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GROWTH RESPONSES OF NORWAY SPRUCE (*PICEA ABIES* (L.) KARST.) TO THE CLIMATE IN THE SOUTH-EASTERN PART OF THE ČESKOMORAVSKÁ UPLAND (CZECH REPUBLIC)

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Abstract: The research was conducted in selected 80- to 110-year-old spruce stands in the south-eastern part of the Českomoravská Upland at altitudes from 350 m a.s.l. to 465 m a.s.l. The regional standard tree-ring chronology shows very low increments for years 1974, 1976 and 1992. After 1992, there is a sharp rise in increments with a climax in 1997. Afterwards, increments gradually decrease, reaching minima in 2003 and 2008. The years with low increments were also confirmed by the analysis of negative pointer years when over 80% of the analysed trees responded by a sharp decrease in increment, mainly in years 1976 and 1992. We can usually find values of monthly precipitation or monthly temperature average which can explain or help explain these falls in the radial growth. The correlations of diameter increments with average monthly precipitation gain only positive statistically significant values, namely for the months of May, June, July and August of the particular year. The correlations of diameter increments with average monthly temperatures gain only negative statistically significant values, namely for the months of June, July and September of the previous year and January and August of the particular year. In the examined area there is a significant negative correlation between average temperatures and monthly precipitation in July, August and September. The results of the habitual diagnostics show that with respect to the climatic conditions the health condition of the monitored stands is relatively good. On average, the defoliation does not exceed the values ascertained in different territories of the Czech Republic.

Keywords: the Českomoravská Upland, Norway spruce, precipitation, temperature, tree ring.

1. INTRODUCTION

In respect of the ongoing climatic changes attention is devoted to stands of Norway spruce and their response to the parameters of the climate and their deviations. The relations between the climate and the radial increment of spruce has recently been explored in Europe by e.g. Mäkinen *et al*. (2000; 2001), Vitas (2004), Koprowski and Zielski (2006), Saava *et al*. (2006), Feliksik and Wilczyński (2009), Bouriaud and Popa (2009), Rybníček *et al*. (2009; 2010a; 2012), Aakala and Kuuluvainen (2011), Affolter *et al*. (2010) and Gryc *et al*. (2011, 2012).

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The optimum conditions for the growth of *Picea abies* are perhumid, i.e. those reaching the value of Lang's rain factor over 12 i.e. when the average annual temperature does not exceed 6°C and annual precipitation exceeds 800 mm. Literature sources agree that spruce is a tree species of the continental climate with the original habitat delimited by an annual isohyet of 800 mm or the value of De Martonne aridity index I>60 (Vinš *et al.*, 1997). For economic reasons, a number of spruce stands were founded outside this optimum range, sometimes in markedly different areas. In relation to the current climatic changes, it is highly important and also interesting to explore the differences between growth responses of these stands throughout the range of climatic conditions they grow in. This can bring valuable information regarding spruce adaptability and its reaction to short- and long-term changes of climatic parameters, including the identification of their critical limits.

After our studies carried out in the areas of the Czech Republic where the climatic conditions are optimal, boundary or slightly outside the optimum for spruce (Rybníček *et al.*, 2009; 2010a; 2012), this study examined an area markedly outside the spruce optimum range, still with a relatively high proportion of spruce stands – the south-eastern part of the Českomoravská Upland. The aims of the study were to ascertain the dynamics of the radial growth in the last nearly fifty years and to identify the growth response to the climate; moreover, to put the data obtained from the ring chronology into the relation with the parallelly obtained data on the health condition of the spruce.

2. STUDY AREA

The research was conducted in nine selected forest stands with predominance of Norway spruce in the south-eastern part of the Českomoravská Upland near small towns of Náměšť nad Oslavou and Mohelno in 2010 (**Fig. 1**).

The stands were aged from 80 to 110 years and were located at altitudes from 350 m a.s.l. to 465 m a.s.l. (**Table 1**), i.e. they were in the second and the third forest vegetation zone. All plots were situated on gentle slopes (slope gradient to 10°), the slope orientations were east, southeast and northeast. Forest site conditions are acidic (oligotrophic) and nutrient-rich (mesotrophic). Edaphic categories (according of Viewegh *et al.*, 2003) are: acidophila – grasses are abundant in the herb layer, illimerosa acidophila, mesotrophica – a transitional category between acidic and nutrient-rich series and illimerosa trophica – with ferns in the herb layer. The region is relatively droughty, at least for Norway spruce – the average annual precipitation was 529 mm (for the monitoring period 1961-2009), De Martonne aridity index (I) is 30. The average annual temperature was 7.9°C.

3. MATERIAL AND METHODS

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. Boreholes were done at 1.3 m above the ground. The samples were taken along the terrain contour line so that the increment was not influenced by presence of compression wood (Schweingruber, 1996). At each of the plots, 20 samples were taken for the dendrochronological analysis (in total 180 samples), one sample taken from each 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 thus also the tree ring width. The measuring and the synchronization of tree-ring sequences were carried out using PAST4 (©Sciem) (Knibbe, 2004). The annual wood increments were measured with 0.01 mm accuracy.

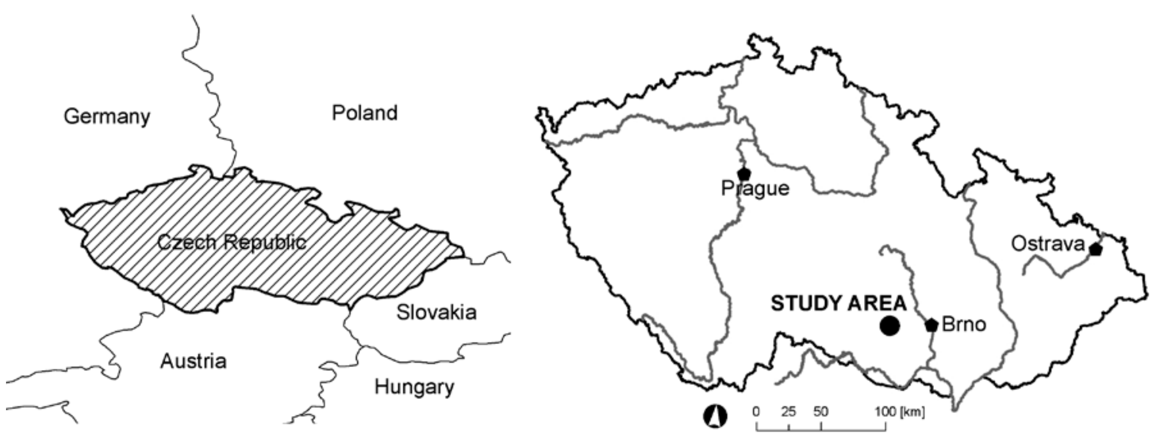

Fig. 1. *Location of the study area.*

Table 1. *A 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 (%)
M1	49°07´00.6"N 16°09´09.1"E	430	SE 135°	5°	2	illimerosa acidophila	76	90
M2	49°08´01.6"N 16°09´46.5"E	400	SE 135°	5°	3	illimerosa trophica	85	100
M3	49°08´20.9"N 16°08´32.8"E	445	E 85°	2°	3	mesotrophica	101	80
M4	49°08´11.8"N 16°08´56.5"E	465	NE 40°	6°	3	acidophila	97	100
M5	49°07´56.2"N 16°08´19.9"E	455	E 85°	5°	2	acidophila	99	90
M6	49°08´54.9"N 16°09´30.6"E	430	E 100°	2°	3	mesotrophica	81	100
M7	49°09´02.7"N 16°09´43.0"E	420	E 90°	2°	3	mesotrophica	76	100
M8	49°09´10.0"N 16°10´00.9"E	421	NE 30°	7°	3	mesotrophica	87	90
M9	49°07´52.1"N 16°13´05.4"E	350	N 350°	10°	2	acidophila	88	90

After measuring, individual measured curves were compared (cross-dated). The degree of similarity between the tree-ring curves is 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*., 2010b).

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 curves which best express the change of the growth trend with age were used (Fritts *et al*., 1969). Other potentially non-climatically conditioned fluctuations 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).

The tree-ring series detrended in this way were used to create the regional index residual tree-ring chronology 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 1912 to 2009.

To model the diameter increments in dependence on the climatic characteristics we used the DendroClim application (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 employed.

The regional index residual tree-ring chronology and the climatic time series of monthly average temperatures and monthly precipitation for 1961-2009 were used to calculate the correlations of diameter increments with climatic factors. They were always calculated from April of the previous year till September of that particular year, i.e. for the period of 18 months. It is the period that should be of the highest influence on the radial increment in each particular year.

Climatic data were derived for the location defined by geographic coordinates 49°19' 3.614" N, 16°46' 10.619" E and an altitude of 555 m a.s.l. based on spot monitoring and application of regression dependence of the quantity to the altitude. For the calculation we used technical series of stations (268 meteorological and 787 precipitation stations in the area of the CR); the original station series were subjected to quality control and homogenization using ProClimDB (Štěpánek, 2007) and the missing values of measurement were added. The calculated values were interpolated in area by the method of universal linear kriging (or linear kriging with possible selection of parameters of the method), while the dependence of a specific meteorological element on the altitude was respected (we applied local linear regression, the radius of the circular surroundings of the spot was 20 km for precipitation and 40 km for temperature characteristics). The resulting grid of each climatologic feature was calculated as a weighted average where the weight coefficient was the value of the coefficient of determination R2 in each grid cell. The size of the grid was 500 m.

To establish the correlations between the radial increments and monthly values of temperature and precipitation in individual years we used the moving response analysis (Biondi, 1997). Due to the relatively short temporal climatic series (1961-2009) it was only possible to calculate the correlations for the period from 1997 to 2008. The DendroClim application requires that the minimal length of the intervals (moving intervals) is a double of predictors (18 in our case); therefore, the minimal possible interval of 36 years was selected.

The statistical comparison of the time series of diameter increments and the time series of climatic factors enabled us to establish the long-term average effect of the studied climatic parameters on the increment. The effects that occur with a low frequency but influence the tree growth fundamentally may not 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 over 40% in comparison with the average ring width in the four previous years; moreover, the strong increment reduction is found in at least 20% of the trees in the area (Kroupová, 2002).

In the habitual stress diagnostic assessment the following were evaluated: the total defoliation, the defoliation of the primary structure, the percentage of secondary shoots, the presence and extent of yellowing and browning, and the 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.

4. RESULTS

The regional standard tree-ring chronology shows very low increments for years 1974, 1976, and 1992. After 1992 there is a sharp rise in increments with a climax in 1997. Afterwards, increments gradually decrease, reaching the minima in 2003 and 2008 (**Fig. 2**). The years with low increments were also confirmed by the analysis of negative pointer years – over 80% of the analysed trees responded by a sharp decrease in increment, mainly in years 1976 and 1992. Except for 2001 and 2004, we can find values of monthly precipitation or monthly temperature average which can explain or help explain the radial growth fall (**Table 2**).

The correlations of diameter increments with average monthly precipitation gain only positive statistically significant values, specifically for the months of May, June, July and August of the particular year (**Fig. 3**). The correlations of diameter increments with average monthly temperatures gain only negative statistically significant

Table 2. *Negative pointer years (over 40% reduction) 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 – month or season values notably distinct from long-term averages
1962	high precipitation in May, subnormal precipitation in June and July, very low precipitation in August and September; subnormal temperature in March
1963	subnormal precipitation in April, very low precipitation in July
1964	very low precipitation in December 1963 and January 1964; subnormal temperature in March
1968	subnormal precipitation in March, April and July
1973	very low precipitation in March and August
1974	very low precipitation from February to April; supernormal temperature from January to March
1976	very low precipitation from March to June (especially in June), very low precipitation in growing season (March – September) – only 285 mm; very cold March
1988	low precipitation in April and May, supernormal temperature in January
1990	very low precipitation in March, subnormal precipitation in July, subnormal precipitation in growing season (March – September)
1992	very low precipitation in growing season (March – September) – only 273 mm, especially in May and July; supernormal temperature from June to August
1993	very low precipitation in growing season (March – September) – only 2 mm, especially in March and April
2000	very low precipitation in April, subnormal precipitation in June; supernormal temperature in April and May
2001	without abnormal climatic characteristics in 2001; warm autumn 2000
2003	very low precipitation in growing season (March – September) – only 240 mm, especially in March, June and August; supernormal temperature in May, June and August
2004	without abnormal climatic characteristics in 2004; hot and dry summer 2003
2008	warm January and February with low precipitation, subnormal precipitation in August

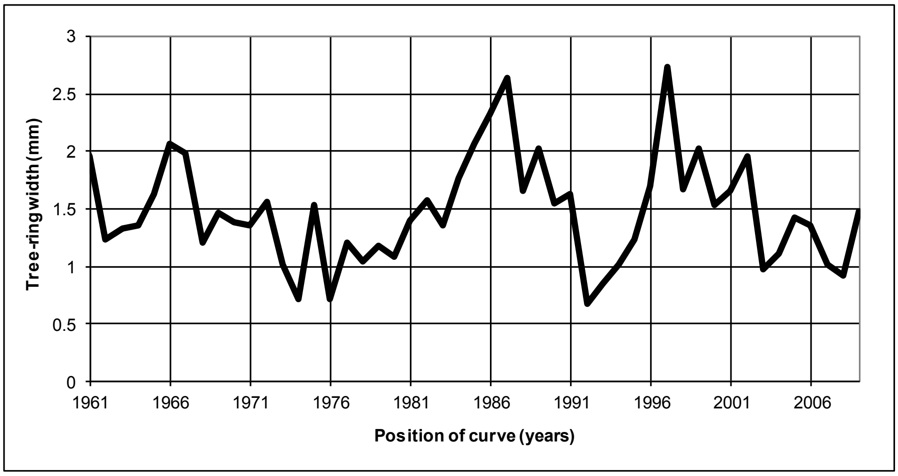

Fig. 2. *Regional standard chronology.*

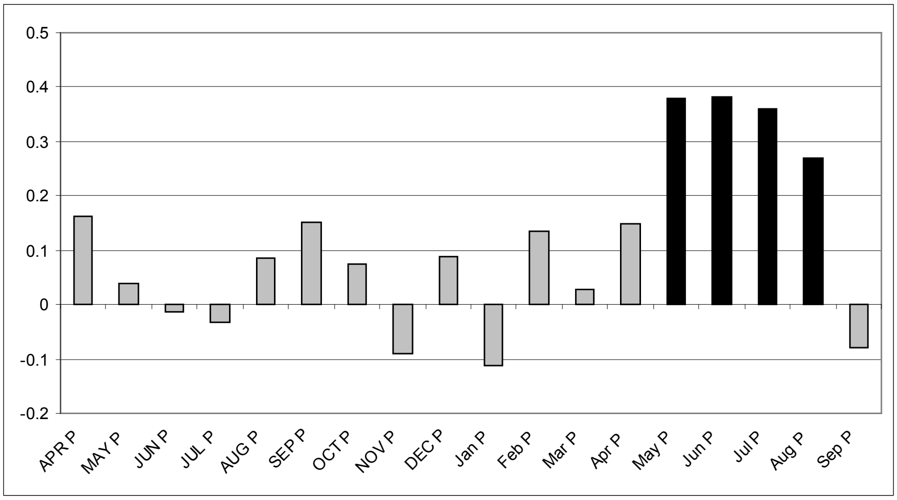

Fig. 3. *The values of correlation coefficients of the regional residual index tree-ring chronology with the average monthly precipitation from April of the previous year to September of that particular year for the period of 1962-2008. Values highlighted in black are statistically significant (α = 0.05).*

values, specifically for the months of June, July and September of the previous year and January and August of the particular year (**Fig. 4**).

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. Negative significant correlations were found for July, August, and September (**Fig. 5**).

The results of the habitual diagnostics are presented in **Table 3**. The average defoliation of spruce was 34.3%. The values of the defoliation of the primary structure reached an average of 58.8% and the percentage of secondary shoots was 37.4% on average. Discolouration was found to an insignificant degree only. The trees in the research plots were classified into categories according to their stress response based on their habitual diagnostics (**Fig. 6**). More than two thirds were classified as resistant, i.e. the internal tolerance of the tree had not been exceeded. Nearly a quarter 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 a formation of a new assimilation apparatus. Only 6% of the trees were damaged and heavily transformed and 4% were resilient trees.

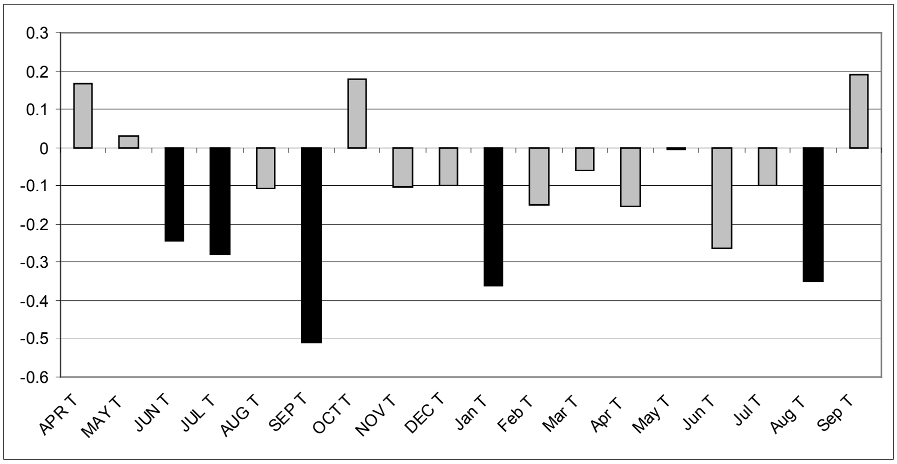

Fig. 4. *The values of correlation coefficients of the regional residual index tree-ring chronology with the average monthly temperatures from April of the previous year to September of that particular year for the period of 1962-2008. Values highlighted in red are statistically significant (α = 0.05).*

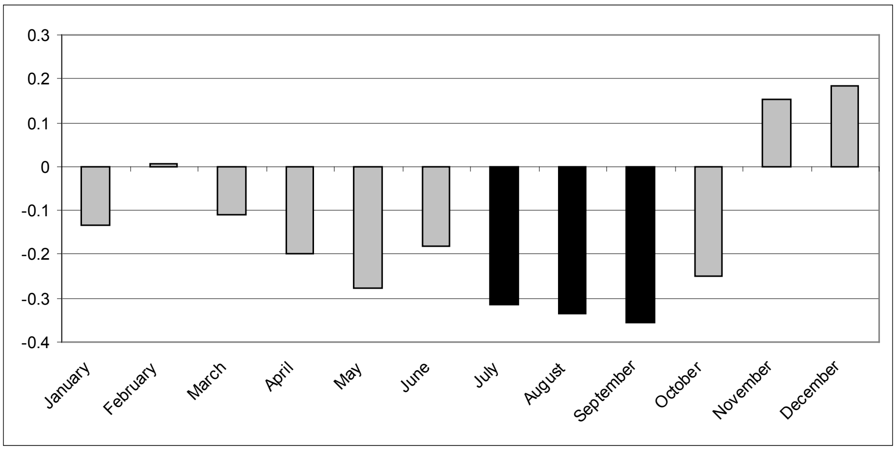

Fig. 5. *The values of correlation coefficients of the average monthly precipitation with the average monthly temperatures for the period of 1961-2009. Values highlighted in black are statistically significant (α = 0.05).*

Table 3. *The results of habitual diagnostics.*

Title of plot	Total defoliation (%)	Def. of prim. structure (%)	% secondary shoots	Degree of transformation	Yellowing (%)	Browning (%)
M1	31.3	59.5	40.8	1.2	1.3	1.0
M2	32.8	55.3	33.0	1.0	1.3	0.8
M3	37.8	62.5	40.3	1.1	0.0	0.3
M4	35.3	61.8	40.5	1.3	0.8	0.0
M5	33.0	56.8	34.3	1.0	0.0	0.0
M6	30.5	52.0	30.8	0.8	0.3	0.0
M7	33.8	53.3	28.8	0.9	0.0	0.0
M8	36.0	61.3	39.5	1.0	0.8	0.3
M9	38.8	67.8	48.8	1.3	1.3	0.3
Mean	**34.3**	**58.8**	**37.4**	**1.0**	**0.6**	**0.3**

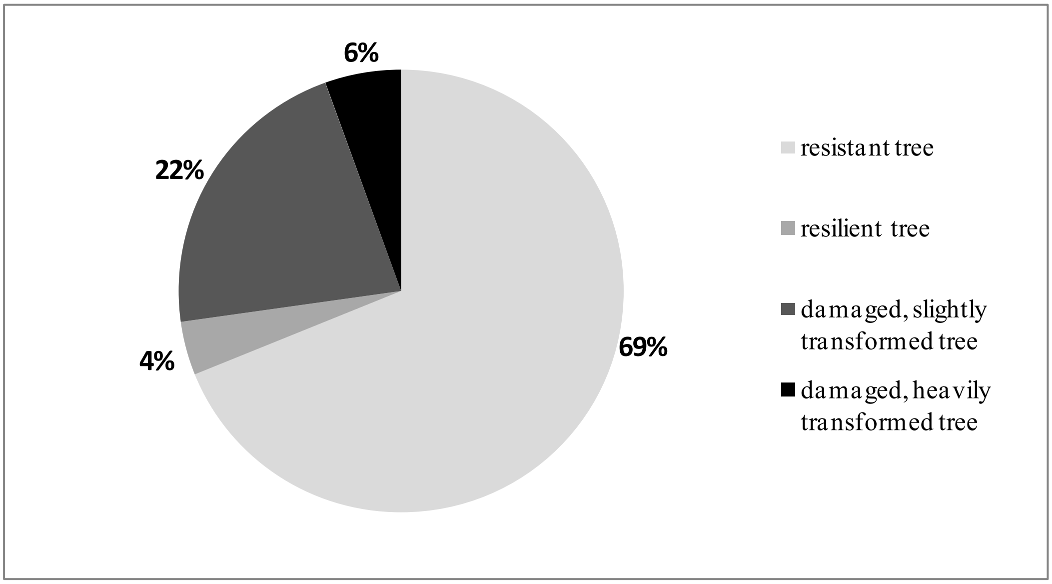

Fig. 6. *The distribution of categories of tree stress response in the explored area.*

5. DISCUSSION AND CONCLUSIONS

The regional standard chronology is characterized by quite large fluctuations of the radial growth (**Fig. 2**). Within the last twenty years, there is a pronounced fall in tree-ring width in the first half of the 1990s, with the minimum in the year 1992, which was the second driest year in the region between 1961 and 2009 regarding the March–September precipitation (273 mm only). There is a sharp rise in increments after 1992, culminating in 1997 – the precipitation in years 1995, 1996, 1997 was highly above average, with March–September precipitation over 470 mm. After this, the increments gradually fall again, with a minimum in 2003 – this year was the driest (March–September 240 mm only) – and another in 2008 – a year which was also very dry. The marked decreases in increments in 1992 and 2003 were recorded for spruce in other regions of the Czech Republic as well – the Silesian Beskids (Rybníček *et al.*, 2010a) and the Drahany Highlands (Rybníček *et al.*, 2012).

The radial increment is statistically significantly positively correlated with summer precipitation of that particular year (**Fig. 3**) in the months of May, June, July and August. The weather from May to August is generally of determining significance for the tree-ring width. Water stress caused by lower precipitation reduces the net photosynthesis, slows down the transfer of nutrients and growth regulators, the growth and division of cells and thus leads to the formation of a narrower tree ring (Fritts, 1966, 1976). Moreover, considering spruce requirements, the areas surrounding the towns of Náměšť and Mohelno are very dry – in the period which is determining for tree growth, i.e. March–September, the average precipitation in the analysed period was only 381 mm. A positive correlation between precipitation and increments for May until September was also found in the nearby Drahany Highlands (Rybníček *et al.*, 2012), with a similar character of the summer weather, yet with considerably higher precipitation (over 500 mm on average in March–September). A positive effect of precipitation in summer or one of summer months on the Norway spruce radial increment has been found in many similar studies in Europe (Feliksik *et al.*, 1994; Desplanque *et al.*, 1999; Vitas, 2004; Koprowski and Zielski, 2006; Feliksik and Wilczyński, 2009; Bouriaud and Popa, 2009; Rybníček *et al.*, 2010a; Affolter *et al.*, 2010). A significant positive correlation was also identified in other conifers, for example pine (Szczepanek *et al.*, 2006; Bouriaud and Popa, 2009).

Summer temperatures were in a negative relation to the radial increment, both the temperatures in the particular year and the temperatures in the year preceding the tree-ring formation. Significant correlations were found for June, July and September of the previous year, and August of each particular year (**Fig. 4**). Warm temperatures during the growing season may induce moisture stress and decrease tree growth (Barber *et al.*, 2000; D'Arrigo *et al.*, 2004; Miyamoto *et al.*, 2010; Aakala and Kuuluvainen, 2011). High temperatures increase evapotranspiration from soils and plant tissues, inducing stomatal closure and a decreased net photosynthesis to minimize water losses in response to an increasing moisture stress (Kozlowski, 2002). An increase in average monthly temperature during the growing season by more than 3°C over the long-term average is considered highly risky (Grabařová, Martinková, 2000, 2001). In the warmest years this was exceeded repeatedly in the examined area. The moisture stress affects growth in the particular year but also in the following year. Lower photosynthetic assimilation leads to a reduction of the allocation of nutrients and thus a lower potential for a fast formation of the cambium in the following year.

The correlation between the average temperatures and monthly precipitation values in July, August and September in the examined area was significant, negative (**Fig. 5**), i.e. higher temperatures are connected with lower precipitation, which further increases the probability of moisture stress occurrence. Significant negative correlations of temperatures in summer months of the previous year and the radial growth of Norway spruce were also found in the nearby Drahany Highlands, specifically for July, August and September (Rybníček *et al*., 2012); out of other European territories also for southern Finland (Mäkinen *et al*., 2001), lower altitudes of the Swiss Alps (Affolter *et al*., 2010), Archangel territory in Russia (Aakala and Kuuluvainen, 2011) and the Romanian Carpathians (Bouriaud and Popa, 2009). Significant negative correlations of temperatures in summer months of the particular year and the radial growth were found in the nearby Drahany Highlands as well, specifically for May, June, July and August (Rybníček *et al*., 2012), out of other European areas also for lower altitudes of the Swiss Alps (Affolter *et al*., 2010) and the Romanian Carpathians (Bouriaud and Popa, 2009).

The negative relationship between January temperatures and radial growth can be explained by the fact that a warmer January leads to higher respiration in the time when the losses cannot be compensated for by photosynthesis. In some years higher January temperatures could also prematurely activate phytohormones and the processes related to the transition of tree species from the winter dormancy period. The same negative correlation was found for February temperatures in the Archangel area in Russia (Aakala and Kuuluvainen, 2011) and in Finland (Mäkinen *et al*., 2000). Still another explanation can be a reduction in water storage available for the beginning of the growth period – in the research area a warmer January was often connected with stronger winds, due to which the surface of soil without vegetation or snow gets drier.

The results of the habitual diagnostics show that the health condition of the monitored stands, or specifically its clinical image represented by the selected parameters, is relatively good (with respect to the climatic conditions which are outside the spruce optimum). The defoliation on average does not exceed the values ascertained by means of the same methodology in other territories of the Czech Republic (Žid and Čermák, 2007; Rybníček *et al*., 2010a; Rybníček *et al*., 2012). The values of the other parameters are close to the values gained a year earlier in the nearby Drahany Highlands (Rybníček *et al*., 2012) in stands which were one vegetation zone higher (above 500 m a.s.l.) and were better saturated with water (average annual precipitation 779 mm, i.e. 250 mm more).

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