3,6	1,6	3,1	x

Species abbreviations as in Figure 1

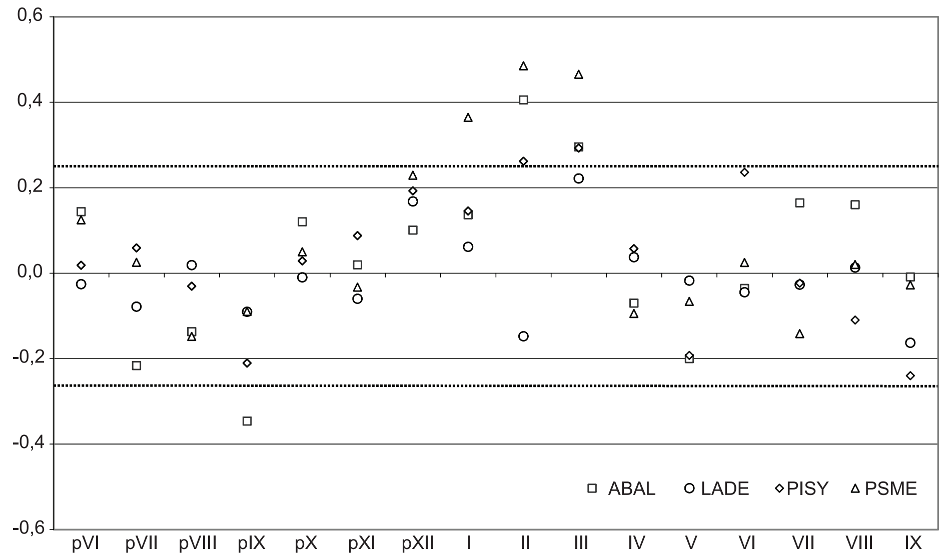

Figure 2. Correlation coefficients between mean monthly air temperature and series of annual sensitivity for analysed coniferous species from Rogów FES: dashed horizontal lines – significancy level (p=0.05); pVI, ..., pXII – months of the year prior to tree-ring formation;
ABAL – Abies alba, LADE – Larix decidua, PISY – Pinus sylvestris, PSME – Pseudotsuga menziesii

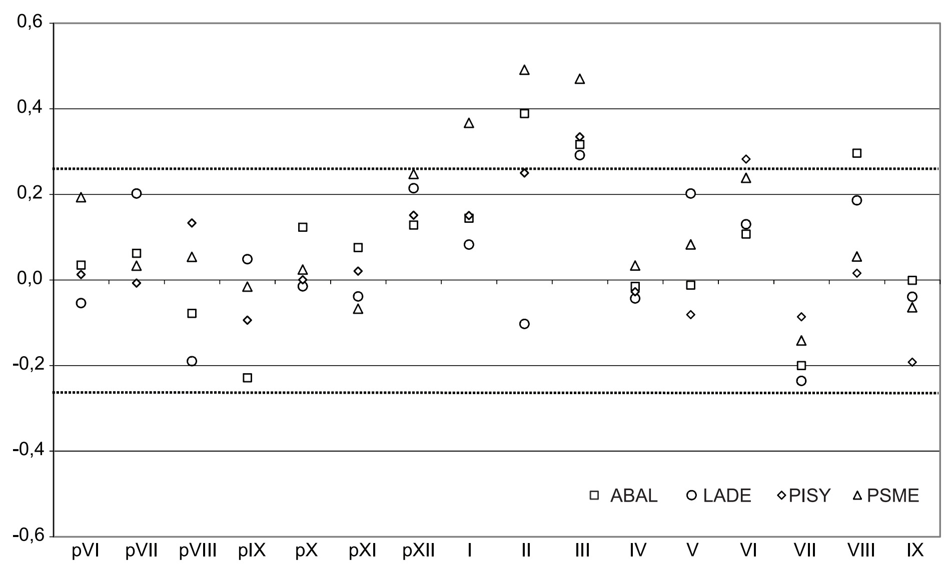

Figure 3. Correlation coefficients between mean monthly minimum air temperature and series of annual sensitivity for analysed coniferous species from Rogów FES. Denotes as in Figure 2

correlation coefficients between these climate parameters and series of annual sensitivity were found in February and March of the year of tree-ring formation. The highest values (r>0.45) were observed for Douglas fir. Thermal conditions of vegetation period and previous year had no influence on growth reaction for the studied trees. Only for silver fir, significant negative correlation between growth in the following year and average temperature in September was found. While response of studied species to thermal conditions was similar, especially in the case of factors with biggest influence on tree-ring width, significant differences were observed for the influence of precipitation. Rainfall was the most important for Scots pine. Significant positive correlations were observed

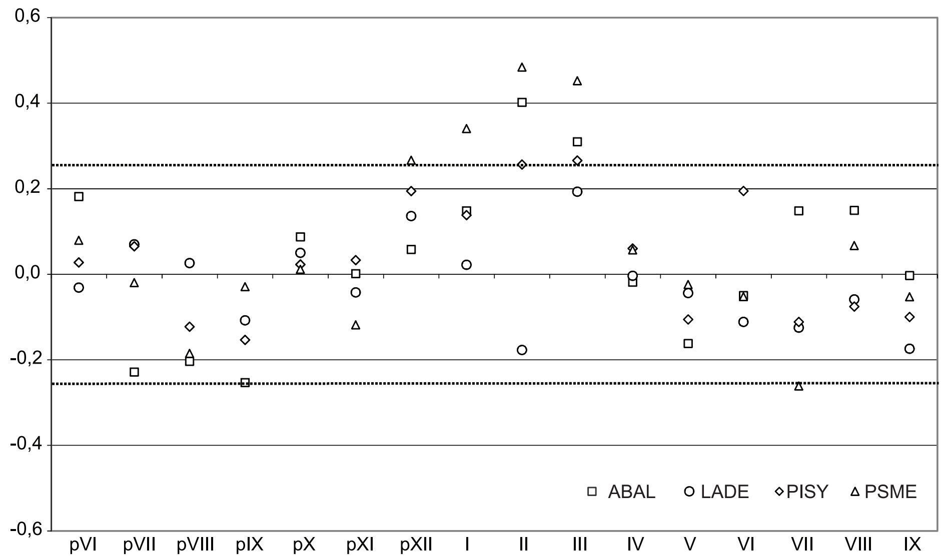

Figure 4. Correlation coefficients between mean monthly maximum air temperature and series of annual sensitivity for analysed coniferous species from Rogów FES. Denotes as in Figure 2

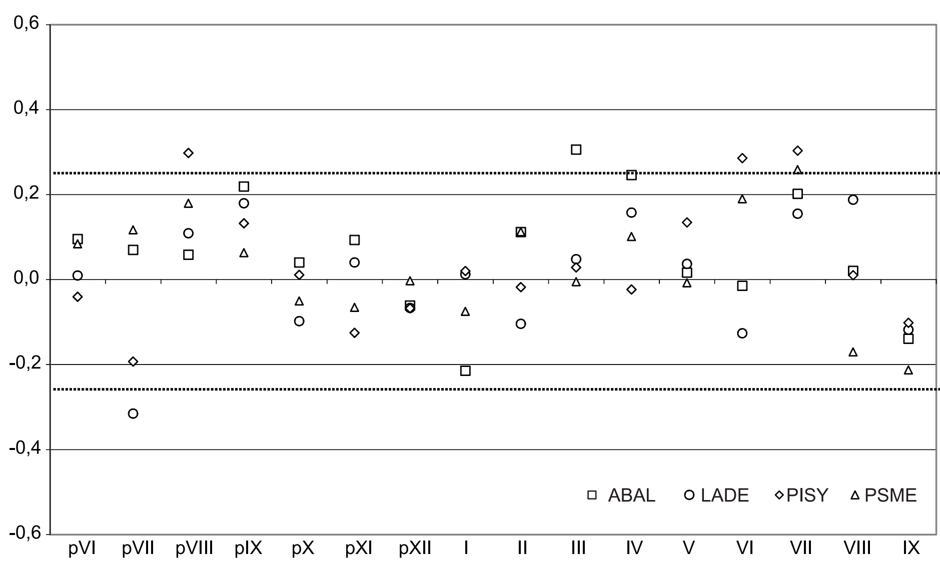

Figure 5. Correlation coefficients between mean monthly precipitation and series of annual sensitivity for analysed coniferous species from Rogów FES. Denotes as in Figure 2

during the summer (June, July) of the current growth year and in August of the previous year (Fig. 5). Silver fir shows the highest demand for water in the form of rain in early spring (March-April). In the case of larch, correlation between increment indexes and precipitation was important in July of the year prior to the annual ring formation, while for Douglas fir also in July, but in the year of growth (Fig. 5).

4. Discussion

Relations between growth of trees and factors forming it have direct influence on the growth trends of particular species, and thus on forest ecosystems production capacity (Spiecker et al. 1996; Jaworski 2003a, b). All changes within this range would cause change not only in plant communities, but also in forestry and fields of economics related to it (Chmura et al. 2010). Dendroclimatological analysis allows us to determine the nature of relation between the climate conditions and cambium activity. It can also be used to learn ecologic demands of particular species of trees and to assess the influence of site conditions on their growth and increment (Fritts 1976; Briffa, Cook 1990; Schweingruber 1996). For the introduced species, it can be a useful tool to rate the extent of their acclimatisation.

Similarity of chronologies built for analysed coniferous species from FES in Rogów points on close character of their reactions to interannual variability of climate conditions. The main factor influencing the radial growth of these trees was temperature of late winter and early spring. Similar observations for a wider range of species from the Sławno Forest District in northern Poland were made by Feliksik and Wilczyński (2009). Cedro (2004) also received analogous results for Scots pine and Douglas fir in north-west Poland. Climate – growth relationships for particular species found in presented studies are consistent with the results of former analysis of influence of climate conditions on cambium activity of trees in Poland. However, location on Forest Experimental Station SGGW in Rogów, at the edge of natural distribution of some of them translates into local specificity for these dependencies.

Presented results referring to the role of climate in the formation of tree-ring of Scots pine are similar to existing findings in this area at lowland (Zielski 1997; Cedro 2004; Koprowski et al. 2012), in the mountains (Wilczyński et al. 2001) as well as in the area of whole Poland (Wilczyński et al. 2001; Zielski et al. 2010). Low temperature in the period of February – March was determined as the main factor limiting the growth of Scots pine. Exactly the same results were received for *Pinus sylvestris* in Rogów. This confirms the supra-regional nature and prominence of temperature of late winter and early spring, in terms of cambium activity of this species. Among the analysed species, the biggest dependency of annual increment on precipitation was found for Scots pine (Fig. 5). Positive role of heavy rainfall during vegetation period (May–July) was also found for pines studied in north-west Poland by Cedro (2001, 2004) and in northern Poland by Koprowski et al. (2012). Results received in these studies are bothersome as pine is a species with wide range of humidity demand and is mostly found at dry sites. Study site in Rogów is located on the fresh habitats. These forest site types are characterised by humidity, which is sufficient or even superior to the standard requirements of Scots pine. It cannot be excluded that some other unidentified factors have influence on water relations for studied pines.

In the case of larch, the received results confirm former studies on climate influence on annual increment for this species, especially at lowland Poland. Oleksyn and Fritts (1991), Danek (2009) and Koprowski (2012) point out that temperature of winter and early spring is not a factor significantly influencing the process of tree-ring formation for larch. All these authors relate this fact to significant frost-resistance of this species, which is caused by low transpiration capacity in the winter (Olaczek 1986). However, studied larches showed significant positive correlation to minimum temperature in March (Fig. 3), which may point to the fact that despite big resistance to frost this species prefer period of early spring without ground frosts. Significant role of temperature in June observed by both Danek (2009) and Danek and Danek (2011) was not confirmed in case of trees from Rogów. It is possible that larch in this region finds its optimal temperature requirements. Such a statement can be declined by values of correlation coefficient between increment indexes and minimum temperature in the vegetation period (Fig. 3). They are not statistically significant, but point to the need of warmth for this species in the period of cambium activity what is partially visible also in the results presented for southern Poland by Danek (2009). Previous dendroclimatological analysis states the significant influence of precipitation on radial increment of larch in Poland (Oleksyn, Fritts 1991; Feliksik 1992; Feliksik, Wilczyński 1998a, b; Danek 2009, Koprowski 2012). Tree-ring widths of the studied larches from Rogów seem to be independent on humidity coming from rainfalls. The only significant correlation was found for July in the previous year. Its negative nature in the formation of current increment can be related to the fact that plant 'invests' in available humidity in this process and not in buds, from which it will take nutrients in the following year.

Dependence of silver fir radial increment on temperature of winter and early spring was found in different regions of Poland. Feliksik (1990) pointed out that thermal conditions of this period are quite important in forming *Abies alba* increment. Positive correlation between temperature in February and March and tree-ring width for this species in northern Poland, outside its natural range, was found by Koprowski and Gławenda (2007). According to Bijak (2010), winter and early spring frosts were the cause of negative pointer years for silver fir from Pojezierze Kaszubskie (Kaszubskie Lakeland). This statement is confirmed by high and significant correlation coefficients between annual sensitivity series and both minimum and maximum temperature presented in this study (Fig. 3, 4). Feliksik et al. (2000) reported similar results for Świętokrzyski National Park. However, Bronisz et al. (2010), who studied silver fir stands in Zagnańsk Forest District located not far from Świętokrzyski National Park, found completely different nature of temperature – increment relation. According to their observation, correlation between March temperature and incremental indexes was negative. Authors also emphasise the significant role of thermal conditions in vegetation period, especially in the summer, which is confirmed by Feliksik (1990). Growth limiting influence of temperature can be explained by soil desiccation, often resulting in deficit of humidity which is crucial for plants during that time (Bernadzki 2008). In addition, almost no relation between precipitation and fir growth was observed in northern Poland (Koprowski, Gławenda 2007; Bijak 2010). Similarly to these places, silver fir in Rogów is on the border of its range. Lack of significant influence of precipitation may be caused by sufficient amount and proper distribution within the year or by the fact that this distribution border is caused by thermal conditions. Within its natural range in North America, Douglas fir grows on sites extremely different in terms of humidity and thermal conditions, which causes significant variability of resistance to frost and droughts for this species (Bellon et al. 1977). Wide range of climate factors, influencing growth of Douglas fir in Poland, was found by Feliksik and Wilczyński (2004). However, thermal conditions in the winter, especially in February and March, seem to be supra-regional determinant of radial increment for this species. These observations were confirmed by a more detailed analysis by Feliksik and Wilczyński (2008, 2009) as well as Cedro (2004, 2006). 'Climate – increment' relations for Douglas fir from Rogów seem to fit the scheme of dependence of this species increment on climate conditions in Poland. Among the studied coniferous species, it is the Douglas fir that responded to thermal conditions of late winter and early spring the most (Fig. 2–4). This shows high sensitivity towards climate conditions exhibited by species that is foreign to our environmental conditions, especially for frosts in the period before vegetation. Dependence of increment of investigated *Pseudotsuga menziesii* individuals on precipitation partially covers observations made by Feliksik and Wilczyński (2004). This factor has special meaning in the regions with low amount of precipitation and general deficit in humidity balance. Wzniesienia Łódzkie (Łódzkie Hills) is one of such regions. In northern Poland, significant positive correlation with precipitation in February and March was observed (Cedro 2004, 2006; Feliksik, Wilczyński 2008). Such dependence was not found in this study. Probably, similar as for silver fir, lack of significant influence of precipitation may be caused by sufficient amount and proper distribution within a year.

Causes for the observed dependence of studied coniferous species increment on temperature in February–March should be found in plants physiology. Cold winter slows down physiological processes, especially influencing the balance between processes of assimilation and breathing (Żelawski 1967; Szaniawski et al. 1977). Although some species, e.g. larch, are frost-resistant because of their low transpiring capacity during the winter (Olaczek 1986), the soil frost, which is quite possible especially in case of lack of snow, may cause, particularly in the early spring, physiological drought that can further cause damages in plant tissues (Szymański 1986). Additionally, as pointed by Chałupka (1977), low temperature in this period inhibits the activity of buds and needles in the production of phytohormones, decreasing the effectiveness of metabolic processes and xylogenesis. For this reason, cambium activity not only starts later, but is also less intensive and less efficient, so no wonder then that trees produce narrower rings.

5. Summary

Investigated coniferous species from Forest Experimental Station in Rogów (central Poland) express quite high similarity of radial increment dynamics, which seems to be more an effect of taxonomic dependences than provenience. Introduced Douglas fir adapted very well to local growth conditions and growth pattern similar to native coniferous species. Obtained picture of influence of climate conditions on radial growth of Scots pine, silver fir, European larch and Douglas fir is typical for dendroclimatological relations observed for these species on the other sites in the lowland part of Poland, where temperature in winter and early spring is the main factor influencing radial growth. This proves that the thermal conditions of this period have supra-regional and interspecies influence on the process of tree-ring formation of coniferous trees species in Poland.

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References

Bellon S., Tumiłowicz J., Król S. 1977. Obce gatunki drzew w gospodarstwie leśnym. Warszawa, PWRiL, 267 s. ISBN 00-01-13477-9.

Bernadzki E. 2008. Jodła pospolita – ekologia, zagrożenia, hodowla. Warszawa, PWRiL. ISBN 978-83-09-01028-9.

Bijak Sz. 2010. Tree-ring chronology of silver fir and its dependence on climate of the Kaszubskie Lakeland (northern Poland). *Geochronometria,* 35: 91–94.

Bijak Sz., Bronisz A., Bronisz K. 2012a. Wpływ czynników klimatycznych na przyrost radialny dębu szypułkowego i czerwonego w LZD Rogów. *Studia i Materiały CEPL w Rogowie,* 14/1 (30): 121–128.

Bijak Sz., Bronisz A., Bronisz K. 2012b. Wpływ ekstremalnych warunków klimatycznych na przyrost radialny dębu czerwonego *Quercus rubra* w LZD Rogów. *Studia i Materiały CEPL w Rogowie,* 14/4 (33): 163–170.

Biondi F., Waikul K. 2004. DendroClim2002: A C++ program for statistical calibration of climate signals in tree-ring chronologies. *Computers and Geosciences,* 30: 303–311.

Briffa K., Cook E. R. 1990. Methods of response function analysis, in: Cook E., Kairiukstis L. Methods of dendrochronology. Applications in the Environmental Sciences. Dordrecht, Boston Kluwer Academic Publishers, s. 240−247. ISBN 0-7923-0586-8.

Bronisz A., Bijak Sz., Bronisz K. 2010. Dendroklimatologiczna charakterystyka jodły pospolitej (*Abies alba* Mill.) na terenie Gór Świętokrzyskich. *Sylwan,* 154 (7): 463–470.

Cedro A. 2001. Dependence of radial growth of *Pinus sylvestris* L. from western Pomerania on the rainfall and temperature conditions. *Geochronometria,* 20: 69–74.

Cedro A. 2004. Zmiany klimatyczne na Pomorzu Zachodnim w świetle analizy sekwencji przyrostów rocznych sosny zwyczajnej, daglezji zielonej i rodzimych gatunków dębów. Oficyna IN PLUS. ISBN 83-89402-03-3.

Cedro A. 2006. Influence of thermic and pluvial conditions on the radial increments of *Pseudotsuga menziesii* Franco from Western Pomerania, Poland, in: Heinrich I., Gärtner H., Monbaron M., Schleser G. (ed.). TRACE – Tree Rings in Archaeology, Climatology and Ecology 4: 132–140.

Chałupka W. 1977. Zagadnienia fizjologii wzrostu i rozwoju, in: Nasze Drzewa Leśne. Świerk pospolity. Warszawa−Poznań, PWN, p. 153–198.

Chmura D. J., Howe G. T., Anderson P. D., St. Clair J. B. 2010. Przystosowanie drzew, lasów i leśnictwa do zmian klimatycznych. *Sylwan* 154 (9): 587−602.

Cook E. R., Briffa K. 1990. Data analysis, in: Cook E., Kairiukstis L. Methods of dendrochronology. Applications in the Environmental Sciences. Dordrecht, Boston, Kluwer Academic Publishers, p. 99−162. ISBN 0-7923-0586-8.

Danek M. 2009. Wpływ warunków klimatycznych na szerokość przyrostów rocznych modrzewia (*Larix decidua* Mill.) rosnącego w północnej części województwa małopolskiego. *Sylwan,* 153 (11): 768−776.

Danek M., Danek T. 2011. Zastosowanie alternatywnych metod przetwarzania danych w analizie dendroklimatologicznej modrzewia *Larix decidua* Mill. Z Polski południowej. *Sylwan,* 155 (3): 147−158.

Feliksik E. 1990. Badania dendroklimatologiczne dotyczące jodły (*Abies alba* Mill.) występującej na obszarze Polski. *Zeszyty Naukowe Akademii Rolniczej w Krakowie,* 151.

Feliksik E. 1992. Wpływ warunków klimatycznych na wielkość przyrostów radialnych modrzewia europejskiego (*Larix decidua* Mill.) występującego w Karpatach. *Sylwan,* 136 (5): 61−67.

Feliksik E., Wilczyński S. 1996. Dendrochronologiczna charakterystyka sosny zwyczajnej (*Pinus sylvestris* L.) z Kotliny Kłodzkiej i Karpat. *Sylwan,* 140 (9): 77–84.

Feliksik E., Wilczyński S. 1998a. Wpływ temperatury i opadów na przyrost roczny drewna świerka, sosny i modrzewia występujących w leśnictwie Pierściec u podnóża Pogórza Wilamowickiego. *Prace Komitetu Zagospodarowania Ziem Górskich PAN*, 44: 77–86.

Feliksik E., Wilczyński S. 1998b. Wpływ warunków termicznych i pluwialnych na przyrost drewna modrzewi (*Larix decidua* Mill.). *Sylwan,* 142 (3): 85–90.

Feliksik E., Wilczyński S. 2001. Influence of temperature and rainfall on the increment width of native and foreign tree species from the Istebna Forest District. *Folia Forestalia Polonica*, ser. A. 43: 103–114.

Feliksik E., Wilczyński S. 2004. Klimatyczne uwarunkowania przyrostu radialnego daglezji zielonej (*Pseudotsuga menziesii* (Mirb.) Franco) rosnącej na obszarze Polski. *Sylwan,* 148 (12): 31–38.

Feliksik E., Wilczyński S. 2008. Sygnał klimatyczny w słojach *Picea sitchensis* (Bong.) Carriere oraz *Pseudotsuga menziesii* (Mirb.) Franco. *Sylwan,* 152 (6): 3–13.

Feliksik E., Wilczyński S. 2009. The effect of climate on tree-ring chronologies of native and nonnative tree species growing under homogenous site conditions. *Geochronometria*, 33: 49–57.

Feliksik E., Wilczyński S., Podlaski R. 2000. Wpływ warunków termiczno-pluwialnych na wielkość przyrostów radialnych sosny (*Pinus sylvestris* L.), jodły (*Abies alba* Mill.) i buka (*Fagus sylvatica* L.) ze Świętokrzyskiego Parku Narodowego. *Sylwan,* 144 (9): 53–64.

Fritts H. C. 1976. Tree rings and climate. London-New York-San Francisco, Academic Press.

Jaworski A. 2003a. Zmiany tendencji wzrostowych głównych lasotwórczych gatunków drzew w Europie i obszarach górskich Polski oraz ich przyczyny. Część I. Zmiany tendencji wzrostowych. *Sylwan,* 147 (6): 99–106.

Jaworski A. 2003b. Zmiany tendencji wzrostowych głównych lasotwórczych gatunków drzew w Europie i obszarach górskich Polski oraz ich przyczyny. Część II. Przypuszczalne przyczyny zmian tendencji wzrostowych. *Sylwan,* 147 (7): 69–74.

Kondracki J. 2000. Geografia regionalna Polski. Warszawa, PWN. ISBN 83-01-13897-1.

Koprowski M. 2012. Long-term increase of March temperature has no negative impact on tree rings of European larch (*Larix decidua*) in lowland Poland. *Trees,* 26: 1895–1903. DOI 10.1007/s00468-012-0758-8.

Koprowski M., Gławenda K. 2007. Dendrochronologiczna analiza przyrostów rocznych jodły pospolitej (*Abies alba* Mill.) na Pojezierzu Olsztyńskim (Nadleśnictwo Wichrowo). *Sylwan,* 151 (11): 35–40.

Koprowski M., Przybylak R., Zielski A., Pospieszyńska A. 2012. Tree rings of Scots pine (*Pinus sylvestris* L.) as a source of information about past climate in northern Poland. *International Journal of Biometeorology,* 56: 1–10. DOI: 10.1007/s00484-010-0390-5.

Mäkinen H., Vanninen P. 1999. Effect of sample selection on the environmental signal derived from tree-ring series. *Forest Ecology and Management,* 113: 83–89.

Olaczek R. 1986. Zarys ekologii i fitocenologii, in: S. Białobok (ed.) Modrzewie *Larix* Mill. Warszawa−Poznań, PWN, s. 379−440.

Oleksyn J., Fritts H. C. 1991. Influence of climatic factors upon tree rings of *Larix decidua* and *L. decidua* × *L. kaempferi* from Pulawy, Poland. *Trees,* 5: 75−82.

Opała M.. 2009. Wpływ warunków klimatycznych na kształtowanie się szerokości przyrostu rocznego *Fagus sylvatica*, *Pinus silvestris* i *Abies alba* z Ojcowskiego Parku Narodowego. *Prądnik. Prace i Materiały Muzeum im. Prof. Wł. Szafera,* 19: 231–230.

Schweingruber F. H. 1996. Tree Rings and Environment – Dendroecology. Berne, Paul Haupt Publishers. ISBN 3258054584.

Spiecker H., Mielikainen K., Kohl M. Skovsgaard J. P. (ed.). 1996. Growth trends in European forests. European Forest Institute, Research Report 5, Springer-Verlag, Heidelberg.

Szaniawski R., Żelawski W., Wierzbicki B. 1977. Wymiana gazowa i gospodarka wodna, in: Nasze Drzewa Leśne. Świerk pospolity. Warszawa-Poznań, PWN, p. 131–152.

Szymański S. 1986. Ekologiczne podstawy hodowli lasu. Warszawa, PWRiL. ISBN 83-09-01728-6 .

Trampler T., Kliczkowska A., Dmyterko E., Sierpińska A. 1990. Regionalizacja przyrodniczo-leśna Polski na podstawach ekologiczno-fizjograficznych. Warszawa, PWRiL, 159 p.

Wigley T. M. L., Briffa K. R., Jones P. D. 1984. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *Journal of Climate and Applied Meteorology,* 23: 201–213.

Wilczyński S. 1999. Wpływ klimatu na przestrzenne zróżnicowanie reakcji przyrostowych sosny zwyczajnej (*Pinus sylvestris* L.), in: Feliksik E. Klimatyczne uwarunkowania życia lasu. Wrocław, Polskie Towarzystwo Ludoznawcze, p. 197–203.

Wilczyński S. 2010. Uwarunkowania przyrostu radialnego wybranych gatunków drzew z Wyżyny Kieleckiej w świetle analiz dendroklimatologicznych. *Zeszyty Naukowe Uniwersytetu Rolniczego im. Hugona Kołłątaja w Krakowie, Rozprawy:* 464 (341): 1–221.

Wilczyński S., Krąpiec M., Szychowska-Krąpiec E., Zielski A. 2001. Regiony dendroklimatyczne sosny zwyczajnej (*Pinus sylvestris* L.) w Polsce. *Sylwan* 145 (8): 53–61.

Wilczyński S., Wertz B. 2012. Sygnał klimatyczny w seriach przyrostów radialnych jodły pospolitej oraz modrzewia europejskiego. *Studia i Materiały CEPL w Rogowie* 14/1 (30): 66–74.

Zielski A. 1997. Uwarunkowania środowiskowe przyrostów radialnych sosny zwyczajnej (*Pinus sylvestris* L.) w Polsce Północnej na podstawie wielowiekowej chronologii. Toruń, Wydawnictwo Naukowe Uniwersytetu Mikołaja Kopernika.

Zielski A., Krąpiec M. 2004. Dendrochronologia. Warszawa, PWN, 328 s. ISBN 830114226X.

Zielski A., Krąpiec M., Koprowski M. 2010. Dendrochronological data, in: Przybylak R., Majorowicz J., Brazdil R., Kejna M. (ed.). The Polish climate in the European context: an historical overview. Springer, p. 191–217. DOI: 10.1007/978-90-481-3167-9.

Żelawski W. 1967. Wymiana gazowa i bilans wodny igliwia, in: Zarys fizjologii sosny zwyczajnej. Warszawa-Poznań, PWN, p. 33–94.

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