Regional analysis of climate change impact on Norway spruce (*Picea abies* L. Karst.) growth in Slovak mountain forests

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ABSTRACT: The paper presents the results of a regional analysis of climate change impacts on Norway spruce growth in the north-western part of Slovakia (Orava region). Radial increment was determined from nine X-tree sample plots established in the forests of natural character in the region. The analysis of PTT radial increment was done on tree disks cut from a height of 1.3 m by measurements of four perpendicular directions corresponding to the cardinal points. It was derived from the tree-ring width measured at breast height (1.3 m) while all the basic principles of tree-ring analyses were observed (transport and borehole treatment, measurements with digital positiometer to the nearest 0.01 mm, synchronisation of the tree-ring diagrams). A dendroclimatic model belongs to the category of empirical models based on the statistical evaluation of empirically derived dependences between the time series of tree-ring parameters and the monthly climatic characteristics. This statistical evaluation is based on a multiple linear regression model. Climatic models were used as basic tools for climatic change prediction. There is a scenario coming from the GCM category, which is derived from the models of Canadian Centre for Climate Modelling and Analysis in Victoria (British Columbia, Canada), used for a solution of this task. It is the latest connected model from the second generation designated CCCM 2000. For the purpose of this study the area averages were modified for the meteorological station Oravská Polhora with the 1951–1980 reference period. The modification includes two climatic characteristics, total monthly precipitation and monthly temperature means. The frequency analysis indicates that 24.4% of trees would react to the assumed climatic change negatively, i.e. by decreasing the increment, and 75.6% of trees would react positively. Most of the reactions are moderately positive. It is to conclude that 14.6% of trees will react to a climatic change significantly in a negative way, the reactions of 34.1% trees are considered to be unchanged and 51.3% of trees should react to the assumed climatic change positively ($P = 0.95$). It results from the analysis of the climatic change impact that the highest effect on stands situated on the upper forest limit can be expected.

Keywords: climate change impact; tree ring; radial increment; dendroclimatology; Norway spruce

The potential impact of climate change on forest ecosystems is of great interest in Slovakia due to a large proportion of forest area (41%). Basically the first works in the field of forestry in Slovakia reporting on possible impacts of global climatic changes in this sector indicated the wide spectrum of these impacts (Minďáš, Škvarenina 1994). One of the most serious impacts should occur in the form of changes in the process of tree growth. So one task in the framework of the solution to National Climate Programme of the Slovak Republic was aimed at the quantification of these changes in the most endangered regions of the Slovak Republic (Minďáš, Škvarenina 1996).

Recently growth-yield analyses indicated a forcing of the growth process of forest trees on a regional level in many parts of Europe, and in general it is to state that the increment in our forests increased (Spiecker et al. 1996; Kauppi et al. 1992). This fact is supposed to be mainly a result of increased nitrogen inputs and climate change leading to the growing season extension. On the other hand, there are also regions where the pollution load causes a decrease of growth intensity and a decomposition of forest ecosystems (Pretzsch 1999). The combination of both these effects may bring about different increment situations which complicate research in the field of forest growth and the interpretation of the present growth-yield process.

A different set of models has been developed to study the potential effects of climatic changes on forests. There are several types of models applied to study climate impacts on forest ecosystems which are based on different approaches: climate-vegetation classification approach (e.g. Lenihan, Neilson 1995), stochastic physiological approach (e.g. Bugmann 2001), and statistical dendrochronological approach (Ďurský 1995; Fritts 1976). The last mentioned approach was used for our analyses due to a possibility of quantification of tree growth changes.

The main goals of this paper were defined as follows:

- Construction of a dendroclimatic model of Norway spruce growth based on historical climate data and tree-ring analyses taken from mountain forests in the Orava region (northern part of Slovakia);
- Analysis of possible growth reactions of Norway spruce to specified scenarios of climate change according to model CCCM 2000 in the Orava region;
- Evaluation of growth reactions to scenarios of the time series of monthly climate data especially air temperature and total precipitation till 2090;
- Analysis of possible growth increment changes dependent on varied absolute altitude.

METHODOLOGY

Radial increment

Radial increment was determined on nine X-tree sample plots established in the forests of natural character in the region (Table 1). Plot selection enabled to cover all the site conditions in the Horná Orava Mountains at different absolute altitudes.

X-tree sample plot consists of a variable number of trees which are divided into primary target trees (PTT), secondary target trees (STT) and trees representing primary competitors (PC) to target trees. Primary target tree (PTT) also satisfies and corresponds to particular selection criteria and conditions. Secondary target tree (STT) is directly in the neighbourhood of PTT as its primary competitor and it itself is a subject of the same process of observation as PTT. Their definitions and measurements are necessary because of the effective plot establishment. Primary competitors (PC) directly influence the growth of target trees. There are influences in the aboveground and underground growth space. This selection design makes it possible to detail the growth process of each individual tree in different natural and site conditions and also to research their relationships and the resulting influence on their growth process.

Each PTT and PC position was fixed through the polar coordinates, dendrometric stem and crown parameters were measured and a detailed analysis of site conditions was done on each X-tree sample plot. Primary target tree had to be cut for a complete stem and crown analysis done later. The analysis of PTT radial increment was carried out on a tree disk cut from a 1.3 m height by measurement of four perpendicular directions corresponding to the cardinal points. Radial increment of STT was determined by a borehole method with increment borer. It was derived from a tree-ring width measured at breast height (1.3 m) while all the basic principles of tree-ring analyses were observed (transport and borehole treatment, measurement with digital positiometer to the nearest 0.01 mm, synchronisation of tree-ring diagrams).

Finally 41 tree-ring diagrams were analysed which cover site conditions in the range of 900 m to 1,430 m of absolute altitude in the Horná Orava Mountains.

Table 1. Basic characteristics of X-tree sample plots in the Pilsko and Babia Hora region

No.	*n*	Altitude (m a.s.l.)	Exposure	Stand density	Slope (°)
OR 1	3	1,370	W	0.5	25
OR 2	6	1,270	W	0.7	27
OR 3	4	1,320	W	0.3	15
OR 4	5	1,360	W	0.5	10
OR 5	4	1,480	SW	0.3	6
OR 6	2	1,430	SW	0.1	10
OR 7	6	1,200	SW	0.2	20
OR 8	6	1,000	S	0.8	25
OR 9	5	900	SW	0.8	16

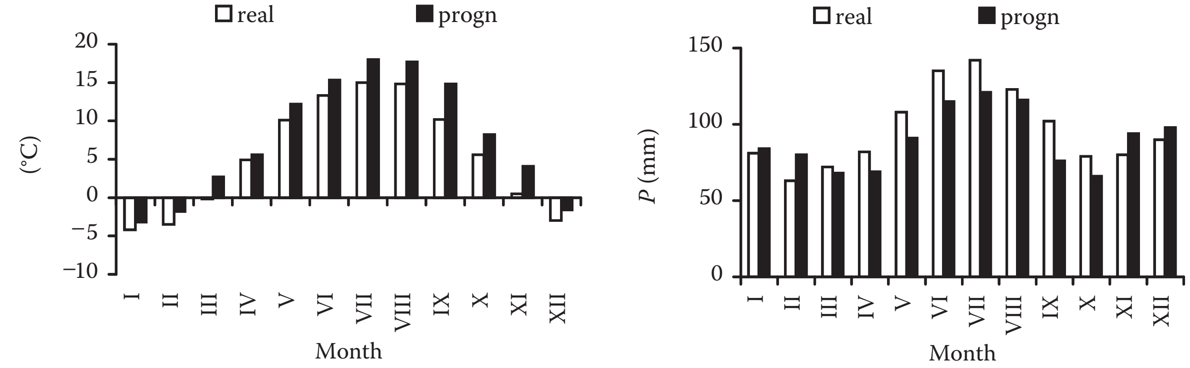

Fig. 1. The annual course of present and prognosed monthly temperature means and monthly precipitation means

Climatic scenario

Climatic models were used as basic tools for climatic change prediction. These models take into consideration all the elements of climatic system including radiation balance. This radiation balance is influenced by a change in GHG concentration. Nowadays connected General Circulation Models (GCMs) simulate the present climatic state with sufficient accuracy. Models are truest on a global level. Their accuracy decreases on a region level.

There is a scenario coming from the GCM category which is derived from the models of Canadian Centre for Climate Modelling and Analysis in Victoria (British Columbia, Canada), used to solve this task. It is the latest connected model from the second generation designated CCCM 2000. This model was presented in short on the Internet in 2000 and one year later in literature (Flato, Boer 2001). The model assumes a gradual increase in active radiative gases (GHGs) in the atmosphere corresponding to observations done in the time period 1850–1996, i.e. an increase by 1% per year till 2100. The model expects direct impacts of sulphate aerosols on the albedo of the earth surface. This new generation of models is characterised by its interactive connection of all the climatic variables, which ensures a physical consistence of prognosis. This physical consistence can be disturbed during the regional modification, so finally we can solve it either analytically or by a statistical analysis (Lapin et al. 2001).

GCM outputs do not represent a real climate at a concrete point. But certainly we can expect them to represent the area averages of climatic variables of 60–100 thousand square kilometres in the space of grid points, a double area of Slovakia. In addition it is the space of mellow orography without any existing local windward and leeward effects. It is necessary

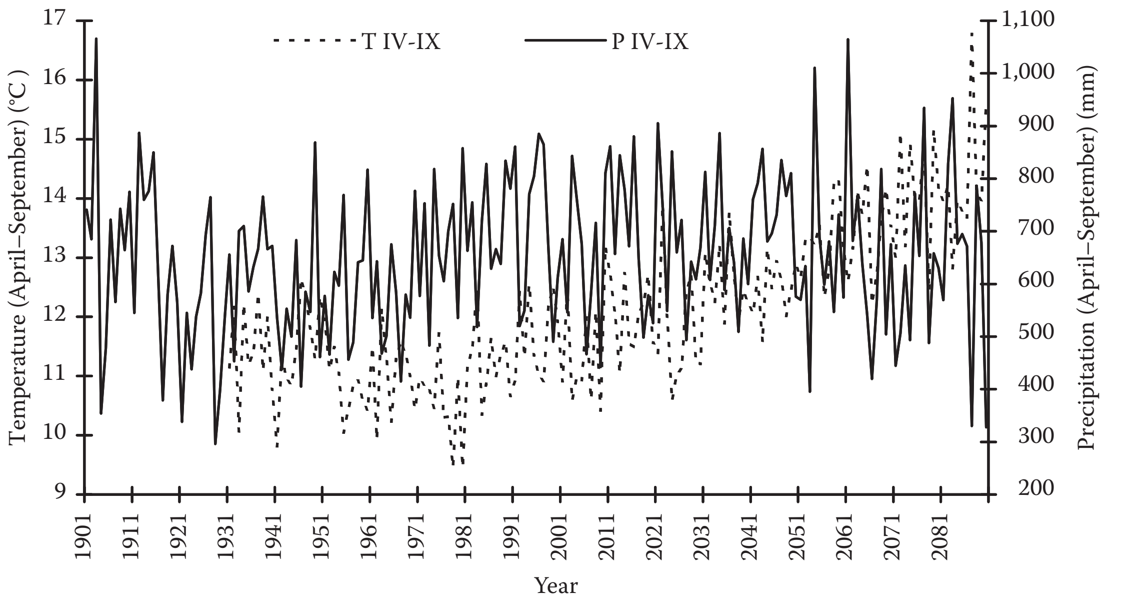

Fig. 2. Climatic conditions in Oravská Polhora (precipitation means since 1901, temperature means since 1931) and temperature and precipitation according to CCCM 2000 model till 2090 in the growing season (Lapin et al. 2001)

to find out a relationship between the time data on the area averages of climatic variables and the time series of each station to acquire the time data of each station during the modification of GCM outputs and consequently to modify the area averages of climatic variables. For the purpose of this study the area averages were modified for the meteorological station Oravská Polhora with the 1951–1980 reference period. The modification included two climatic characteristics, total monthly precipitation and monthly temperature means. The team of Lapin, Melo and Damborská did this modification as a part of the project solution of National climatic programme in 2001.

The climatic scenario expects an increase in temperature means by 2.4°C compared to the reference period (in the vegetation season on average by 2.6°C) on a service area in the 2060–2090 period. The precipitation level is expected to decrease by 7% with its change in year distribution and variability. In the vegetation season this level will decrease by 16%, but noticeable is the increase in winter precipitation.

Construction of dendroclimatic model

A dendroclimatic model belongs to the category of empirical models based on the statistical evaluation of empirically derived dependences between the time series of tree-ring parameters and the monthly climatic characteristics. This statistical evaluation is based on a multiple linear regression model (Fritts 1976; Cook, Kairiukštis 1990):

$$\hat{y}_i = \sum_{k=0}^{K} x_{i,k} \times \beta_k + a + \varepsilon_i \qquad (1)$$

where: $\hat{y}_i$ – the estimation of the tree-ring parameter value,
$x_{i,k}$ – the independent variable representing climatic characteristics per month in i-th year,
β_k – the coefficient of regression,
a – the constant,
ε_i – the residual after regression estimation.

This dendroclimatic model was constructed as an individual-tree model serving for the entry of the independent variables such as standardised average monthly temperature and monthly precipitation means from July of the year prior to growth to August of the year of growth, providing a total of 28 climatic variables. An advantage of this process is that we do not have to know physiological processes which are related with a growth reaction to estimate the growth process dependent on climatic factors with a high level of accuracy. The result is that we are not able to record growth reactions on the cell level, but we can evaluate only the summary processes, for example the tree-ring width. The dendrochronological series was represented by relativised (after indexation) and standardised values of dated radial increments from each tree.

The influence of age trend on an increment amount had to be eliminated by indexation to satisfy one of the important conditions for dendroclimatic modelling – stationarity of time series. The age trend was mathematically predicted by a defined growth function describing the process of radial increment in connection with age (Šmelko 2000). This operation removes the site influence on absolute values of increment. Tree-ring width index was obtained from the relation:

$$I_t = \frac{y_t}{\bar{y}_t} \qquad (2)$$

where: I_t – the index of radial increment,
y_t – the real increment,
$\bar{y}_t$ – the equal value corresponding to age trend.

Parametrisation of the model, i.e. determination of the vector of regression coefficients, was done in the 1932–2000 period. It is assumed that this time period existed without any influences related with global change in the atmosphere on the growth process of forest trees. The prognosis was performed for a climatic scenario of monthly temperatures and monthly precipitation means for each analysed tree in the 2001–2090 period.

EXPERIMENTAL REGION DESCRIPTION

Natural and climatic conditions

This area is situated in the external part of the West Carpathian Mountains (Fig. 3). It belongs to the external flysch zone of the Carpathian Mountains. There are zones of parallel mountains separated by long washout-denudative furrows and only a few typical folds. This arrangement of flysch zones northerly from the klippen zone is a result of different rock resistance. Flysch rocks containing mainly sandstone create mostly monticules and contrariwise regions of clayey evolution create depressions. From the view of hypsometric classification the mountains in the service area belong to the category of middle highlands (800–1,500 m). The tops of Pilsko and Babia Hora rise above the upper forest limit and can be assigned to the category of high highlands.

From the climatic point of view this area is situated in the temperate climatic zone with temperate Central-European climate. In the growing season the mean air temperature (season IV–IX) varies on

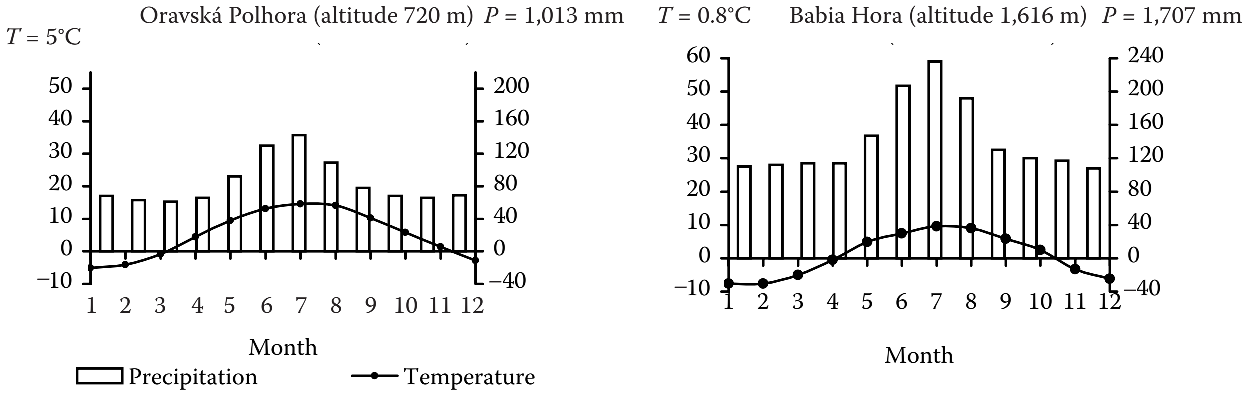

Fig. 3. Climate diagrams of two meteorological stations in the Orava region

average from 8 to 12°C. The number of days with air temperatures higher than 10°C is from 30 to 100 days on sample plots. Total precipitation means amount to 1,200–1,600 mm per year. The majority of rains occur in the growing season. February is the poorest month in this precipitation. Snow cover generally occurs from 170 to 210 days and it rapidly increases with the ascending absolute altitude. Its maximum height is on average 120–160 cm. A graphical representation of varying climatic rates in Horná Orava is presented in Fig. 3 in a climate diagram for two meteorological stations.

Description of forest stands

The territory of Horná Orava mountain forests belongs to the Forest Management Unit Oravská Polhora with the area of 7,943 ha. The percentage of woodland is 64.4. All the forests of this management unit are assigned to the category of special-purpose forests. Coniferous species dominate in the total species composition (90.3%), primarily Norway spruce (83%). Beech (*Fagus sylvatica*) is the most frequent species out of the broadleaves (7.5%). In connection with tree species evolution there is a tendency of increasing the portion of broadleaves in this region. Average stand density in the Forest Management Unit has been in the range of 0.80–0.85 for several decades. There is a remarkable tendency of its decrease according to age classes of its structure. It follows from a comparison of the areas of each age class that this age structure is very different from "normal age class distribution". A clear deficit of stands in age class 3, 4 and 6 is characteristic and contrariwise a surplus of stands in age class 1 and 2. An even-aged silvicultural system was the most frequently used silvicultural system in the past. Shelterwood system was applied to a lesser extent, which resulted in a small portion of forest natural reproduction. In the past tending felling was mostly realised by moderate thinning from above.

RESULTS AND DISCUSSION

Course of prognosed increment

An expectation increment index was calculated for each individual tree from the constructed dendroclimatic model and climate scenario for the time period 2001–2090. The average values of prognosed rela-

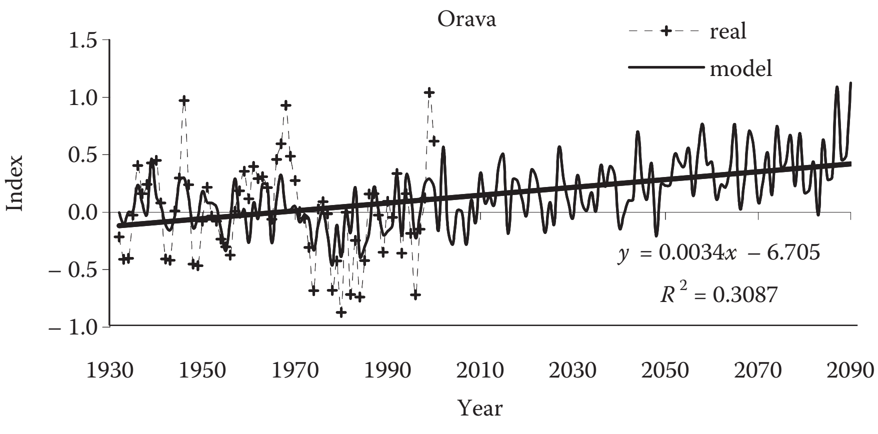

Fig. 4. The course of prognosed mean relative increments for the Horná Orava Mountains

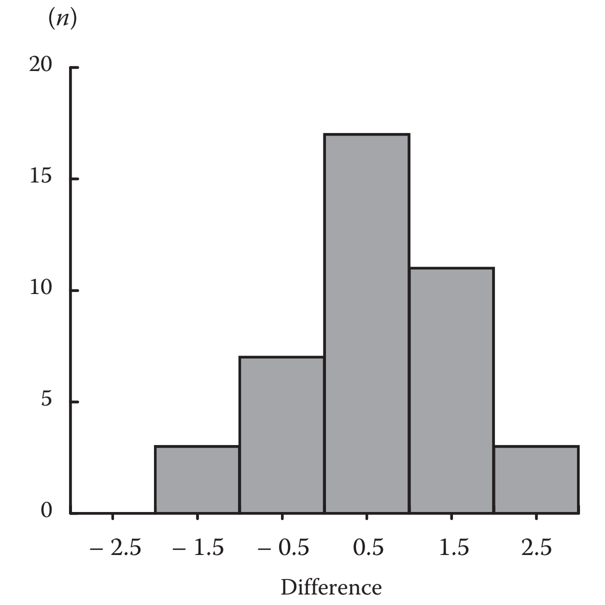

Fig. 5. A frequency histogram of relative differences in the increment indices

tive increment were calculated using the predicted prognoses of each tree for each plot and service area (Fig. 4).

It is expected that the increment trend will grow in future. We can explain it through the increasing temperature in these mountain conditions which changes tree growth conditions to be closer to their ecological optimum which causes more intensive growth.

Quantification of increment changes

The differences in standardised increment indices (DIF_{rel}) were calculated using the prognosed increment from the 2060–2090 period (I_{prog}) and the average increment related to the 1970–2000 reference period (I_{ref}):

$$DIF_{rel} = (I_{prog} - I_{ref}) \quad (3)$$

These differences represent growth reactions to the assumed climatic change. Their frequency analysis is shown in Fig. 5.

This frequency analysis indicates that 24.4% of trees would react to the assumed climatic change negatively, i.e. by decreasing the increment, and 75.6% of trees would react positively. Most of the reactions are moderately positive. 41.5% of all sample trees would react in this way. As natural variability of increment reactions is in the reference time $s_x = 0.22$, we can certainly consider the beginning of considerable reactions to climatic change over the limit of this natural variability. It may be stated that 14.6% of trees will react to climatic change considerably in a negative way, the reactions of 34.1% of trees are considered to be unchanged and 51.3% of trees should react positively to the assumed climatic change ($P = 0.95$).

This result showing the high level of increment reaction variability should not surprise us, but it is necessary to realise that a biological mass (forest tree) is tested coming from different microclimatic and site conditions, differing in genetic origin, age and health. Regarding the forest biometry this statement is sufficiently statistically backed to declare all the growth reactions of spruce to climate change will be mostly positive in the Pilsko and Babia Hora Mountains.

Dependence of increment growth reactions on absolute altitude

In a further step the increment reactions were analysed to test their relationship to absolute altitude in the Pilsko and Babia Hora Mountains. For each sample tree the average indices were calculated for the period 2060–2090 and later these indices were connected with appropriate X-tree sample plots. Consequently, the average value from each X-tree sample plot was obtained to derive relationships between the increment reactions and absolute altitude in the framework of correlation analysis.

Fig. 6 shows that the climatic change is supposed to affect stands situated on the upper forest limit to the largest extent. By the more detailed analysis we

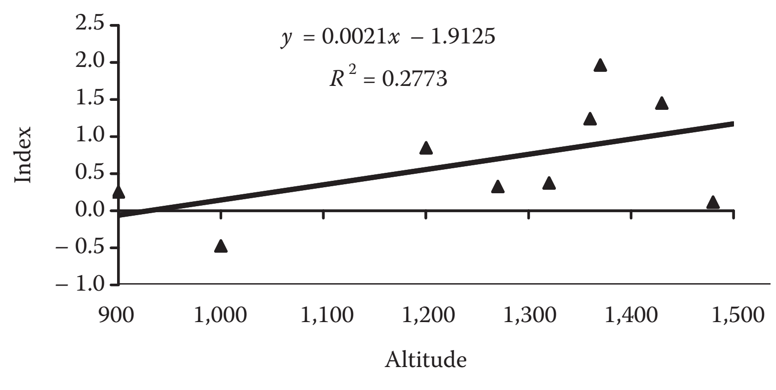

Fig. 6. Dependence of increment on the absolute altitude in changed climatic conditions

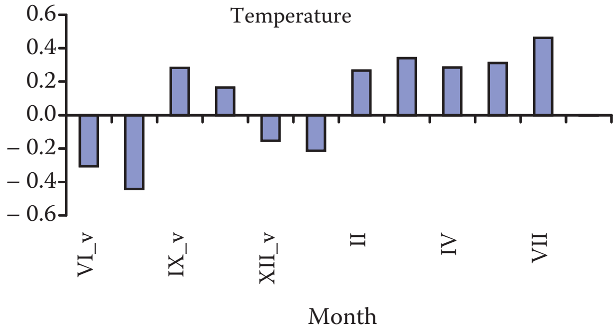

Fig. 7. Standardised partial regression coefficients of monthly temperature influence on growth increment

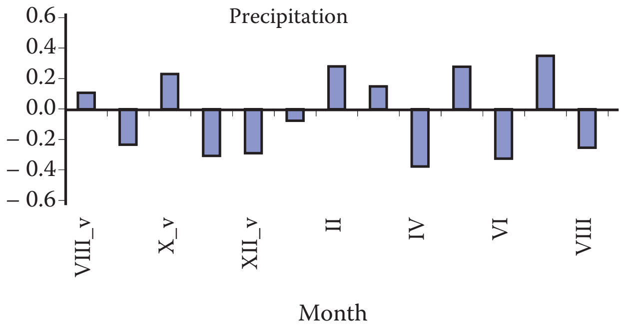

Fig. 8. Standardised partial regression coefficients of monthly precipitation influence on growth increment

can find out that the most limiting factor for spruce growth on these sites seems not to be the soil environment, but roughness and unfavourable climate, mainly low temperatures at the present time. The scenario of future climate development indicates a shifting of the present stands to better bioclimatological conditions because of the increased temperature. The precipitation amount according to the offered scenario of climate change has a tendency of minimal or no decrease characteristic of its remarkable ecological effect on spruce growth in these site conditions. It would not be correct to take this information out from the whole context of impacts on the forest system, which result from the changed chemical status of the atmosphere because the above-mentioned statements consider only the influence of changed temperature and precipitation means. Negatively acting factors (persisting atmospheric deposition, ozone increase in the troposphere, breaking the protective facilities of the atmosphere) did not enter into a dendroclimatological model, therefore the future development of the upper forest limit cannot be prognosed only on the climate change basis.

Dependence of increment growth on climatic factors

The influence of single climatic characteristics on increment was observed by standardised partial coefficients. Figs. 7 and 8 show their average values.

Figs. 7 and 8 confirm the assumed relations which lead to conclusions that spruce increment will react to temperature mostly in a positive way in the Horná Orava region mainly in spring and summer months of the current year. The temperature in the year prior to growth will influence the increment positively. Winter temperatures and temperatures of late summer in a preceding year will affect the increment negatively. Precipitation does not influence the growth in such a way as temperature does, as we can see it from lower values of partial regression coefficients and their variable behaviour.

CONCLUSION

This study offers preliminary results of research on spruce growth reactions to expected climatic changes in the mountain forest area Horná Orava (Pilsko and Babia Hora Mts.). Climatic changes were predicted by CCCM 2000 model on the level of monthly values of air temperature and precipitation till 2091. Materials which were objects of tree-ring analysis were obtained from eight temporary sample plots established especially for this research in the absolute altitude range of 900–1,430 m. Tree-ring series were represented by relative (indexation was carried out) values of measured radial increments of single trees. The dendrochronological model was constructed as an individual-tree model using the method of Fritts (1976). The results of dendrochronological modelling indicated the following findings:

- air temperature will be the most essential factor of growth,
- 14.6% of trees will react to climatic changes negatively, the reaction of 34.1% of trees is supposed not to change and 51.3% of trees will have a positive reaction to climatic changes, at 95% statistical probability,
- the assumed climate change will affect the stands on the upper forest limit at higher absolute altitudes the most intensively.

The carried out analysis of tree growth did not take into consideration other negative factors on forest growth (atmospheric depositions, increasing concentration of ozone in the troposphere, weakening of protective atmospheric properties), only future changes of bioclimatic conditions.

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Analýza regionálnych dopadov zmeny klímy na rast smreka obyčajného (*Picea abies* L. Karst.) v horských lesoch Slovenska

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ABSTRAKT: Práca prezentuje výsledky regionálnej analýzy dopadov zmeny klímy na rastový proces smreka v severozápadnej oblasti Slovenska (Orava). Radiálny prírastok sa skúmal na deviatich skusných plochách, založených v prírode blízkych lesoch. Analýza radiálneho prírastku sa robila na báze odobraných kruhových výrezov z výšky 1,3 m obvyklým metodickým postupom, rešpektujúc základné princípy analýzy letokruhov. Meranie sa vykonalo digitálnym poziciometrom s presnosťou merania 0,01 mm a synchronizáciou letokruhových diagramov. Použitý dendroklimatický model sa radí do kategórie empirických modelov, založených na štatistickom hodnotení empiricky odvodených závislostí medzi časovými sériami parametrov letokruhov a mesačnými klimatickými charakteristikami. Model je postavený na báze štatistického hodnotenia viacnásobnou lineárnou regresiou. Klimatický model sa použil ako základný nástroj pre predpoveď zmeny klímy na báze scenárov GCM (globálne cirkulačné modely), odvodené v Kanadskom centre pre modelovanie klímy a analýzy. Tento model bol regionálne modifikovaný pre územie Slovenska pre mesačné teploty vzduchu a úhrny zrážok. Ako referenčné klimatické obdobie sa zvolil interval 1951–1980 pre meteorologickú stanicu Oravská Polhora. Frekvenčná analýza ukázala, že 24,4 % stromov by reagovalo negatívne na predpokladanú klimatickú zmenu a 75,6 % stromov by reagovalo pozitívne, pričom väčšina z týchto reakcií sú mierne pozitívne. Môžeme povedať, že významne bude reagovať 14,6 % stromov negatívnym prírastkom, 34,1 % stromov bude reagovať bez signifikantnej zmeny a 51,3 % skúmaných stromov vykazuje pozitívnu reakciu na očakávanú zmenu klímy (P = 0,95). Na základe výsledkov priestorovej analýzy môžeme konštatovať, že najvyššia zmena v prírastku sa vyskytuje v oblasti hornej hranice lesa.

Kľúčové slová: dopady zmeny klímy; letokruhová analýza; radiálny prírastok; dendroklimatológia; smrek obyčajný

Rastovo-produkčné analýzy v poslednom období naznačujú, že na regionálnej úrovni v mnohých oblastiach Európy sa rastový proces lesných drevín zintenzívnil a vo všeobecnosti možno konštatovať, že prírastok v našich lesoch sa zvýšil, ako to napr. dokumentujú citované práce (Spiecker et al. 1996; Kauppi et al. 1992). Predpokladá sa, že je to predovšetkým v dôsledku zvýšeného inputu dusíka a v dôsledku klimatických zmien predĺženej dĺžky vegetačného obdobia. Na druhej strane však existujú lokality, kde predovšetkým imisná záťaž spôsobuje, že lesné ekosystémy znižujú intenzitu rastu a rozpadávajú sa (Ďurský 1993; Pretzsch 1999). Kombináciou týchto oboch efektov môžu vznikať rôzne prírastkové situácie, ktoré komplikujú výskum v oblasti rastu lesa a celkovú interpretáciu súčasného rastovo-produkčného procesu.

Štúdia prináša predbežné výsledky výskumu rastových reakcií smreka v podmienkach horských lesov Hornej Oravy (Piľsko a Babia hora) v podmienkach očakávaných klimatických zmien. Klimatické zmeny boli prognózované modelom CCCMprep (Lapin et al. 2001) na úrovni mesačných hodnôt teploty vzduchu a zrážok do roku 2091. Predmetom dendrochronologickej (letokruhovej) analýzy bol empirický materiál z 9 špeciálne pre tento výskum založených temporálnych výskumných plôch vo výškovom rozpätí 900–1 430 m n. m. Dendrochronologický rad predstavovali relativizované (vykonala sa indexácia) hodnoty nameraného radiálneho prírastku jednotlivých stromov na výskumných plochách. Dendroklimatický model bol konštruovaný ako jednotlivo-stromový, pričom bol využitý postup podľa Frittsa (1976).

Z priebehu prognózovaných indexov prírastku vyplýva, že budúci prírastok bude mať stúpajúci trend a že vplyv skúmaných scenárov vývoja klímy (CCCMprep -RR1 a CCCMprep -RR3) na prírastok je skoro rovnaký. Stúpajúci prírastok sa dá vysvetliť tým, že rastúce teploty v týchto horských podmienkach posunú smrek bližšie k jeho ekologickému optimu, čo sa prejaví jeho zvýšenou intenzitou rastu. To, že sa neprejavil rozdiel v intenzite rastu medzi oboma scenármi, vyplýva z toho, že tieto scenáre sa líšia nie v teplotách, ale v rozdielnych zrážkach, ktoré v oblasti horských lesov pre drevinu smrek nemajú limitujúci charakter. Preto sa v ďalšom analyzoval iba jeden z pripravených scenárov (CCCMprep -RR1).

Z frekvenčnej analýzy vyplýva, že 19,2 % stromov by reagovalo na predpokladané klimatické zmeny záporne, t.j. znížením prírastku, a 80,8 % stromov by reagovalo kladne. Z reakcií najviac prevládajú reakcie mierne kladné (do +40 %). Takto by reagovalo asi 46 % všetkých skúmaných stromov. Keďže prirodzená variabilita prírastkových reakcií sa v referenčnom období pri P = 0,95 rovná 24 %, môžeme za signifikantné reakcie na zmenu klímy považovať reakcie nad túto prirodzenú variabilitu. Potom možno konštatovať, že signifikantne negatívne na zmenu klímy bude reagovať 11,5 % stromov, reakcie 34,6 % stromov možno považovať za nezmenené a 53,9 % stromov by malo na predpokladané klimatické zmeny reagovať pozitívne (P = 0,95).

Z výsledkov vyplýva, že predpokladaná zmena klímy najintenzívnejšie ovplyvní porasty na hornej hranici lesa. Ak tento poznatok budeme bližšie analyzovať, zistíme, že už v súčasnosti limitujúcim faktorom rastu smreka v týchto polohách nie je pôdne prostredie, ale drsnosť a nepriaznivosť klímy – predovšetkým nízke teploty. Scenár budúceho vývoja klímy posunie súčasné porasty predovšetkým v súvislosti so zvýšením teploty do lepších bioklimatických podmienok. Zrážky podľa scenára klimatickej zmeny budú mať tendenciu len minimálneho, resp. žiadneho poklesu, čo však v týchto stanovištných podmienkach nebude mať pre drevinu smrek zásadnejší ekologický vplyv.

Nebolo by správne tieto poznatky vytrhnúť z celkového kontextu vplyvov zmien chemizmu atmosféry na lesy, pretože vyššie uvedené konštatovania sú vztiahnuté len na vplyv zmenenej teploty vzduchu a zrážok. Negatívne pôsobiace faktory (pretrvávajúca atmosferická depozícia, zvyšovanie koncentrácie troposferického ozónu, oslabovanie ochranných vlastností atmosféry a i.) nevstupovali do dendroklimatického modelu, preto budúci vývoj hornej hranice lesa nemožno prognózovať iba na základe zmien klímy.

Sumárne výsledky dendroklimatického modelovania ukázali, že:

- budúci prírastok bude mať vo všeobecnosti stúpajúci trend a vplyv skúmaných dvoch modifikácií scenárov vývoja zrážok (CCCMprep -RR1 a CCCMprep -RR3) na prírastok je takmer rovnaký,
- určujúcim faktorom rastového procesu bude teplota vzduchu,
- negatívne na zmenu klímy bude reagovať 11,5 % stromov, reakcie 34,6 % stromov možno považovať za nezmenené a 53,9 % stromov by malo na predpokladané klimatické zmeny reagovať pozitívne, a to všetko pri 95% štatistickej spoľahlivosti,
- predpokladaná zmena klímy najintenzívnejšie ovplyvní porasty na hornej hranici lesa vo vyšších nadmorských výškach.

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