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DENDROCHRONOLOGICAL ANALYSIS AND HABITUAL STRESS DIAGNOSTIC ASSESSMENT OF NORWAY SPRUCE (*PICEA ABIES*) STANDS IN THE DRAHANY HIGHLANDS

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ABSTRACT

The research was conducted in selected spruce stands of the Drahany Highlands aged from 80 to 120 years at altitudes from 490 m a.s.l. to 576 m a.s.l. The regional standard chronology shows an obvious decrease in the radial increment during the first half of the 1990s. After this, there is an increment increase, interrupted in 2000, 2003, and 2004. The years with the lowest radial increment were also confirmed by the analysis of negative pointer years. The diameter increment correlates statistically significantly in a positive way with the precipitation in May and September of the previous year, and May, June, July and August of the year in question. At the same time, it correlates statistically significantly in a positive way with the temperatures in October of the previous year and in a negative way with the temperatures in July, August and September of the previous year and May, June, July and August of the year in question. The total defoliation in the Drahany Highlands ranged slightly above the Czech Republic average. The values of the primary structure defoliation and the percentage of secondary shoots were average and discoloration did not appear in the area.

KEYWORDS: Drahany Highlands, spruce, precipitation, temperature, tree ring, habitual diagnostics.

INTRODUCTION

Today, wood is very frequently used material. Relation between growth ring structure and wood properties was described in many papers e.g. by Gryc et al. (2007), Gryc and Horáček (2007), Vavrčík et al. (2008), Jelonek et al. (2009). The relation between the radial increment of Norway spruce and climatic conditions is a frequent subject of research. At the same time, there is a long series of studies monitoring the health conditions using defoliation as the main factor. The relationship between the climate and the radial increment of spruce in Europe has recently been explored e.g. by Mäkinen et al. (2001, 2002), Feliksik and Wilczyński (2000), Vitas (2004), Koprowski, Zielski (2006), Saava et al. (2006), Büntgen et al. (2007), Pichler and Oberhuber (2007), Rybníček et al. (2009), Čermák et al. (2010), Affolter et al. (2010). The defoliation is used in the ICP Forests, or Forest Focus, LIFE+ (FutMon) and further follow-up or specialized studies (e.g. Solberg and Tørseth 1997; DeVries et al. 2000; Dobbertin and Brang 2001). On the other hand, only few studies use the combination of the indicators to assess the vitality of spruce.

However, it seems that the changes and trends in the defoliation are much less sensitive indicators than it was assumed (DeVries et al. 2000). Therefore, to monitor the state of forest stands and their vitality the need is growing to use new indicators, such as the transformation of the crown structure (Cudlín et al. 2001), or to use a wider range of indicators so that various types of response could be captured. A wider range of indicators makes it possible to use various sensitivity for various situations (various synergies) in which trees appear. For example, the response of the radial increment and the defoliation often appear in different time intervals. In some cases, the first discernible response to a factor (e.g. insects) is the defoliation while the growth response lags behind; in other cases (e.g. extreme droughts), first the decrease in growth appears, while the reduction of needle amount can only be seen several months later.

The aim of the study was to explore the dynamics of the radial increment in the Drahany Highlands (Proklest forest district) in a period of over a hundred years and to identify the growth response to the climate. The data from the tree ring chronology will be related to the data obtained on the health condition of Norway spruce *Picea abies*.

MATERIAL AND METHODS

The research was conducted in selected spruce stands of the Drahany Highlands aged from 80 to 120 years at altitudes from 490 m a.s.l. to 576 m a.s.l. in 2009. In total, 270 samples were taken for the dendrochronological analysis and 180 trees were selected for the habitual diagnostics (Tab. 1).

In the habitual stress diagnostic assessment the following were especially evaluated: the total defoliation, the defoliation of the primary structure, the percentage of secondary shoots, the presence and extent of yellowing and browning, and stem damage (Cudlín et al. 2001).

In a representative number of trees basic habitual characteristics according to Cudlín et al. (2001) were evaluated by means of binoculars. First, the growth habit of a tree was described, namely social position, type of branching, type of the tree top, crown form, the presence of stem, crown and top breaks. Crowns were visually divided into three parts: the upper juvenile part, the central production part and the lower saturation part. In the juvenile part, its form was evaluated (according to a modified method by Lesinski and Landman 1995), in the production part, it was the total defoliation, the defoliation of the primary structure, the percentage of secondary shoots and types of damage (Cudlín et al. 2001). Subsequently, discoloration was assessed, i.e. yellowing and browning – the percentage of the total volume of an assimilatory apparatus with the presence of discoloration (in an interval of 5 %) was estimated. The results of habitual diagnostics were compared with a previous study (Čermák et al. 2005).

Tab. 1: Detailed overview of all areas.

Title of plot		GPS	Altitude (m a.s.l.)	Slope orientation	Slope gradient	Forest vegetation zone	Edaphic category	Age (2010)	Stocking (%)
Ours	**(Čermák et al. 2005)**								
D1	15	49°19´59N; 16°42´43E	490	S 185°	10°	3	trophica	90	90
D2	4	49°19´02N; 16°43´23E	540	NW 300°	5°	4	illimerosa trophica	119	100
D3	6	49°19´09N; 16°44´51E	545	SW 240°	2°	4	illimerosa trophica	107	90
D4	7	49°19,399´N; 16°46,028´E	576	E 110°	2°	4	trophica	94	80
D5	8	49°19,148´N; 16°45,945´E	572	NE 25°	1°	4	mesotrophica	117	100
D6	5	49°18,683´N; 16°46,465´E	500	E 100°	7°	3	illimerosa trophica	121	70
D7	11	49°18,868´N; 16°46,358´E	505	NW 330°	5°	4	trophica	96	110
D8	9	49°19,053´N; 16°46,190´E	523	SW 230°	5°	4	mesotrophica	86	90
D9	11	49°18,604´N; 16°47,157´E	564	x	0°	4	mesotrophica	89	90

Dendrochronological samples were taken and processed in correspondence with the standard methodology (Cook and Kairiukstis 1990). The samples were taken by means of the Pressler borer. Bore holes were done at 1.3 m above the ground. The samples were taken along the contour line so that the increment was not influenced by the presence of compression wood. At each of the plots, 30 samples were taken for the dendrochronological analysis (in total 270 samples), one sample taken from one tree. The samples were fixed into wooden slats and their surface was ground off. The wood samples were then measured using a specialized measuring table equipped with an adjustable screw device and an impulsemeter recording the interval of the table top shifting and in this way also the tree ring width. The measuring and the synchronization of tree-ring sequences were carried out using the PAST4 (©Sciem) software. The annual wood increments were measured with 0.01 mm accuracy.

After measuring, individual measured curves were compared (cross-dated). The cross-dating is a method for finding the synchronous positions of two tree-ring series. Both series are compared in all possible mutual positions. The aim is to identify the tree rings in each sample created in the same year. If there is a synchronous position, it is demonstrated by a sufficiently high similarity in the area where they overlap (Cook and Kairiukstis 1990). The excellently correlating curves were used to create the average tree-ring curve. The curve sets off the common extremes related to climatic changes and reduces all the other oscillations caused by other factors. The degree of similarity between the tree-ring curves was evaluated using the correlation coefficient and the parallelism coefficient (Gleichläufigkeit). These calculations facilitate the optical comparison of both curves, which is crucial for the final dating (Rybníček et al. 2010).

Individual tree-ring series were exported from PAST4 to the ARSTAN application (Grissino–Mayer et al. 1992), where they were detrended, autocorrelation was removed and the regional standard tree-ring chronology and the regional residual tree-ring chronology were created. The removal of the age trend was carried out using a two-step detrending method (Holmes et al. 1986). First, a negative exponential function or a linear regression curve, which best express the change of the growth trend with age, were used (Fritts et al. 1969). Other potentially non-climatically conditioned fluctuations of values of diameter increments, brought about by e.g. competition or forester's interference, were balanced using the cubic spline function (Cook and Peters 1981). The chosen length of the spline function was 67 % of the detrended tree-ring curve length (Cook and Kairiukstis 1990).

From the tree-ring series detrended in this way the regional index residual tree-ring chronology was created in the ARSTAN application (Grissino–Mayer et al. 1992). The chronology has low values of autocorrelation. Also the standard regional tree-ring chronology was established. The range of the created regional tree-ring chronologies is from 1898 to 2008.

To model the diameter increments in dependence on the climatic characteristics the DendroClim application was used (Biondi and Waikul 2004). Before the modelling itself it was necessary to convert the output data from ARSTAN to the input format of DendroClim. To convert the data the YUX application (web.utk.edu/~grissino/) was used.

The regional index residual tree-ring chronology and a hundred-year-long time series of monthly average temperatures and monthly precipitation for 1908–2008 were used to calculate the correlations of values of diameter increments with climatic factors. They were always calculated from April of the previous year till September of the year in question, i.e. for the period of 18 months. It is the period that should have the highest influence on the radial increment in that particular year. The climatic data were derived for the site defined by geographical coordinates 49°19' 3.614" N, 16°46' 10.619" E and an altitude of 555 m a.s.l.

The procedure of monthly average temperatures and monthly precipitation time series derivation consisted of two steps. In the first step, the missing temperature and precipitation data had to be reconstructed based on the data from the nearest site where precipitation and temperature had been measured in the long term. This site is the research plot in Rájec-Němčice (49°26'40''N, 16°41'54'' E, 625 m a.s.l.), which has been run by the Department of Forest Ecology, Faculty of Forestry and Wood Technology, Mendel University in Brno since 1961 (Hadaš 2002). The missing monthly average temperatures and monthly precipitation data were added by means of the correlation and regression analysis. The reconstruction of the monthly average temperatures and monthly precipitation consisted in defining a multiple regression function which expressed the relation of the temperatures and the precipitation at the Rájec-Němčice site and in climate monitoring stations Protivanov, Brno-Tuřany, Wien-Hohe Warte and Prague-Klementinum. The data on the temperatures and precipitation from stations Protivanov (1961–2008) and Prague-Klementinum (1775–1975) were obtained from the Czech Hydrometeorological Institute Prague or from literature (Svoboda et al. 2003), and the data from Brno-Tuřany (1908–2008) and Wien-Hohe Warte (1908–2008) from the HISTALP project database (Auer et al. 2007). The reason why climate monitoring stations Brno-Tuřany, Wien-Hohe Warte and Prague-Klementinum were used is that these are the closest stations with a verified homogeneity of the time series of temperatures and precipitation. The Protivanov station is located at an altitude of 670 m a.s.l. about 5 km north-east from the Rájec-Němčice research site (625 m a.s.l.).

The regression and correlation analysis shows that the precipitation has a wider spatial and temporal variability. Therefore, to improve the correlation dependences of multiple regression functions and to explain the development of the precipitation, we used the data on the development of the monthly relative number of sunspots (from the database of the National Aeronautics and Space Administration – NASA), the monthly average temperature anomalies in the northern hemisphere (from the database of the National Oceanic and Atmospheric Administration - NOAA), and the monthly average precipitation in the area of Moravia (Brázdil et al. 1987). A similar procedure was used for the reconstruction of the temperature data.

We assumed that the development of precipitation in the explored area of the Drahany Highlands (PRE_{RAJ}) depends on the development of the relative number of sunspots (SUNSPOT), the development of precipitation at the stations in Prague-Klementinum (PRE_{KLEM}), Wien-Hohe Warte (PRE_{WIEN}), Brno-Tuřany (PRE_{BRNO}), Protivanov (PRE_{PROT}), and the average precipitation in the area of Moravia (PRE_{MOR}). The multiple regression function has a general form:

$$PRE_{RAJ} = f(SUNSPOT, PRE_{KLEM}, PRE_{WIEN}, PRE_{MOR}, PRE_{BRNO}, PRE_{PROT}) \qquad (1)$$

The missing data on precipitation before 1975 was derived on the basis of this multiple regression model:

$$PRE_{RAJ} = -0.0271 \cdot SUNSPOT + 0.0802 \cdot PRE_{KLEM} - 0.0202 \cdot PRE_{WIEN} + 0.3112 \cdot PRE_{MOR} + 0.4261 \cdot PRE_{BRNO} + 0.2716 \cdot PRE_{PROT} + 1.2402 \qquad (2)$$

which is characterized by this regression diagnostics – determination coefficient 0.8626 and correlation coefficient 0.9288. The missing data on precipitation for the period 1976–2007 was derived on the basis of this multiple regression model:

$$PRE_{RAJ} = -0.022 \cdot SUNSPOT + 0.1236 \cdot PRE_{WIEN} + 0.3648 \cdot PRE_{BRNO} + 0.6145 \cdot PRE_{PROT} + 1.0735 \qquad (3)$$

which is characterized by this regression diagnostics – determination coefficient 0.7997 and correlation coefficient 0.8943.

When deriving the time series of temperatures we assumed that the development of the temperature in the studied area of the Drahany Highlands (TEP_{RAJ}) is dependent on the development of the relative number of sunspots (SUNSPOT), the development of temperature anomalies of the northern hemisphere (TEPANOM), and the development of temperature in Prague-Klementinum (TEP_{KLEM}), Wien-Hohe Warte (TEP_{WIEN}), Brno-Tuřany (TEP_{BRNO}) and Protivanov (TEP_{PROT}) stations. The multiple regression function has a general form:

$$TEP_{RAJ} = f(SUNSPOT, TEPANOM, TEP_{KLEM}, TEP_{WIEN}, TEP_{MOR}, TEP_{BRNO}, TEP_{PROT}) \qquad (4)$$

The missing data on temperatures before 2003 was derived on the basis of this multiple regression model:

$$TEP_{RAJ} = -0.063 \cdot SUNSPOT + 0.1249 \cdot TEPANOM + 0.6662 \cdot TEP_{KLEM} - 0.7083 \cdot TEP_{WIEN} + 0.4479 \cdot TEP_{BRNO} + 0.5602 \cdot TEP_{PROT} + 0.216 \qquad (5)$$

which is characterized by this regression diagnostics – determination coefficient 0.9536 and correlation coefficient 0.9765.

In the second step of monthly average temperatures and monthly precipitation derivation, the method of downscaling (Matulla et al. 2003) was used, in which orographic interpolation (Hadaš 1997) is employed. The orographic interpolation is based on the application of the multiple linear regression, the parameters of regression functions are derived based on the method of least squares. By the system of multiple linear functions, the vertical space interpolation is conducted, i.e. it is the expression of the dependence of meteorological parameters, e.g. temperature (TEP_{DRAH}) and precipitation (PRE_{DRAH}), on the altitude. The multiple regression function has a general form:

$$TEP_{DRAH}, PRE_{DRAH} = a_X + b_Y + c_Z + d \quad (6)$$

where: x, y, z are space coordinates of the climate monitoring stations a, b, c, d are coefficients of regression functions.

For each month of 1908–2008 a separate multiple regression function is derived. To derive the regression functions, we used all the time series of temperatures (TEP_{KLEM}, TEP_{WIEN}, TEP_{BRNO}, TEP_{PROT}) and precipitation (PRE_{KLEM}, PRE_{WIEN}, PRE_{BRNO}, PRE_{PROT}) which were used in the first step, i.e. also the time series for the Rájec-Němčice research site (TEP_{RAJ}, PRE_{RAJ}). By substituting the coordinates of the spot (x, y, z – altitude) defining the location in the Drahany Highlands in equation 6 (x=X, y=Y, z=Z) we can derive the value of the air temperature or precipitation corresponding to the location. Also the coordinate systems S-42 (Gauss) or S-JTSK can be used, which pictures the location of the spot on the surface of the Earth. The same coordinate system has to be used for the picturing of the location of climate monitoring stations as well.

It is obvious that the partial regression functions approximate the explored dependence of the daily or monthly value of a climatic parameter on the altitude with some residuum deviation. To enhance the accuracy, the location-derived residua of the values of climatic parameters from the stations are interpolated into the coordinates of nodal point network in the second step. The interpolation of residua increased or decreased the value of a parameter calculated according to (6) in the appropriate referential point. In the spatial interpolation of residua, the method of distance inversion (horizontal interpolation) was used according to

$$\pm RES_{(x,y,z)} = [\sum RES_i\ (1/d_i^2)\ ] / [\sum\ (1/d_i^2)\ ] \quad (7)$$

where: $\sum$ is the summation for i=1 up to N stations, RES_i is the residuum between two neighbouring stations, d_i is the distance between these stations, N is the number of stations. Eq. (6) can now be expressed as

$$TEP_{DRAH}, PRE_{DRAH} = a_X + b_Y + c_Z + d \pm RES_{(x,y,z)} \quad (8)$$

To evaluate the development of temperature and precipitation series we used the long-term temperature and precipitation average of individual months. The development of temperatures and precipitation is characterized by means of a summation curve of monthly deviations from their long-term normal. Summation curves were chosen as they could prove to be a suitable tool for the characteristics of the climate development in the Drahany Highlands with respect to the temporal retardation of spruce stands response to the climate development.

The statistical comparison of the time series of diameter increments and the time series of climatic factors will enable us to establish the long-term average effect of the studied climatic parameters on the increment. The effects that occur with a low frequency and but fundamentally influence the tree growth do not have to be demonstrated in the correlation analysis to a statistically significant degree (Kienast et al. 1987). To establish these effects the analysis of negative pointer years was employed. A negative pointer year is defined as an extremely narrow tree ring with the growth reduction exceeding 40 % in comparison with the average ring width in the four previous years; a strong increment reduction was found in at least 20 % of the trees from the area (Kroupová 2002).

RESULTS

The regional standard tree ring chronology shows an obvious decrease in the radial increment between 1913 and 1922, when one of the smallest increments in the monitored period was found. The decrease is followed by a gradual increase in the radial increment until 1937. In the following twenty years the radial increment decreased with an interruption from 1953 to 1955. During the following twenty years, there are three periods when the radial increment increases shortly, but is interrupted by a sharp drop, especially in 1974 and 1976. The lowest increment was found for years 1992 and 1993. Since 1995 there was an obvious increase, interrupted in 2000 and then in 2003 and 2004 (Fig. 1).

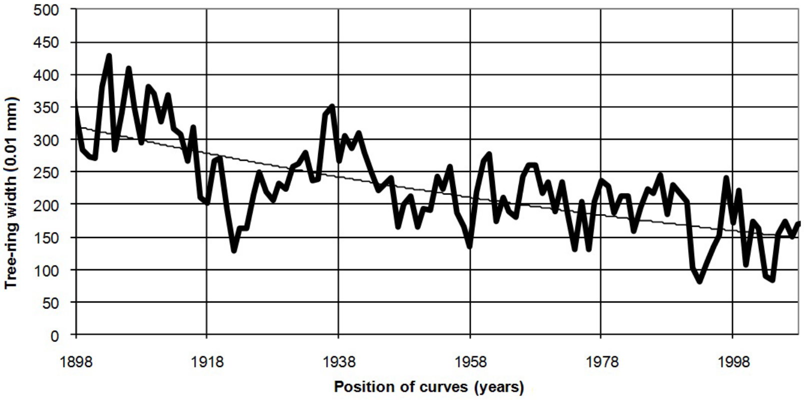

Fig. 1: Regional standard chronology from the Drahany Highlands with an exponential trend line of 1898–2008.

The results of the analysis of negative pointer years identify the greatest growth depressions in 1992, 1993 and 2003, when 80–100 % of the analysed trees responded in this way. The vegetation periods of all these three years were below average as far as precipitation is concerned (generally or at least in some months) and above average as far as temperature is concerned. Other significant negative pointer years were 1922, 1928, 1930, 1947, 1957, 1958, 1974, 1976, 1983, 1994, 2000, and 2004. Except for 2004, we can find values of monthly precipitation or monthly temperature average which can explain or help explain the radial growth fall (Tab. 2).

Tab. 2: Negative pointer years (over 40 %) and climatic characteristics which may be their interpretation. White field, black number – 40–60 % of trees sampled; grey field, black number – 60–80 % of trees sampled; black field, white number – 80–100 % of trees sampled.

Negative pointer year	Abnormal climatic characteristics
1922	very low precipitation in February and May, subnormal precipitation in June
1928	very low precipitation and supernormal temperature in July
1930	very low precipitation in February and June
1947	very cold January and February, very low precipitation in May
1957	low precipitation in May
1958	very cold March
1974	very low precipitation from February to April
1976	very low precipitation from February to April
1983	low precipitation and supernormal temperature in July
1992	low precipitation in January and August, very low precipitation in May, supernormal temperature from June to August
1993	very low precipitation in April, subnormal precipitation in May
1994	very low precipitation in February, low precipitation in June and July, supernormal temperature from July to September
2000	very low precipitation in April, subnormal precipitation in June, supernormal temperature from April to June
2003	very low precipitation in February, March, June and August, supernormal temperature from May to August
2004	without abnormal climatic characteristics

The development of temperature and precipitation has been characterized by means of the summation curve of monthly deviations from their long-term normal (Tab. 3). Using the analysis of the summation curve of monthly precipitation (Fig. 2) we can identify dry and damp periods. In the driest period, 1970–1977, the precipitation deficit was 888.5 mm, which is more than normal annual precipitation. The peak of this period came at the end of the vegetation period, in August 1976. Other losses of precipitation, reaching up to 126 % of precipitation normal, came in 1935 (August), 1957 (June), 1964 (July), and 1994 (July). Starting in 1994, in spite of minor falls, there is a permanent increase in precipitation, reaching precipitation surplus of up to 238 mm. The greatest precipitation surplus exceeding the precipitation normal of the vegetation period occurred in August 1920 (503.3 mm). This peak was related to a damp period with precipitation above average which ended in 1927. After a deep fall in the precipitation which had its climax in 1935, another precipitation surplus of over 200 mm came in October 1941. After this year, the precipitation falls within the values of precipitation deficit until 2002.

The analysis of the summation curve of monthly average temperatures (Fig. 3) shows, that we can identify quite a long period with temperatures below average from 1908 to 1972. A marked cold character of the climate culminates in 1966–1972. Starting in December 1972 there is a considerable breaking point in the temperature progress. The breaking point is marked by an increase of predominant temperatures above average in nearly all months. There were several short periods with temperatures below average (most significantly around 1996); however, these do not have any effect on the overall predominant trend of temperature increase. The warm character of the climate remains until the end of the examined period in 2008.

Tab. 3: Long-term monthly precipitation and monthly average temperatures in 1908–2008.

Parameters	**I.**	**II.**	**III.**	**IV.**	**V.**	**VI.**	**VII.**	**VIII.**	**IX.**	**X.**	**XI.**	**XII.**	**I.-XII.**	**IV.-IX.**
Precipitation	45.7	41.9	45.1	52.6	78.3	92.6	101.4	89.4	62.1	54.6	55.5	51.4	771.0	476.4
Temperature	-3.7	-2.3	1.8	6.8	11.7	14.9	16.7	15.9	12.0	6.8	1.7	-1.9	6.70	13.0

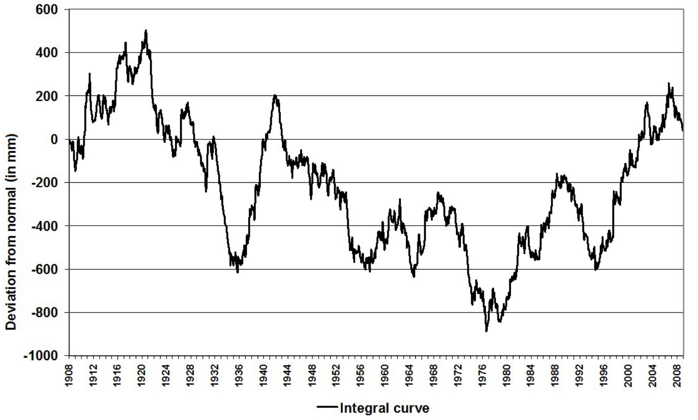

Fig. 2: The summation curve of monthly precipitation deviations from long-term precipitation normal in 1908–2008 in the Drahany Highlands.

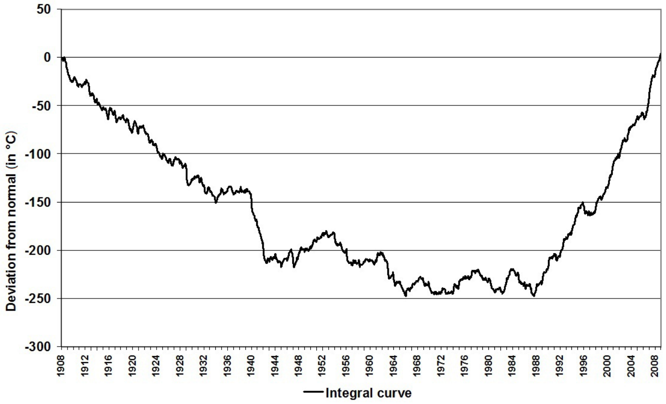

Fig. 3: The summation curve of monthly average temperature deviations from long-term temperature normal in 1908–2008 in the Drahany Highlands.

The correlations of the diameter increment with monthly average precipitation are only positive and statistically significant. The diameter increment statistically significantly correlates with the precipitation in May and September of the previous year and with the precipitation in May, June, July and August of the year in question (Fig. 4).

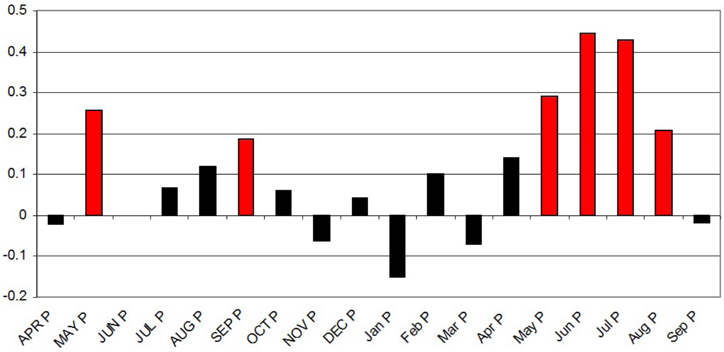

Fig. 4: The values of correlation coefficients of the regional residual index tree-ring chronology with the average monthly precipitation from April of the previous year (P) to September of the year in question for the period of 1908–2008. Values highlighted in red are statistically significant (α = 0.05).

The correlation of the diameter increment is statistically significant in a positive way with the temperatures in October of the previous year. At the same time, the correlation is statistically significant but negative with the temperatures in July, August and September of the previous year and with the temperatures in May, June, July and August of the year in question (Fig. 5).

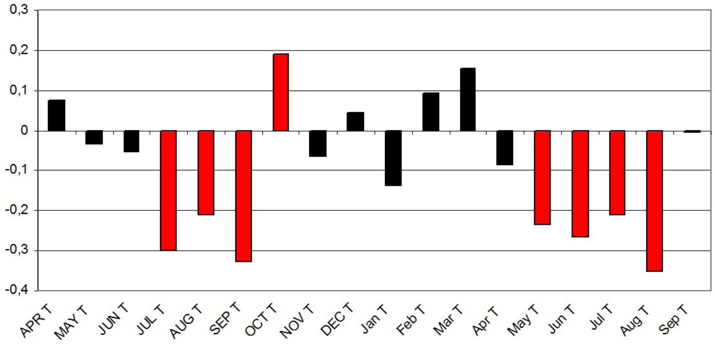

Fig. 5: The values of correlation coefficients of the regional residual index tree-ring chronology with the average monthly temperatures from April of the previous year (P) to September of the year in question for the period of 1908–2008. Values highlighted in red are statistically significant (α = 0.05).

To improve the possible interpretation of the radial growth correlations with temperatures and precipitation, we explored the correlations between the monthly precipitation and monthly average temperatures. Positive significant correlations were found for January and December and negative for April, May, June, July, August, September and October (Fig. 6).

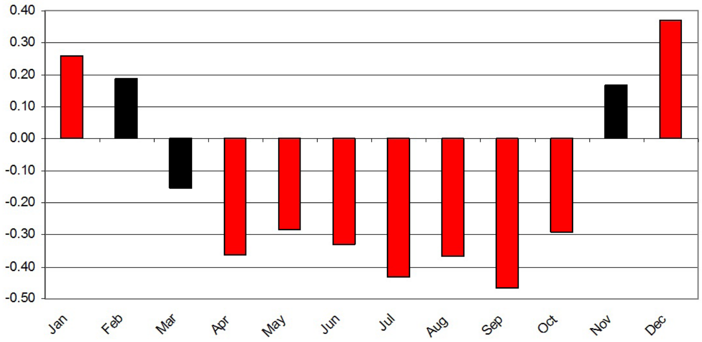

Fig. 6: The values of correlation coefficients of the average monthly precipitation with the average monthly temperatures for the period of 1908–2008. Values highlighted in red are statistically significant (α = 0.01).

The results of the habitual diagnostics are presented in Tab. 4. The table shows the average values of all basic characteristics of habitual diagnostics for individual plots and the mean value for the entire examined area.

Tab. 4: The results of habitual diagnostics.

Plot	**Total defoliation (%)**	**Defoliation of primary structure (%)**	**Secondary shoots (%)**	**Degree of transformation**	**Yellowing (%)**	**Browning (%)**	**Stem damage**
D1	34.75	52.50	26.75	0.60	0.00	0.00	0.15
D2	36.25	63.50	42.75	1.10	0.00	0.00	0.00
D3	38.00	63.00	40.50	1.05	0.00	0.00	0.00
D4	38.75	64.25	41.50	1.00	0.00	0.00	0.05
D5	35.75	56.25	32.00	0.80	0.00	0.00	0.20
D6	38.50	60.00	35.00	1.00	0.00	0.00	0.10
D7	34.75	57.75	34.50	1.00	0.00	0.00	0.20
D8	34.25	60.00	38.50	1.00	0.00	0.00	0.50
D9	37.25	61.25	37.75	1.00	0.00	0.00	0.15
Mean	36.47	59.83	36.58	0.95	0.00	0.00	0.15

The total defoliation in the area ranged only slightly above the average of the Czech Republic and the mean is 36.47 %. The values of the defoliation of the primary structure and the percentage of secondary shoots were average. The discoloration did not appear in the area in contrast to the previous monitoring (Čermák et al. 2005) (Tab. 5).

Tab. 5: The comparison of results (average values) of habitual diagnostics from the Drahany Highlands.

Explored area	**Total defoliation (%)**	**Defoliation of primary structure (%)**	**Secondary shoots (%)**	**Degree of transformation**	**Yellowing (%)**	**Browning (%)**	**Stem damage**
Drahany Highlands (present study)	36.47	59.83	36.58	0.95	0.00	0.00	0.15
Drahany Highlands (Čermák et al. 2005)	31.87	66.02	51.42	1.57	0.68	1.86	x

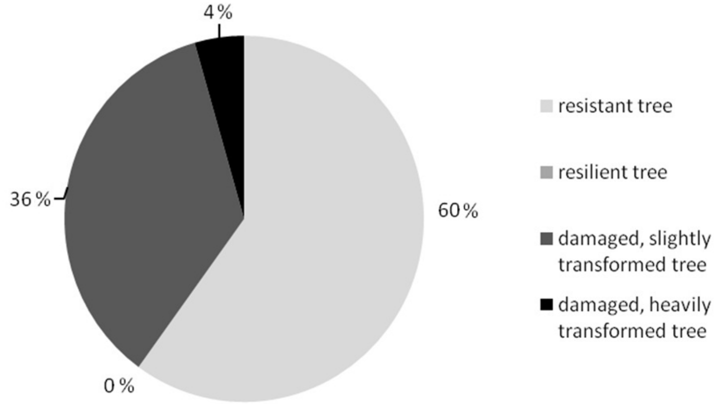

Fig. 7: The distribution of categories of tree stress response in the explored area.

The trees in the research plots were classified into categories according to their stress response on the basis of their habitual diagnostics (Fig. 7). Nearly two thirds were classified as resistant, i.e. the internal tolerance of the tree had not been exceeded. Over a third of the trees were classified as damaged, slightly transformed, where the internal tolerance had been exceeded but the trees had not started to respond by the formation of a new assimilation apparatus. Four percent of the trees were damaged and heavily transformed. There were no resilient trees.

DISCUSSION

The trend observable in the regional standard chronology is a constant decrease in the radial increment (Fig. 1). In the last twenty years, there is an obvious significant decrease in ring width in the first half of the 1990s. After this, there is an increase in increment, interrupted in 2000 and especially in 2003 and 2004. This trend was also observed in the Orlicke hory Mts. (Rybníček et al. 2009) and the Silesian Beskids (Čermák et al. 2010).

The comparison of the growth curve (Fig. 1) and the summation curves of deviations in monthly precipitation and monthly average temperatures (Fig. 2 and Fig. 3) shows that their progress is different although we consider the climate to be the main factor affecting the growth (see below). The discrepancy among the curves can be probably explained by the fact that in many cases spruce does not reflect a long-term accumulative precipitation deficit. More often it reflects shorter (a month or several months long) significant deficiencies of water in the soil when the precipitation in the vegetation period is deeply below normal. If sufficient precipitation comes after that, at least for a partial renewal of water storage in the surface layer of the soil (although still slightly below monthly average), the spruce makes use of this in spite of the fact that the summation of the precipitation deficit is still slightly rising. Naturally, the link between the sum of the deviations from the normal and the growth is even looser.

Nevertheless, both curves make us able to draw some interesting interpretations. For example, the drop in the growth in the 1920s well corresponds with the breaking point of the summation precipitation curve after 1920; the drop in the growth at the beginning of the 1990s corresponds to the precipitation deficit in the same period. The development of the curves after 1998 is highly interesting. Whereas precipitation reached a surplus and temperatures rose markedly, both of which make us assume that the conditions for the growth improved, the spruce increment did not increase. An explanation could probably be the large temperature and precipitation fluctuations during the vegetation periods, which are not clearly reflected in the summation curve, however, they affect the growth and the vitality of the spruce considerably.

The radial increment correlated especially with summer temperatures (in the previous year and the year in question) and precipitation in the year in question (Fig. 4 and Fig. 5). The character of the weather in May up to August in the year when a tree ring is formed is of a significant influence on its width. With an increasing monthly precipitation the radial increment increases, with an increasing monthly average temperature the radial increment decreases. The reverse relation of both parameters to the increment is a logical consequence of the existing correlation between the precipitation and temperatures (Fig. 6).

For the area of the Drahany Highlands, there is a general rule that from spring to autumn lower average temperatures are accompanied by higher precipitation and vice versa. This is a consequence of high cloudiness during the passages of cold fronts and the predominance of less strong precipitation. The relation of the low precipitation and high temperatures with the increment, and the mechanism of their negative effect on the tree ring formation have also been commented upon by Fritts (1966, 1976). The water stress caused by lower precipitation and higher temperatures decreases the net photosynthesis, slows down the transfer of nutrients and growth regulators, the growth and division of cells and leads thus to the formation of a narrower tree ring. The positive effect of precipitation in summer or one of summer months on the spruce radial increment has been found in many similar studies in lower or middle locations in Europe (Feliksik et al. 1994; Desplanque et al. 1999; Koprowsky and Zielski 2006; Čermák et al. 2010; Affolter et al. 2010). On the other hand, summer precipitation was not significant for the spruce in lower altitudes in the north of Europe (Mäkinen et al. 2002) or in damper locations (Vitas 2004).

A significant negative effect of summer temperatures on the radial growth has been found less often, it has been manifested for the colline level and partially for the submontane level of the Swiss Alps by Affolter et al. (2010), for south of Finland by Mäkinen et al. (2001). On the contrary, in montane levels and in northern Europe the positive correlation of summer temperatures and the growth has been observed several times (Petitcolas 1993; Sander et al. 1995; Mäkinen et al. 2001; Saava et al. 2006; Büntgen et al. 2007). The negative effect of summer temperatures on the radial growth in the year preceding the year of the tree ring formation (Fig. 5), found out within this study, can be again explained by water stress (Fritts 1966, 1976) and the subsequent lower net photosynthesis. There are assimilation results in the reduction of the allocation of nutrients and thus in a lower potential for a fast formation of the cambium in the following year.

One of the significant factors for the radial growth seems to be the character of the weather at the end of summer and the beginning of autumn in the year preceding the ring formation, specifically in September and October (Fig. 4 and Fig. 5). The precipitation in September significantly affects the water storage in the soil at the end of the vegetation period and thus its availability in the initial stage of ring formation in the following year. A positive effect of the September precipitation on the growth was found out for the Beskids (Čermák et al. 2010), a positive effect of the precipitation sum for the entire vegetation season of the preceding year in Poland, forest district Bukowiec (Feliksik 1993). Higher average October temperature is often connected with a more balanced progress of day temperatures without more sudden drops. This character of the weather makes a more gradual transition of the spruce to dormancy possible and also probably contributes to the transfer and deposition of assimilates. A significant correlation of October temperatures of the previous year and the radial growth was also found in the Polish Tatras (Savva et al. 2006) and the Beskids (Čermák et al. 2010).

The positive correlation between the precipitation in May of the previous year and the radial growth cannot be satisfyingly interpreted.

Comparing the values for the area of the forest district Proklest found out in 2003 (Čermák et al. 2005) and 2009 (the presented study), the average total defoliation in 2009 was 4.6 % higher than in 2003, the defoliation of the primary structure was 6.2 % lower, the percentage of secondary shoots was 14.8 % lower, and the average degree of crown transformation was 0.62 lower (Tab. 5). The research plots of 2009 were located in the same stands as in 2003 or in the adjacent stands. As the defoliation is estimated in an interval of 5 %, the only significant difference between the two years is the difference in the percentage of secondary shoots and the consequent degree of crown transformation – the trees in 2003 were considerably better regenerated. This change can find various explanations. Generally speaking, the decrease in the formation of secondary shoots can point at the reduction of the adaptation potential of spruce stands. However, it can also be a consequence of the reduction in the stress load in 2004–2007 – the trees did not need to regenerate. A possible explanation is that as a consequence of recurrent fluctuations of climatic conditions in the vegetation period the root systems were reduced (the decrease in the volume of thin roots, shallow root system). The current aboveground biomass more or less corresponds to this reduction, i.e. the degree of the current total defoliation corresponds with the reduction of the belowground biomass – then the trees do not replace lost primary shoots with secondary ones. This explanation also corresponds with the results of the dendroclimatology, i.e. the found trend of the radial increment decrease and the significant correlations of the growth with summer precipitation and temperatures.

CONCLUSIONS

For the purposes of the research, nine spruce stands in the Drahany Highlands were selected at altitudes of 490–576 m a.s.l. In each stand samples were taken from eighty- up to a hundred-and-twenty-year-old trees for the dendrochronological analysis. The habitual diagnostics was conducted directly at the place. The analysis of negative pointer years identified the most significant drops in 1992 and 1993. The following gradual increase in increment starting in 1995 was interrupted in 2000 and then mainly in 2003 and 2004. The vegetation periods of 1992, 1993 and 2003 in the Drahany Highlands were below average as regards the precipitation and above average as regards the temperatures.

Based on the summation curves of monthly precipitation we can identify dry and damp periods. In the driest period 1970–1977 with a peak in 1976, the precipitation deficit reached 888.5 mm, which represents more than a sum of annual precipitation. Other precipitation deficits came in 1935 (August), 1957 (June), 1964 (July), and 1994 (July). Starting in 1994, with minor drops, there is a permanent increase in precipitation, reaching a precipitation surplus of 238 mm.

The analysis of the summation curve of monthly average temperatures shows that there was a relatively long period with temperatures below average from 1908 to 1972. The markedly cold character of the climate peaked in 1966–1972. Starting in December 1972, there is a sharp breaking point in the temperature progress and the warm character of the climate lasts until 2008.

The diameter increment significantly correlates in a positive way with the precipitation in May and September of the previous year, and in May, June, July, and August of the year in question. The diameter increment significantly correlates in a positive way with the temperatures in October of the previous year, and in a negative way with the temperatures in July, August and September of the previous year and with the temperatures in May, June, July, and August of the year in question.

The total defoliation in the explored plots ranged only slightly above the average of the Czech Republic and the mean was 36.47 %. The values of the defoliation of the primary structure and the percentage of secondary shoots were average and discoloration did not appear in the area. When comparing the results of the present study with the previous study in 2003 (Čermák et al. 2005), the only significant difference was that the trees in 2003 manifested a higher percentage of secondary shoots and the consequent higher degree of crown transformation.

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REFERENCES

1. Affolter, P., Büntgen, U., Esper, J., Rigling, A., Weber, P., Luterbacher, J., Frank, D., 2010: Inner Alpine conifer response to 20th century drought swings. European Journal of Forest Research 129(10): 289–298.
2. Auer, I., Böhm, R., Jurkovic, A., Lipa, W., Orlik, A., Potzmann, R., Schöner, W., Ungersböck, M., Matulla, C., Briffa, K., Jones, P.D., Efthymiadis, D., Brunetti, M., Nanni, T., Maugeri, M., Mercalli, L., Mestre, O., Moisselin, J.M., Begem, M., Müller-Westermeier, G., Kveton, V., Bochnicek, O., Stastny, P., Lapin, M., Szalai, S., Szentimrey, T., Cejnar, T., Dolinar, M., Gajić-Čapka, M., Zaninovic, K., Majstorovic, Z., Nieplova, E., 2007: HISTALP – Historical instrumental climatological surface time series of the greater Alpine region 1760-2003. International Journal of Climatology 27(1): 17-46.
3. Biondi, F., Waikul, K., 2004: DendroClim2002: AC++ program for statistical calibration of climate signals in tree ring chronologies. Computers and Geosciences 30(3): 303–311.

4. Brázdil, R., Dobrovolný, P., Kolář, K., Kříž, V., Litschmann, T., 1987: Monthly and yearly sums of precipitation in Moravia in 1901-1980 and their temporal and spatial changes. Anthology of Czech Hydrometeorological Institute. (Měsíční a roční úhrny srážek na Moravě v období 1901-1980 a jejich časové a prostorové změny. Sborník prací ČHMÚ 32), Praha, 152 pp (in Czech).
5. Büntgen, U., Frank, D.C., Ryszard, J.K., Verstege, A., Zwijacz-Kozica, T., Esper, J., 2007: Growth responses to climate in a multi-species tree-ring network in the Western Carpathian Tatra Mountains, Poland and Slovakia. Tree Physiology 27(5): 689–702.
6. Cook, E.R., Peters, K., 1981: The smoothing spline: A new approach to standardizing forest interior tree–ring width series for dendroclimatic studies. Tree Ring Bulletin 41: 45–53.
7. Cook, E.R., Kairiukstis, L.A., 1990: Methods of dendrochronology – Applications in the environmental sciences. Kluwer Academic Publisher and International Institute for Applied Systems Analysis, Dordrecht, Boston, London, 394 pp.
8. Cudlín, P., Novotný, R., Moravec, I., Chmelíková, E., 2001: Retrospective evaluation of the response of montane forest ecosystems to multiple stress. Ekológia 20(1): 108–124.
9. Čermák, P., Plašil, P., Petlach, R., 2005: Evaluation of the response of Norway spruce *Picea abies* (L.) Karst. on synergetic effects of abiotic and anthtropogenic stress factors in two localities of the Drahany Highland. Acta univ. agric. et silvic. Mendel. Brun. (Brno) LIII(1): 59–69.
10. Čermák, P., Rybníček, M., Žid, T., Kolář, T., Bočková, H., Přemyslovská, E., 2010: The effects of climatic factors on radial growth of Norway spruce *Picea abies* in the Silesian Beskids. The Beskids bulletin 3(1): 9–18.
11. Desplanque, C., Rolland, C., Schweingruber, F.H., 1999: Influence of species and abiotic factors on extreme tree ring modulation: *Picea abies* and *Abies alba* in Tarentaise and Maurienne (French Alps). Trees 13(4): 218–227.
12. DeVries, W., Klap, J.M., Erisman, J.W., 2000: Effects of environmental stress on forest crown condition in Europe. Part I: Hypotheses and approach to the study. Earth and Envitonmental Science, Water, Air, & Soil Pollution 119(1-4): 317-333.
13. Dobbertin, M., Brang, P., 2001: Crown defoliation improves tree mortality models. Forest Ecology and Management 141(3): 271–284.
14. Feliksik, E., 1993: The effects of climate on the radial increments of the forest tree species occurring in the Bukowiec Forest district. (Wpływ klimatu na wielkość przyrostów radialnych lasotwórczych gatunków, występujących na terenie leśnictwa Bukowiec). Acta Agraria et Silvestria, Series Silvestris 31: 39–46 (in Polish).
15. Feliksik, E., Wilczyński, S., Wałecka, M., 1994: Climatic conditions of the cambial tree-rings of spruce (*Picea abies* (L.) Karst.) in the forest district of Piersciec. (Klimatyczne uwarunkowania pryzrostów kambialnych świerka pospolitego (*Picea abies* (L.) Karst.) w leśnictwe Pierściec). Acta Agraria et Silvestria. Series Silvestris 32: 53–59 (in Polish).
16. Feliksik, E., Wilczyński, S., 2000: Dendroclimatological analysis of the Norway spruce (*Picea abies* (L.) Karst.) from the Beskid Śląski Mountains. Zpravodaj Beskydy 13: 161–170.
17. Fritts, H.C., 1966: Growth-rings of trees: Their correlation with climate. Science 154(3752): 973–979.
18. Fritts, H.C., Mosimann, J.E., Bottorff, C.P., 1969: A revised computer program for standardizing Tree – Ring series. Tree Ring Bulletin 29(1-2): 15–20.
19. Fritts, H.C., 1976: Tree-rings and climate. London, New York, San Francisco, Academic Press, 567 pp.

20. Grissino-Mayer, H.D., Holmes, R., Fritts, H.C., 1992: International tree–ring data bank program library. Version 1.1. Laboratory of Tree–Ring Research, University of Arizona, Tucson.
21. Gryc, V., Vavrčík, H., Horáček, P., 2007: Variability in swelling of spruce (*Picea abies* (L.) Karst.) wood with the presence of compression wood. Journal of Forest Science 53(6): 243–252.
22. Gryc, V., Horáček, P., 2007: The variability of spruce (*Picea abies* (L.) Karst.) wood density with present reaction wood. Journal of Forest Science 53(3): 129–137.
23. Hadaš, P., 1997: Special application for derivation of climatic data for the area of the Moravskoslezské Beskydy Mts. (Speciální program pro odvození klimatických dat pro oblast Moravskoslezských Beskyd). Zpravodaj Beskyd „Vliv imisí na lesy a lesní hospodářství Beskyd“ 9: 229–234 (in Czech).
24. Hadaš, P., 2002: Temperature and precipitation conditions in the high elevation spruce stands of the Drahaská vrchovina upland. Ekológia (Bratislava) 21(1): 69–87.
25. Holmes, R.L., Adams, R.K., Fritts, H.C., 1986: Tree–Ring chronologies of Western North America: California, Eastern Oregon and Northern Great Basin with procedures used in the chronology development work including users manuals for computer programs Cofecha and Arstan. – Chronology Series VI. Laboratory of Tree – Ring Research, University of Arizona, Tuscon, AZ, USA. Pp 50–56.
26. Jelonek, T., Pazdrowski, W., Tomczak, A., Spława-Neyman, S., 2009: The effect of biological class and age on physical and mechanical properties of European larch (*Larix decidua* Mill.) in Poland. Wood Research 54(1): 1–14.
27. Kienast, F., Schweingruber, F.H., Bräker, O.U., Schär, E., 1987: Tree ring studies on conifers along eco-logical gradients and the potential of single-year analyses. Canadian Journal of Forest Research 17(7): 683–696.
28. Koprowski, M., Zielski, A., 2006: Dendrochronology of Norway spruce (*Picea abies* (L.) Karst.) from two range centres in lowland Poland. Trees 20(3): 383–390.
29. Kroupová, M., 2002: Dendroecological study of spruce growth in regions under long-term air pollution load. Journal of Forest Science 48(12): 536-548.
30. Lesinski, J.A., Landman, G., 1995: Crown and branch malformation in conifers related to forest decline. In: Cape J.N., Mathy P., (eds.) Scientific basis of forest decline symptomatology. Air Pollution Research Report 15: 92–105.
31. Mäkinen, H., Nöjd, P., Mielikäinen, K., 2001: Climatic signal in annual growth variation in damaged and healthy stands of Norway spruce (*Picea abies* (L.) Karst.) in southern Finland. Trees 15(3): 177–185.
32. Mäkinen, R., Nöjd, P., Kahle, H.P., Neumann, U., Tveite, B., Mielikäinen, K., Röhle, H., Spiecker, H., 2002: Radial growth variation of Norway spruce (*Picea abies* (L.) Karst.) across latitudinal and altitudinal gradients in central and northern Europe. Forest Ecology and Management 171(3): 243–259.
33. Matulla, C., Scheifinger, H., Menzel, A., Koch, E., 2003: Exploring two methods for statistical downscaling of Central European phenological time series. International Journal of Biometeorology 48(2): 56–64.
34. Petitcolas, V., 1993: Dendroecological comparison of 4 species of conifers in altitudinal forest limit in the massif of the Taillefer (Alpes du Nord). (Dendroécologie comparée de 4 espèces de conifères en limite forestière altitudinale dans le massif du Taillefer (Alpes du Nord)). Rapport DEA, University of Grenoble 1, France, 66 pp (in French).
35. Pichler, P., Oberhuber, W., 2007: Radial growth response of coniferous forest trees in an inner Alpine environment to heat-wave in 2003. Forest Ecology and Management 242(2-3): 688–699.

36. Rybníček, M., Čermák, P., Kolář, T., Přemyslovská, E., Žid, T., 2009: Influence of temperatures and precipitation on radial increment of Orlické hory Mts. spruce stands at altitudes over 800 m a.s.l. Journal of Forest Science 55(6): 257–263.
37. Rybníček, M., Koňas, P., Kolář, T., 2010: The benefits of tree-ring curves detrending for dating archaeological wood. Geochronometria 35(1): 85–90.
38. Sander, C., Eckstein, D., Kyncl, J., Dobry, J., 1995: The growth of spruce (*Picea abies* (L.) Karst.) in the Krkonose (Giant) Mountains as indicated by ring width and wood intensity. Annales Des Sciences Forestieres 52(5): 401–410.
39. Savva, J., Oleksyn, J., Reich, P.B., Tjoelker, M.G., Vaganov, E.A., Modrzynski, J., 2006: Interannual growth response of Norway spruce to climate along an altitudinal gradient in the Tatra Mountains, Poland. Trees 20(6): 735–746.
40. Solberg, S., Tørseth, K., 1997: Crown condition of Norway spruce in relation to sulphur and nitrogen deposition and soil properties in southeast Norway. Environmental Pollution 96(1): 19–27.
41. Svoboda, J., Vašků, Z., Cílek, V., 2003: Big Book on the climate of Czech Lands. (Velká kniha o klimatu zemí Koruny české). Regia Praha, 655 pp (in Czech).
42. Vavrčík, H., Gryc, V., Rybníček, M., 2008: Variability of selected physical and mechanical properties of English oak wood. Influence of age, trunk radius and height. (Variabilita vybraných fyzikálních a mechanických vlastností dřeva dubu letního. Vliv věku, poloměru kmene a výšky). Folia Lignaea Bohemica 2, Lesnická práce, Kostelec nad Černými Lesy, 52 pp (in Czech).
43. Vitas, A., 2004: Tree rings of Norway spruce (*Picea abies* (L.) Karst.) in Lithuania as drought indicators: Dendroecological approach. Polish Journal of Ecology 52(2): 201–210.

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