Diversification of increment reactions of Douglas fir (*Pseudotsuga menziesii* Franco) from mountainous regions of southern Poland

E. Feliksik, S. Wilczyński

Agricultural University, Faculty of Forestry, Department of Forest Climatology, Cracow, Poland

ABSTRACT: Dendroclimatological research presented in this paper concerns Douglas fir (*P. menziesii*) at 17 sites located in the area of the Sudetes Mountains, the Polish part of the Carpathians and Roztocze. The methods of principal components analysis, response function and coefficients of convergence allowed the researchers to determine that the factor which integrated chronologies and determined the annual rhythm of changes in radial increment of the trees under research was the thermal conditions of winter preceding the vegetation season. Thermal conditions and summer rainfall had a slightly smaller impact on the tree increment. The influence of thermal and pluvial conditions on the process of xylem cell formation changed as longitude changes occurred. The pressure of winter temperatures and summer rainfall increased with an increase in the degree of climate continentality. On the other hand, the role of summer temperatures decreased. Despite these differences, the rhythm of annual changes in tree-ring width of Douglas fir from the Sudetes, Carpathians and Roztocze is highly similar. Southern Poland can be considered as dendrochronologically homogeneous for this species. We can distinguish two areas that are dendroclimatologically homogeneous.

Keywords: Douglas fir; dendroclimatology; tree ring

At the turn of the 19th century, European forestry began to be increasingly interested in the acclimatization of trees of foreign origin. Large amounts of Douglas firs were introduced into forest crops in the hope of good results of wood production (Białobok, Chylarecki 1965; Bellon et al. 1972). In Poland, interest in this species was smaller and varied in different regions of the country. The highest number of forest crops and research areas was established in the west. In other parts of Poland, particularly in the Carpathians, Douglas fir was introduced sporadically, usually in large private forest properties. Today, these trees are sometimes over 100 years old and are excellent research subjects. The purpose of this research was a possibility of determining the adaptive capability of this species in new habitats.

Among the environmental factors determining the ability of vegetation to adapt to new conditions, the climate plays a crucial role. The analysis of the climatological conditioning of tree growth and of its ability to adapt to certain conditions is made possible by methods used in dendrochronological and climatological research (Huber 1943; Fritts 1976; Schweingruber 1983). Dendroclimatology looks for a "climatic signal" in the annual increment of the tree vascular tissue. The basic assumption of dendroclimatological analysis is a commonly accepted belief that meteorological conditions are the main factor determining the annual fluctuations in tree-ring sizes. The annual variability of radial increments is recorded in the chronology of the width of tree-rings and it can be interpreted as historical information about the sensitivity and reaction of a particular species to climatological conditions of the environment.

The purpose of our research was to identify and evaluate the diversification of Douglas fir's sensitivity to thermal and pluvial conditions. Our research was concerned with the sensitivity of Douglas firs growing in southern Poland. Douglas firs selected for research grow in the Sudetes, Carpathians and Roztocze, in the area of over 600 km, extending from 15º (λ E) longitude in the west to almost 24º (λ E) in the east of Poland. Among other things, this location of research areas allowed us to check whether the eastern direction of the increasing continentality of climate is reflected in the incremental reactions of Douglas firs.

MATERIALS AND METHODS

The study was conducted in 17 Douglas fir stands situated in the Sudetes Mts. (6 stands – LWK, SNK, KMN, JGW, BRD, BST), in the Western Beskids Mts. (4 stands – UJS, IST, BLK, AND), in the Eastern Beskids Mts. (5 stands – LSI, DKL, LSK, KRS, KNC) and Roztocze (2 stands – ZWR, HRB) (Fig. 1). At each of the above-mentioned sites, 20 dominant trees without symptoms

The investigation was supported by the Polish State Committee for Scientific Research (KBN) under Grant No. 6 PO6H 096 20.

of disease or signs of damage were selected. The tree trunks were bored on two opposite sides, at the height of 1.3 meters with Pressler bore. Samples that were obtained in this way were used to measure the width of tree-rings. As a result, we obtained 680 sequences of values known as dendroscales. Each site was represented by 40 dendroscales.

In order to verify the accuracy of measurements and to conduct time synchronization of radial increments, we used the COFECHA program (HOLMES 1986). Verified tree-ring dendroscales underwent the process of indexation according to the following formula:

$$I_i = R_i \cdot Y_i^{-1}$$

where: I – tree-ring index,
R – width of tree-ring,
Y – value of matched curve,
i – year.

This procedure was conducted using the ARSTAN program (COOK, HOLMES 1986). Thanks to indexation, we were able to eliminate long-term fluctuations of tree-ring sizes from the dendroscales, keeping their annual variability determined mainly by meteorological conditions at the same time (FRITTS 1976).

Tree-ring dendroscales became the basis for creating 17 local site tree-ring chronologies that are time sequences of mean values of annual tree-ring widths of 20 trees from each stand. Index dendroscales were used in a similar way to create site index chronologies.

We used the method of convergence (HUBER 1943; ECKSTEIN, BAUCH 1969) in order to analyze similarities of chronologies and to compare them with the annual variability of climatological elements. Convergence coefficients (*GL*) were calculated according to the following formula:

$$GL = 100 \cdot m \cdot (n-1)^{-1} \quad (\%)$$

where: m – number of convergent sections of compared curves,
n – number of compared years.

While looking for the factors that determine the spatial diversification of annual variability of local chronologies, we used the principal components analysis (PCA) (HOLMES 1994a) and response function (FRITTS 1976; HOLMES 1994b). Meteorological data necessary for dendroclimatological analyses and for characterization of the climate of mountainous regions of southern Poland came from the records of IMGW (Polish Meteorological and Hydrological Institute) in Szklarska Poręba (A), Kłodzko (B), Żywiec (C), Lesko (D) and Zamość (E) (Fig. 1).

RESULTS AND DISCUSSION

High values of coefficients of convergence (GL) and dendroscale correlation ($P < 0.01$) within particular populations allowed us to create site tree-ring chronology and site index chronology for each stand (Fig. 2). We compared 17 chronologies with one another by calculating coefficients of convergence (GL). The results indicate a high similarity ($P < 0.001$) of the rhythm of annual variability in tree-ring width of Douglas firs, even in the cases where distances between sites were more than 500 km. The values of convergence coefficients decrease, however, with an increase in the distance between sites (Fig. 3).

Principal components analysis of index chronologies created three groups of Douglas fir sites. One is composed of site chronologies from the Sudetes Mountains (Region I). The second, similar to the Sudetes chronologies, includes chronologies of sites located in the West-

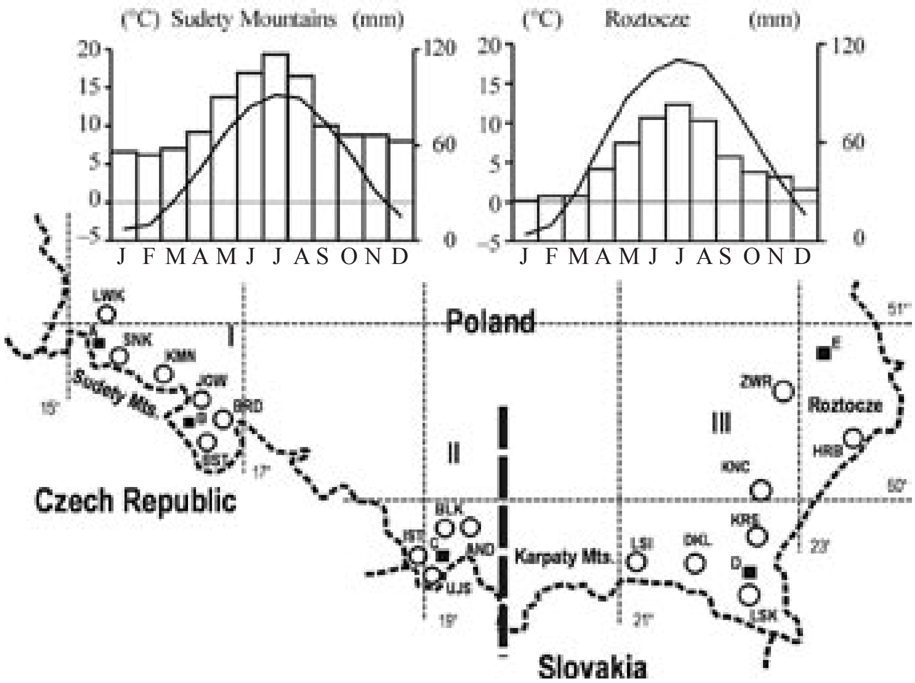

Fig. 1. Map of southern Poland: location of the study sites (circles) and meteorological stations (squares). The dashed line separates the western and eastern areas as shown in Fig. 4. The regions are indicated by Roman numerals (I, II, III). Climatic diagrams: monthly total precipitation (bars), mean monthly air temperatures (line)

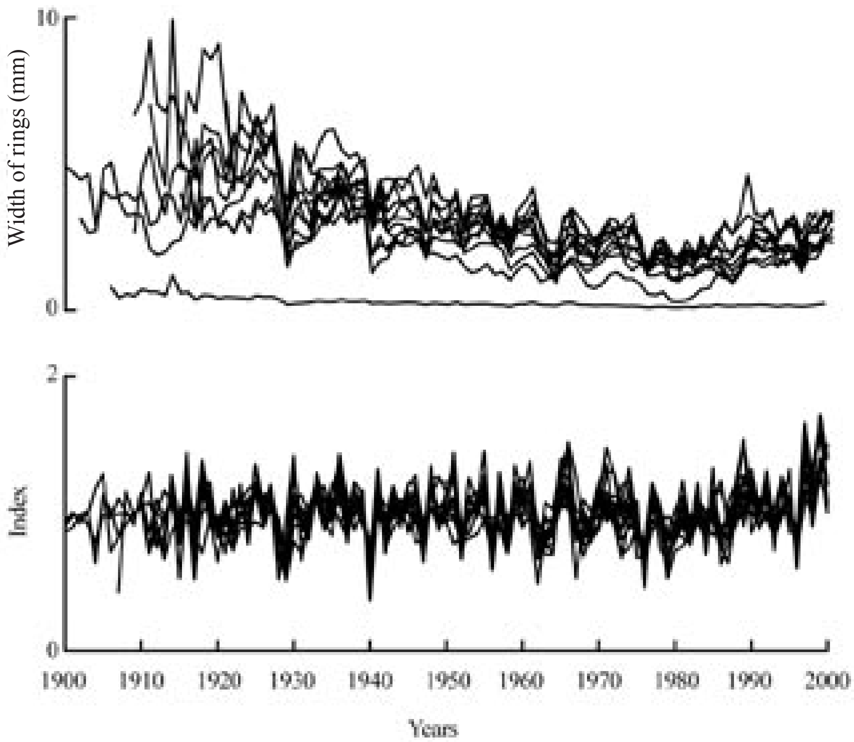

Fig. 2. Tree-ring chronologies of the 17 study sites: tree-ring widths (top) and tree-ring indices (bottom)

ern Beskids Mountains (Region II). The third comprises chronologies from sites located in the Eastern Beskids Mts. and Roztocze (Region III) (Fig. 4). Douglas fir sites are grouped according to geographic location along the latitude parallel.

The first principal component integrates chronologies and explains 64% of their total variability, while the second one accounts for only 8% of the variability and it diversifies chronologies into the three groups mentioned above. The first principal component indicates a strong correlation with the values of tree-ring widths formed in the years with extreme winter conditions, particularly in February and March (frosty winters – negative correlation; mild winters – positive correlations). The second principal component correlates with tree-ring widths formed in the years abundant in rainfall during the vegetation season (positive correlation) or in the years with small amounts of rainfall (negative correlation). Both principal components describe 72% of common variability of chronologies.

The results of PCA (Fig. 4) and the high values of coefficients of convergence (GL) (Fig. 3) between chronologies from a given group authorized us to create three regional index chronologies which illustrate the variability of tree-ring width of Douglas firs from the Sudetes Mts., Western Beskids Mts. and Eastern Beskids Mts. and Roztocze (Fig. 5). These chronologies became the basis for the response function procedures which analyze the influence of thermal and pluvial conditions on the size of radial increments.

The results of response function indicate that the main factor influencing the size of Douglas fir increments was thermal conditions of winter for all regions. Low tempera-

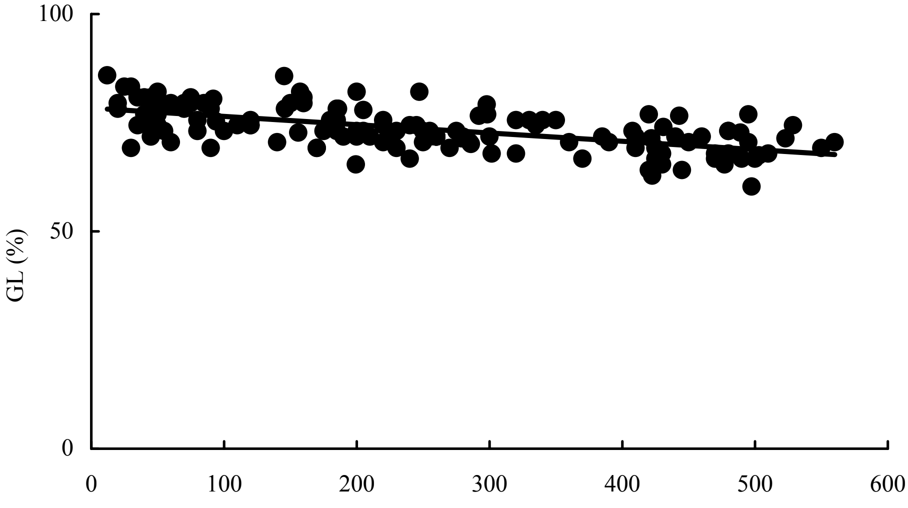

Fig. 3. Coefficient of convergence between seventeen site tree-ring chronologies for the common interval from 1920 to 1998

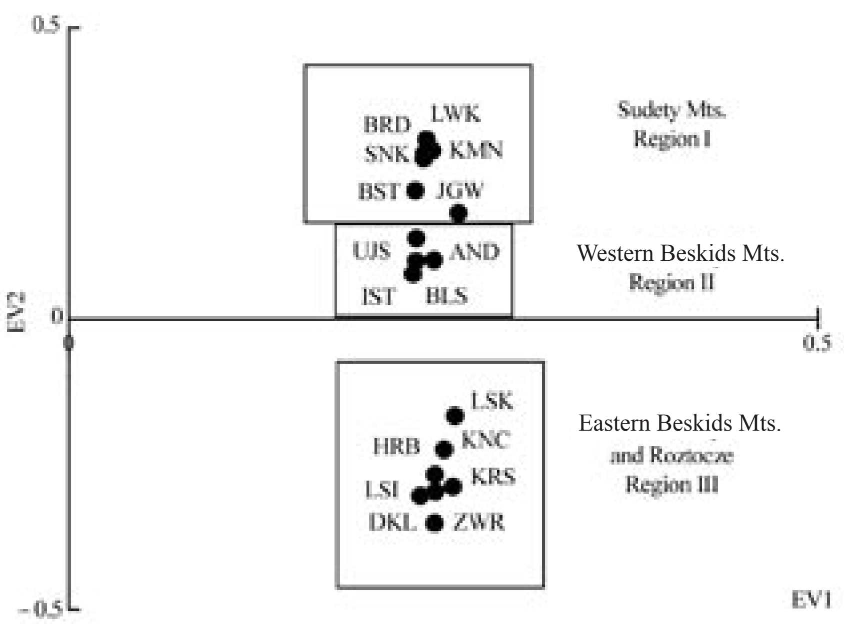

Fig. 4. Principal components analysis: dispersion of chronologies with regard to the first (EV1) and the second (EV2) eigenvectors

tures of January and particularly those of February and March negatively influenced the cambial activity of trees in the upcoming vegetation season (Fig. 6). Increment reactions of the analyzed trees were also connected with the thermal conditions of summer (July, August). Douglas firs growing in the area of the Sudetes and Western Beskids formed large tree-rings during warmer summers. For firs from the Eastern Beskids and Roztocze, thermal conditions of warmer, more continental summer were probably optimal and were not reflected in the increment sizes. However, abnormally high temperatures of May in this region had a negative impact on tree-ring sizes (Fig. 6). Apart from the thermal conditions, radial increments of Douglas firs were also significantly influenced by pluvial conditions. In particular regions, the requirements of trees in regard to amounts of rainfall in subsequent months were very diversified. However, larger than normal amounts of summer rainfall had a significant positive impact on the production of wood cells everywhere (Fig. 6).

The role and significance of thermal and pluvial conditions in tree-ring width of trees is a consequence of geographic location of the regions in terms of longitude. In Poland, an increase in this parameter means an increase in climate continentality. The Sudetes Mts., which are located in the West (15°–17° λE), are under a strong influence of oceanic air masses. In this region, winters are usually milder and summers are colder and more rainy than in the Eastern part of the Carpathians and Roztocze (21°–24° λE) (Fig. 1).

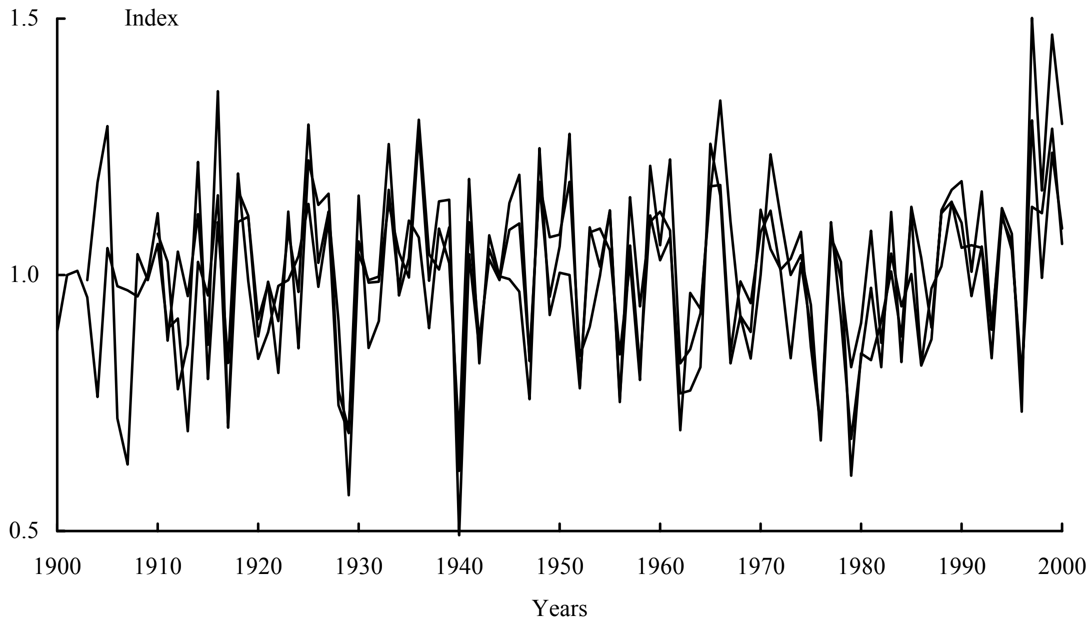

Fig. 5. Regional indexed chronologies

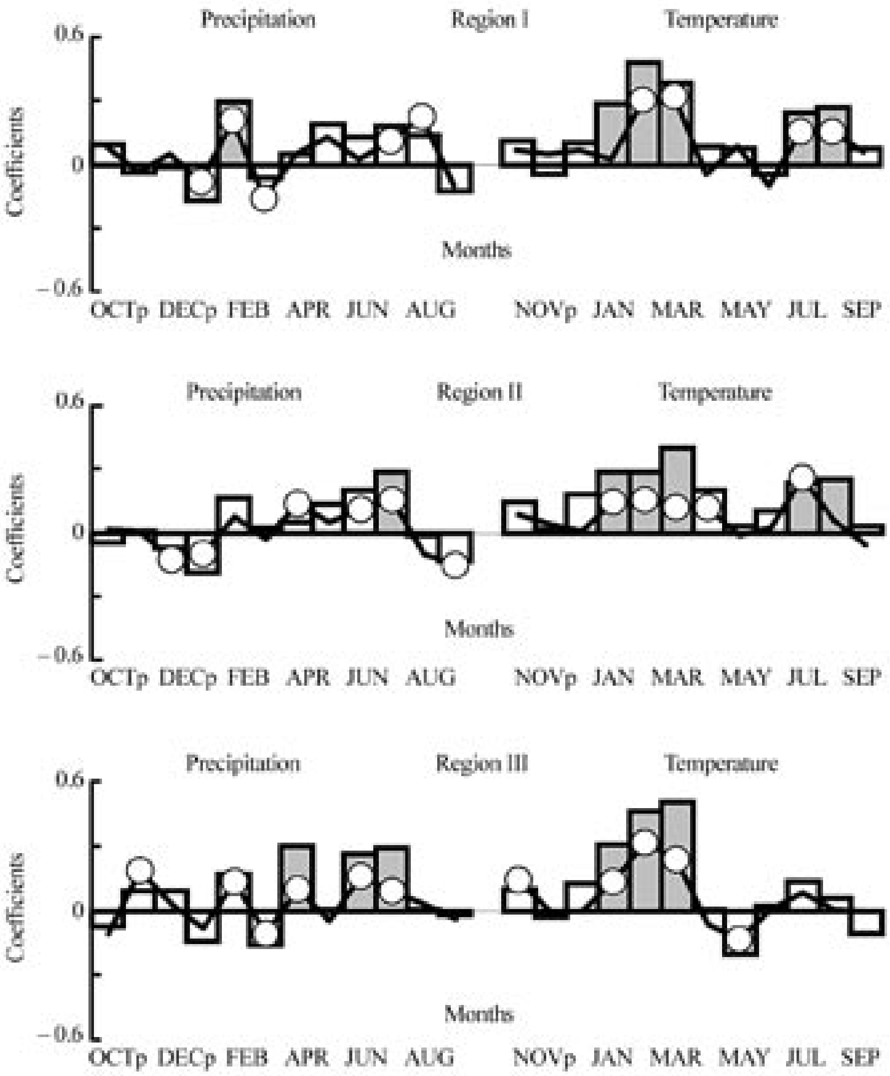

Fig. 6. Response functions and simple correlations of radial increments in Douglas fir. Coefficients of correlation – bars; significant values ($P \leq 0.05$) – solid bars. Coefficients of multiple regression – line; significant values ($P \leq 0.05$) – open circles. Previous year – *p*

The values of convergence coefficients that increase along the geographic parallel illustrate the increasing (from west to east) pressure of thermal conditions of winter and pluvial conditions of summer on the process of xylem cell formation (Fig. 7). There is a visible trend of the relationship between the fir increments and the increasingly continental features of climate in the eastern direction in the case of summer temperatures. The positive influence of warmer temperatures of July and August on radial increments decreases in the eastern direction. The impact is smallest in the region of the Western Beskids (Fig. 7). This fact seems to be climatologically justified since the Western Beskids are a climatically distinct area, particularly in the spring-summer period when the warm and humid masses of tropical-ocean air reach the region through the Moravian Gate (ROMER 1962). It decreases the role of the meteorological factor on the life processes of trees in that region. This fact seems to be confirmed by the values of coefficients of determination (Fig. 8). The negative role of the analyzed climatological factors was smallest in Douglas firs from the Western Beskids Mts. for the factors influencing the process of xylem cell formation in Douglas firs in the Western Beskids, the role of temperature and rainfall accounted for only 39%. In the case of firs from the Sudetes Mts. and the Eastern Beskids Mts. and Roztocze, it was 56% and 53% respectively. As the values of coefficients of determination indicate, thermal conditions were the main climatic element that determined the variability of radial increment sizes. On the other hand, rainfall influenced the chronologies to a smaller extent (Fig. 8).

CONCLUSIONS

The main factors that influenced the process of radial increment formation in Douglas firs from the Sudetes, the Carpathians and Roztocze were the thermal conditions of winters (February, March) that preceded the vegetation season and the thermal and pluvial conditions of summers (June–August).

The significance of the above-mentioned factors for the process of xylem cell formation depended on the geographical location of the sites in terms of longitude. The influence of winter temperatures and summer rainfall on the increment increases in the eastern direction, as the

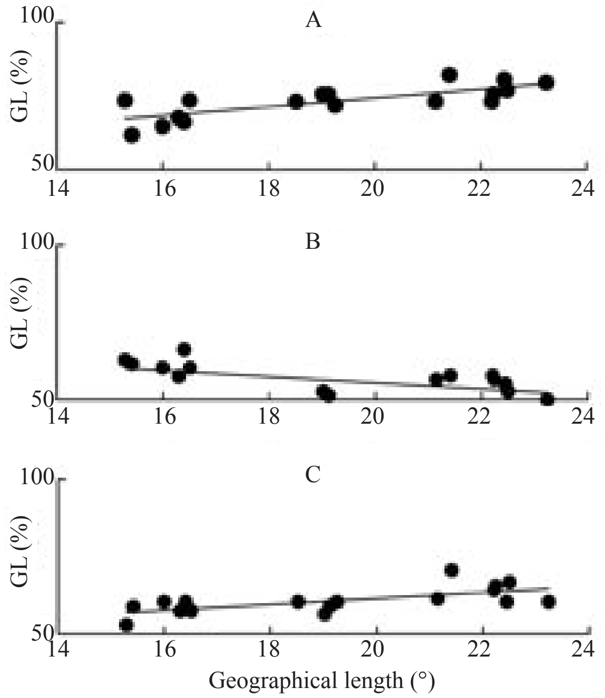

Fig. 7. Coefficient of convergence plot: between the tree-ring chronologies and mean air temperature of the period January – March (A), July – August (B), and between the tree-ring chronologies and rainfall totals of the period May – August (C)

climate becomes more and more continental. On the other hand, the role of summer thermal conditions decreases.

Despite these differences, the rhythm of annual changes in tree-ring width of Douglas fir from the Sudetes, the Carpathians and Roztocze is highly similar. Therefore the region of southern Poland can be considered as dendrochronologically homogeneous for this species. However, we can distinguish two areas (Eastern and Western) that are dendroclimatologically homogeneous.

SUMMARY

This dendroclimatological research concerned Douglas fir (*P. menziesii*) in 17 stands located in the area of the Sudetes Mountains, Polish Carpathians and Roztocze (Fig. 1). The values of coefficients of convergence (Fig. 3) allowed the researchers to determine a high and statistically significant level of similarity between site tree-ring chronologies (Fig. 2) of the analyzed trees. The principal components analysis of site chronologies isolated three groups of sites (Fig. 4). One group was composed of the chronologies of Sudetes firs, the second of the chronologies of trees from the Western Beskids while the third group comprised the chronologies of firs from the Eastern Beskids Mts. and Roztocze. The regional tree-ring chronologies created for these three groups (Fig. 5) underwent dendroclimatological analyses with the use of *response function* and method of convergence. The researchers found out that the main factor that determined the annual variability in the sizes of radial increments was the thermal conditions of winters preceding vegetation seasons (Fig. 6). This factor integrated the chronologies of individual sites (Fig. 4). Incremental reactions of the analyzed trees were influenced by temperatures and rainfall of summer months to a smaller extent (Fig. 6). The role and significance of thermal and pluvial conditions in the process of xylem cell formation in Douglas firs clearly changed as the changes in longitude occurred. As the climate became more and more continental, the impact of winter temperatures and summer rainfall on increments increased while the role of summer temperatures decreased (Fig. 7). The weakest reaction to summer temperatures and precipitation was displayed by Douglas firs from the Western Beskids (Fig. 8). The area of southern Poland can be considered as dendrochronologically homogeneous for Douglas fir. However, we can distinguish two regions (Eastern and Western) that are homogeneous in terms of dendroclimatological conditions.

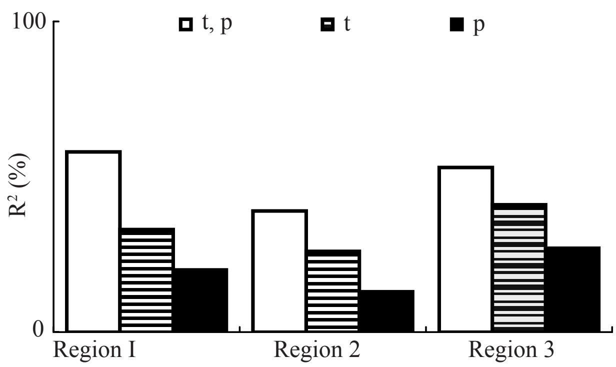

Fig. 8. Coefficients of determination (R^2) for multiple regression with temperature and precipitation – *t*, *p* (white bars), temperature only – *t* (shaded bars), precipitation only – *p* (black bars)

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Received for publication July 22, 2003
Accepted after corrections September 25, 2003

Diverzifikace přírůstových reakcí douglasky tisolisté (*Pseudotsuga menziesii* Franco) z horských oblastí jižního Polska

E. Feliksik, S. Wilczyński

Zemědělská univerzita, Lesnická fakulta, oddělení lesnické klimatologie, Krakow, Polsko

ABSTRAKT: Dendroklimatologický výzkum prezentovaný v článku se týká douglasky tisolisté (*P. menziesii*) na 17 lokalitách v oblasti Sudetských pohoří, polské části Karpat a Roztocze. Metody analýzy hlavních komponentů, response funkce a koeficientů konvergence umožnily určit, že faktor, který integruje chronologie a determinuje roční rytmus změn tloušťkového přírůstu zkoumaných stromů, jsou teplotní podmínky v zimě předcházející vegetačnímu období registrované změny. Teplotní podmínky ve vegetačním období a letní úhrn srážek ovlivnily tloušťkový přírůst v menší míře. Vliv teplotních a vláhových poměrů na proces tvorby xylémových buněk se měnil v závislosti na zeměpisné délce. Tlak zimních teplot a letních srážek se zvyšoval s růstem stupně kontinentality klimatu a naopak vliv letních teplot se snižoval. Přes tyto rozdíly byl rytmus ročních změn v tloušťce letokruhů douglasky ze Sudet, Karpat a Roztocze velmi podobný. Pro tuto dřevinu může být jižní Polsko pokládáno za dendrochronologicky homogenní. Z dendroklimatologického hlediska však lze vylišit dvě homogenní oblasti.

Klíčová slova: douglaska tisolistá; dendroklimatologie; letokruhy

Tento dendroklimatologický výzkum se týká douglasky tisolisté (*P. menziesii*) na 17 lokalitách v oblasti Sudetských pohoří, polské části Karpat a Roztocze (obr. 1). Hodnoty koeficientů konvergence (obr. 3) umožnily určit vysoký a statisticky významný stupeň podobnosti mezi lokálními chronologiemi letokruhů analyzovaných stromů (obr. 2). Analýzou hlavních komponentů byly vylišeny tři skupiny stanovišť (obr. 4). První skupina se skládala z chronologií sudetských douglasek, druhá z chronologií stromů ze západních Beskyd a třetí skupina zahrnovala chronologie douglasek z východních Beskyd a Roztocze. Regionální chronologie letokruhů vytvořené pro tyto tři skupiny (obr. 5) byly vyhodnoceny dendroklimatologickou analýzou s použitím response funkcí a metodou konvergence. Bylo zjištěno, že hlavním faktorem determinujícím roční variabilitu tloušťkového přírůstu byly teplotní podmínky v zimě předcházející analyzovanému vegetačnímu období (obr. 6). Tento faktor integroval chronologie z jednotlivých stanovišť (obr. 4). Přírůstové reakce analyzovaných stromů byly v menší míře ovlivněny také teplotou a srážkami v letních měsících (obr. 6). Vliv a význam teplotních a vláhových poměrů na proces tvorby xylémových buněk se měnil v závislosti na zeměpisné délce. Jak se klima stávalo více a více kontinentální, vliv zimních teplot a letních srážek na přírůst se zvyšoval a naopak vliv letních teplot se snižoval (obr. 7). Nejmenší reakce na letní teplotu a srážky byla zjištěna u douglasek ze západních Beskyd (obr. 8). Oblast jižního Polska může být pro douglasku tisolistou pokládána za dendrochronologicky homogenní. Z dendroklimatologického hlediska však lze vylišit dvě homogenní oblasti (východní a západní).

Corresponding author:

Dr. Sławomir Wilczyński, Agricultural University, Faculty of Forestry, Department of Forest Climatology, al. 29-Listopada 46, 31-425 Cracow, Poland
tel.: + 4812 411 91 44, fax: + 4812 411 97 15, e-mail: rlwilczy@cyf-kr.edu.pl