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Growth of Norway spruce (*Picea abies* [L.] Karsten) from artificial and natural regeneration in the Krkonoše Mts. and air temperature variability

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ABSTRACT: Our research was concerned with a description of the influence of variability in average temperatures on the height growth of selected young populations of spruce in the Krkonoše Mts. Several populations of spruce were evaluated while the majority of them originated by natural regeneration on plots under disturbance of the original tree layer. In addition, several planted spruce populations in similar environmental conditions were also evaluated. The main questions of this study are as follows: is there a difference in height growth between populations of natural and artificial origin? Is it possible to find a relationship between height growth and climate feature during the last several years? The growth of young spruce populations that originated by natural regeneration was different from the growth of the planted populations. The average air temperature in the growing period, estimated as average temperature during the months of May to August, was proved to have a significant influence on year-on-year variability in spruce growth. Based on this finding, it was possible to estimate an increase in the height increment of young spruce caused by warming up since the mid-70s of the 20th century to equal approximately 16% per decade in the spruce altitudinal zone in the Krkonoše Mts.

Keywords: climate; regression models; 8th forest altitudal zone; reforestation

Mountain forest ecosystems in central Europe have undergone rapid development in the last decades. After a period of the complete collapse of some forest ecosystems resulting from the air-pollution situation in the second half of the 20th century, forest regeneration is taking place at present (Vacek et al. 2007; Matějka 2011). Both artificial and natural forest regeneration is realised. This regeneration is markedly influenced by changing ecological conditions (mainly climate change and higher nitrogen deposition). A cardinal feature of further development of forest ecosystems will be their future stability, which is influenced, *inter alia*, by the choice of forest regeneration methods (artificial or natural regeneration).

A generally known fact is that plant growth is influenced by climatic conditions of a given year. It is also to assume that climate variability will be of greater importance in the least favourable localities. This will also apply to *Picea abies* in the 8th forest altitudinal zone (FAZ) – zone of mountain spruce forest.

Currently, the discipline of growth models of forest tree species and forest stands is undergoing rapid development (Hasenauer 2006; Pretzsch 2009). Results are mostly applied to the analysis of production potentials of forest stands. This is the reason why the majority of these models are hardly applicable to the analysis of the growth of young populations of a regenerating stand. Although

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growth should be understood as a physiological process (e.g. Procházka et al. 1998), the relations can be simplified for the purposes of the analysis of height growth (increment) of a young tree population that is in the phase of exponential or constant growth. Such an approach is justifiable because it is not necessary to measure many parameters (e.g. leaf area) and it is sufficient to include very simple variables in a regression model – in our case total tree height and height increments that can be determined also retrospectively over several years during a single measurement.

The present paper is aimed at a description of the influence of average temperature variability on the height growth of selected young spruce populations in the Krkonoše Mts. (Giant Mts.). Several spruce populations were evaluated while the majority of these populations originated by spontaneous natural regeneration on plots where the original tree layer was disturbed. In addition to these sets, several spruce populations from artificial planting were also evaluated. All localities were selected on comparable sites at places with natural occurrence of climax spruce stands. To ensure their comparability all localities were situated in one (eastern) part of the Krkonoše Mts. Is there a difference in height growth between populations of natural and artificial origin? Is it possible to find a relationship between height growth and climate feature during the last several years?

MATERIAL AND METHODS

Plots were localized in the eastern Krkonoše Mts. in the area of the 8th FAZ in such a way that would ensure maximum similarity of their natural conditions. In total six plots designed for observations were identified (Table 1). All plots were covered by forest also in the past, which was verified in stable cadastre maps. Plot 9 is practically identical with a long-term permanent research plot (PRP 22) where various investigations have been performed since 1980 (Vacek et al. 2007). Average age of the spruce populations varies between 15 and 20 years according to the plot (as assessed during field measurement). Stands of dispersed young trees occur at all localities; total coverages of these regenerating canopies are 5–45%. Plots No. 7 and 8 consist of two neighbouring subplots, where on one subplot are trees of natural origin and on the other there are trees from artificial regeneration.

The modelled annual average air temperature for the period 1961–1990 (using the PlotOA software and digital elevation model with 30 m in pixel-size; Matějka 2009) ranges between 2.5 and 3.3°C. Plots are situated on moderate to steep slopes, with acidic and frequently very stony soils. Hence, it is to assume that the selected plots are more or less comparable from the aspect of spruce growth.

Trees from regeneration were measured on selected plots from July to September 2011. Total height of a tree in the given year (variable H_{11}) and height increment in the years 2006–2011 (P_{06}–P_{11}) were recorded. Heights of trees in the particular years 2006–2010 (H_{06}–H_{10}) were calculated. Total age of trees was estimated on some plots, but such estimation involves an error and therefore this variable was considered as an additional one.

As the measurements in 2011 were done at the time when the growing season did not finish yet, it was not possible to carry out the statistical evaluation of growth on all plots until 2011, but only data until 2010 were evaluated, the measurement of which was done retrospectively. The variables (H_{11} and P_{11}) from the last year (2011) were statistically analysed only in the case of later measurement (September) so that height growth had been terminated.

All measured data were entered and primarily processed in MS Visual FoxPro database. Statistical processing was run in the programme STATISTICA, version 8 (Hill, Lewicki 2007).

Table 1. Basic features of selected plots and their localization (JTSK coordinates)

Plot	Reforestation	JTSK-X (m)	JTSK-Y (m)	Altitude (m)	Temperature (°C)	Forest site type
3a	natural	984759	645598	1192	2.52	8N0
5	natural	986310	644359	1161	3.27	8K2/8N1/8N3
6	planting	986893	647355	1209	2.97	8K2
7	natural and planting	983740	638618	1295	2.73	9K1/8Z3
8	natural and planting	985623	639533	1198	2.84	8K2/8K4
9 = PRP 22	natural	984119	639660	1210	3.31	8K4

average air temperatures during 1961–1990 were modelled using PlotOA software (Matějka 2009), PRP 22 – long-term permanent research plot

Relations between the evaluated variables were examined by correlation analysis using the coefficient of linear correlation (*r*). The correlation of height increment (P) with total tree height (H) was modelled as:

$$P = a \times H^{b} \tag{1}$$

where:
a, b – regression coefficients,
H – total tree height (cm).

The advantage of this model is that the respective curves go through the origin of coordinates (H;P) = (0;0). Height increment in two consecutive years (y and y+1) was compared on the basis of the regression:

$$P_{y+1} = a + b \times P_{y} \tag{2}$$

where:
a, b – regression coefficients,
P_y – height increment in the year y (cm).

Data on all plots were evaluated together, but trees from natural regeneration and artificial regeneration were evaluated separately.

The growth of trees of different sizes can be deduced from these models using three notional tree sizes – e.g. 50, 150 and 250 cm.

Climate data (average air temperature and sum of precipitation) were taken from the Labská bouda Station of the Czech Hydrometeorological Institute. The station is situated at an altitude of 1,300 m a.s.l., approximately 10 km from the selected plots, in the same mountain region. Data published in the monthly Měsíční přehled počasí (Monthly Weather Overview) were processed. Missing data were modelled as a technical series (Table 2).

In intensively growing young populations, it is not possible to seek a direct relation between growth rate in a given year and climate characteristics of that year because growth is accelerated as the total size of the tree increases. Therefore, a relation was sought between the parameters describing a change in growth in two consecutive years and the parameters describing a change in climatic conditions between the respective years. This relation was sought:

$$\Delta(P_{y+1}, P_{y}) = \alpha + \beta \times \delta(T_{y+1}, T_{y}) \tag{3}$$

where:
α, β – regression coefficients,
$\Delta(P_{y+1}, P_y)$ – function Δ was equal to the regression parameter b according to Eq. (2), $b = (P_y+1 - a)/P_y$,
$\delta(T_{y+1}, T_y)$ – function δ was equal to the difference in the average air temperatures T (based on data from the Labská bouda Station; in °C) in the months of intensive spruce growth (May to August) in the respective years y and y+1.

Table 2. Average daily sum of precipitation and average air temperature (at a height of 2 m above the ground) in the vegetation (growing) period (May to August) at Labská bouda Station (primary data of Czech Hydrometeorological Institute)

Year	Sum of precipitation ($mm \cdot day^{-1}$)	Air temperature (°C)
1983	3.10	10.62
1984	4.57	7.66
1985	4.13	8.68
1986	5.12	9.23
1987	4.46	7.63
1988	4.12	9.40
1989	3.86	8.89
1990	2.99	9.35
1991	4.09	8.07
1992	3.28	11.11
1993	4.56	9.28
1994	4.36	10.46
1995	5.22	9.92
1996	5.80	9.07
1997	8.38	10.29
1998	5.21	9.74
1999	3.48	9.95
2000	3.71	10.11
2001	4.31	10.03
2002	4.04	11.07
2003	3.54	11.52
2004	4.51	9.26
2005	5.43	9.52
2006	7.34	10.12
2007	5.13	10.53
2008	3.62	10.27
2009	6.77	9.79
2010	8.69	9.79
2011	6.47	9.77

Some other variables of temperature were used in this analysis: average temperature in single months (May, June, July, August) and average temperature during the warmest quarter. The best model was selected according to Pearson's regression coefficient.

Average yearly change in air temperature was calculated on the basis of linear regression between average air temperature and year. This temperature change corresponds to the change in height growth according to the model in Eq. (3). Growth change during a longer period (e.g. 10 years) was estimated as a multiple of the respective one-year growth changes.

RESULTS AND DISCUSSION

The correlation of height increment in two consecutive years (r = 0.86 – 0.90) was higher than a similar correlation of height increment in more distant years. The highest correlation was calculated for the years 2008 and 2009 (Table 3). Height increment in two consecutive years was evaluated by linear regression analysis (Figs 1–4). Based on this analysis, constant acceleration of height growth was proved in spite of weather variability in the particular years (the constant coefficient of regression equations was always positive).

Parameters of growth models were calculated separately for all years (Table 4, Figs 1 and 2). The growth of trees of different sizes can be deduced from these models using three notional tree sizes – e.g. 50, 150 and 250 cm. Small (50 cm in height) recruits from populations of natural regeneration grew faster (average 8.6 cm·yr^{-1} during 2006–2011) than small trees from populations of artificial regeneration (average 5.9 cm·yr^{-1}). Nevertheless, it was vice versa in taller trees. Trees from artificial

Table 3. The correlation matrix among measured growth variables

	H_{11}	H_{10}	P_{11}	P_{10}	P_{09}	P_{08}	P_{07}	P_{06}	AGE
H_{11}	1.000								
H_{10}	0.993	1.000							
P_{11}	0.746	0.663	1.000						
P_{10}	0.809	0.746	0.860	1.000					
P_{09}	0.843	0.808	0.771	0.865	1.000				
P_{08}	0.864	0.846	0.744	0.816	0.896	1.000			
P_{07}	0.825	0.823	0.675	0.732	0.816	0.871	1.000		
P_{06}	0.809	0.821	0.618	0.690	0.771	0.802	0.864	1.000	
AGE	0.595	0.647	0.028	0.095	0.061	0.156	0.000	0.069	1.000

H_x – total height, P_x – height increment, AGE – tree age in the year of measurement (2011), data set of all plots: plot 9 was not counted for variables H_{11} and P_{11}

Table 4. Parameters of the growth model $P = a \times H^b$ (both P and H in cm)

	Natural regeneration			Planting		
Year	a	b	r	a	b	r
2006	0.9311	0.5131	0.5461	0.0445	1.2643	0.6927
2007	0.7965	0.5633	0.5511	0.0271	1.3774	0.7928
2008	0.9113	0.5683	0.5800	0.0334	1.3246	0.8506
2009	1.3288	0.4860	0.4710	0.0331	1.2967	0.8814
2010	2.1781	0.4355	0.4419	0.0475	1.2234	0.8662
2011	0.5840	0.6730	0.4810	0.1129	1.0189	0.8247

a, b – regression coefficients, r^2 – index of determination, their square-root r was used because it is comparable with other data (e.g. Table 3), data on plot 9 was excluded for the 2011 regression because tree growth was not terminated on this plot at the time of measurement

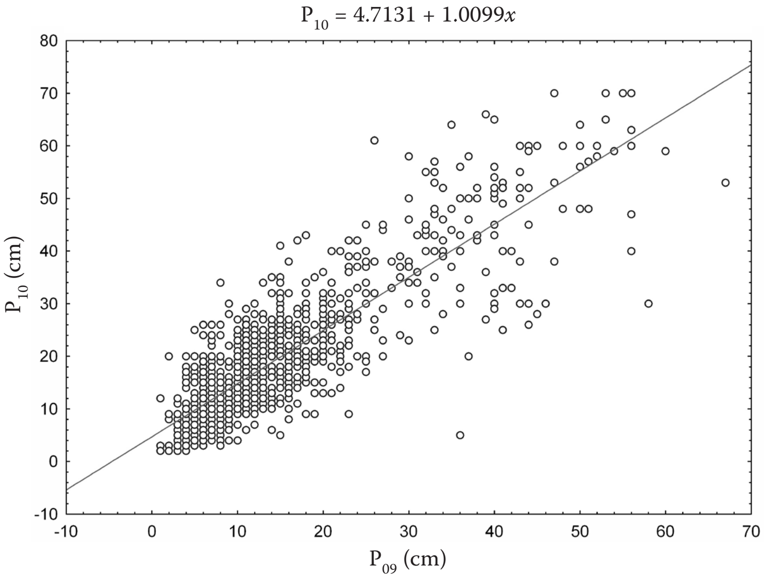

Fig. 1. Relationships between annual height increments in 2009 and 2010

regeneration accelerate their growth very intensively with increasing total height (Fig. 6): trees of 250 cm in height had an average modelled height increase at 44.5 cm·yr^{-1}. Recruits from natural regeneration are lacking such acceleration and, on the contrary, an increase in their height increment is decelerated with total height (Fig. 5): comparable average increase was only 20.4 cm·yr^{-1}. Both models for natural regeneration and planted trees are significantly distinct because corresponding confidence regression bands (at 0.95 probability) are fitted in distinct positions. This fact can be explained by a higher proportion of trees with pioneer growth strategy in young stands that originated by artificial regeneration because slow-growing seedlings are discarded in the course of planting material production in forest nurseries. Nursery technologies largely preferred fast-growing trees in the past (Jurásek et al. 2009). Gömöry et al. (2006) also described in Norway spruce the trees with climax growth strategy (so-called K-strategists in the sense of r- and K-selection; MacArthur, Wilson 1967) and pioneer growth strategy (r-strategists). These trees fulfil different functions in forest regeneration. The observations of growth and development of mountain spruce populations revealed a relation when the lower growth rate was related with higher adaptation to adverse mountainous conditions (Oleksyn et al. 1998). This hypothesis is supported by data documenting that spruce populations originating from higher elevations above sea level or from northward regions have higher frost hardiness (Simpson 1994; Hawkins, Shewan 2000; Westin et al. 2000) and drought resistance (Modrzyński, Eriksson 2002) than seedlings from lower elevations or of southward origin where

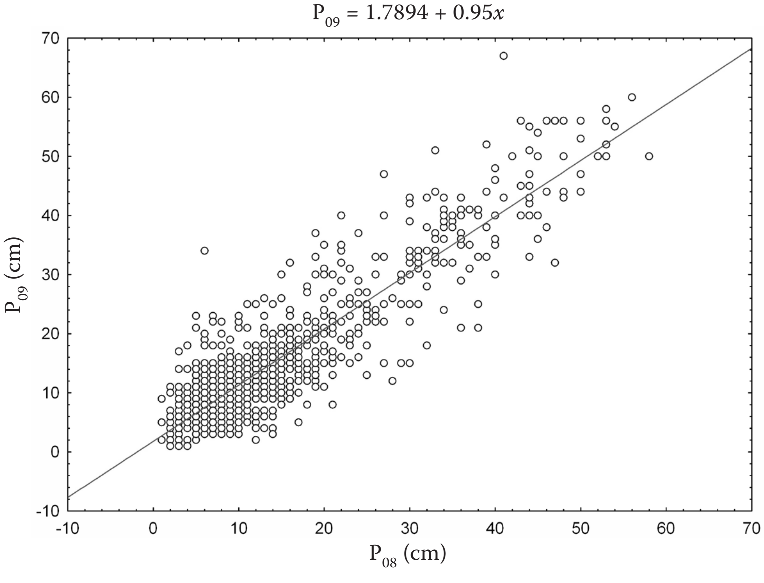

Fig. 2. Relationships between annual height increments in 2008 and 2009

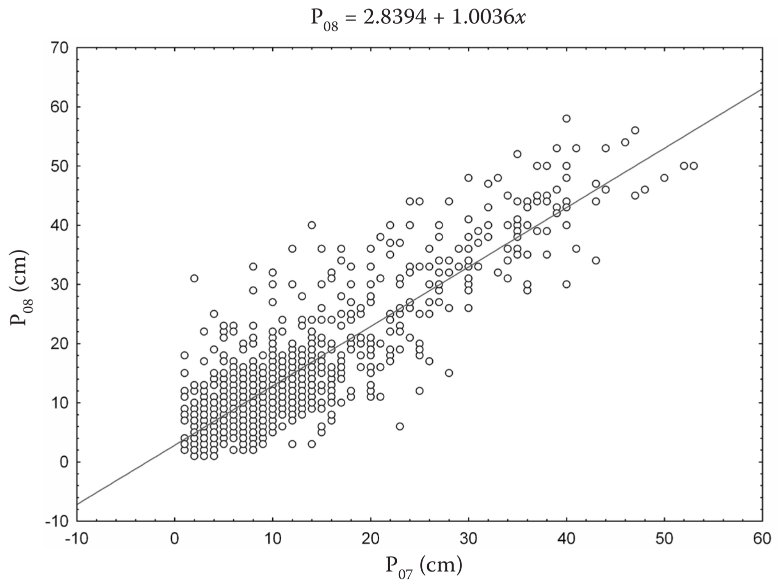

Fig. 3. Relationships between annual height increments in 2007 and 2008

natural spruce populations originally grew mostly on waterlogged soils.

This opinion is also supported by data of some authors illustrating that the shoot height of spruce seedlings decreases with the increasing altitude of their origin (Modrzyński 1995). It is assumed that in the process of adaptation to adverse conditions of the mountainous environment spruce populations acquire higher resistance at the cost of growth rate.

The relation of annual height increment to temperature in the given year (average annual temperature, temperature of the warmest quarter of the year or temperature in the months of May to August, when the intensive height growth of spruce takes place) cannot be proved directly because measured populations are aging and so their increment increases. However, it is possible to make a year-on-year comparison of height increment that was analysed by regression methods (Figs 1–4). The highest values of the linear correlation coefficient were calculated when average values in the months of May and June (dT_{5-6}; $r = 0.956$) or May to August (dT_{5-8}; $r = 0.954$) were used while both values are practically identical. On the contrary, the use of temperatures in the warmest quarter of the year [$dT_{max(Q)}$], which is derived as a maximum of the quarterly moving average of temperatures, provides a negative correlation coefficient ($r = -0.54$), probably as a result of combining the high values of this temperature average with the low precipitation amount causing drought stress in spruce. No statistically significant correlation with a change in height growth was found out for the particular months of May to August – the respective values of correlation coefficients were 0.84, 0.60, –0.86 and 0.52.

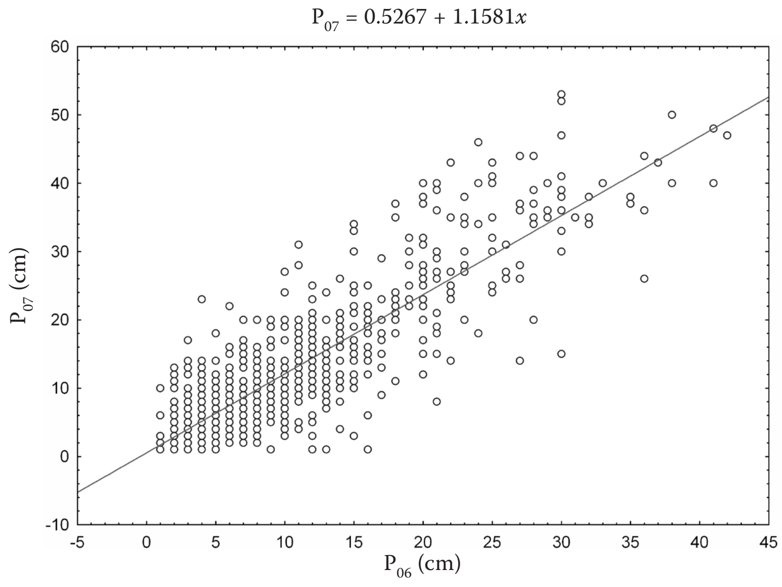

Fig. 4. Relationships between annual height increments in 2006 and 2007

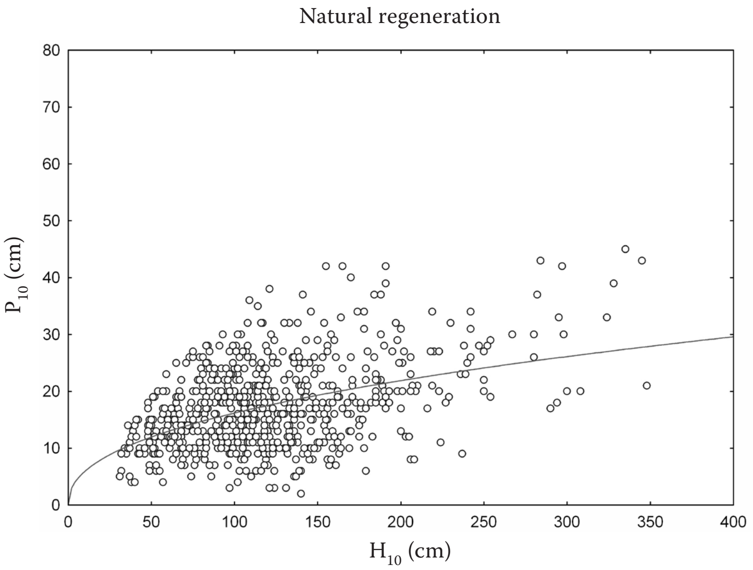

Fig. 5. Annual height increment (P) related to tree height (H) in recruits from natural regeneration. All plots in 2010. The regression model P = a × H^b was applied (for parameters see Table 4)

Therefore, May temperature seems to be the most significant for young spruce growth and, on the contrary, elevated temperatures of high summer reduce its growth. Diameter increment of Norway spruce in the Alps shows a similar correlation with average temperature during May to July (Büntgen et al. 2006).

A difference in average temperatures in the months of May to August at the Labská bouda Station was 1.45°C if the periods 1961–1990 and 1998–2009 were compared, i.e. an average increase in these temperatures was approximately 0.07°C per year (Matějka 2010). This temperature increase is important because, for instance, the value corresponds to 2.1°C over 30 years.

Linear regression of temperatures in the growing season between the years 1983 and 2011 (Table 2) is T = 0.0511 year – 92.256 (r = 0.466; P = 0.011), that means the average year-on-year increase in temperatures was moderately lower in that period, equalling 0.05°C per year. A significant increase in the sum of precipitation was also observed (0.0825 mm·day^{-1}·yr^{-1}; r = 0.477; P = 0.009).

With average temperatures in the growing season around 10°C, the additive effect of gradually increasing temperatures can be taken into account because these values are deeply below the value of spruce growth optimum (14.5°C; Pretzsch 2009). Hence it follows from the relation of a year-on-year change in height increment to temperature (Fig. 7) that the height increment of young spruce trees increased (at the value dT = 0.07°C per year) on average by 1.5 % and the estimate of an increase in height increment for ten years was 16.1%. The average year-on-year increase in average annual height increment adjusted for a change in tempera-

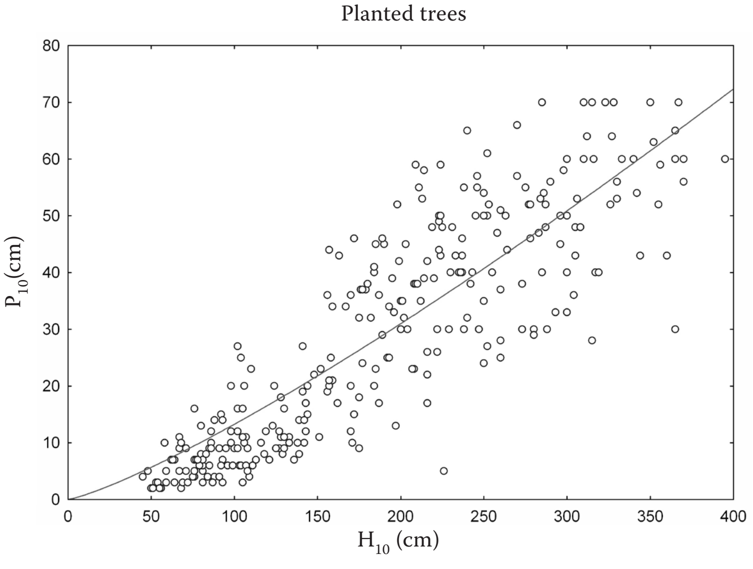

Fig. 6. Annual height increment (P) related to tree height (H) in the planted trees. All plots in 2010. The regression model P = a × H^b was applied (for parameters see Table 4)

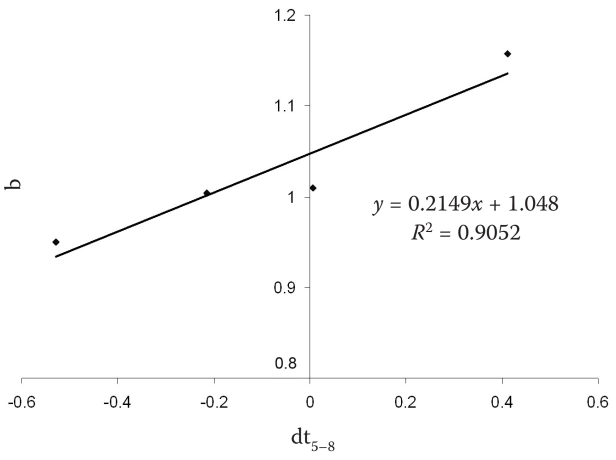

Fig. 7. Change in annual height increment between succeeding years is evaluated as the regression coefficient b (see Figs 1–4), probability $P = 0.046$. These coefficients depend on a difference in average air temperatures during May to August in both years (based on data from Labská bouda Station)

tures may be estimated to be 4.8% for the evaluated young stands. Similar analysis of the influence of precipitation variability on the spruce growth was not meaningful.

Other authors also reported an increase in growth rate in relation with increasing temperatures in higher mountainous locations (Paulsen et al. 2000; Kessler et al. 2007). This fact is explained by a climate change that contributes to a shift of the timberline to higher elevations.

The above-mentioned findings are preliminary because they are based on a very limited data set. Particularly, it is necessary to enlarge the data set on spruce growth in subsequent years with different climate conditions. It should be borne in mind that the results are applicable only to a comparable area of the 8th forest altitudinal zone because this tree species has different growth characteristics at lower elevations.

CONCLUSSIONS

The growth of young spruce populations that originated by natural regeneration is different from the growth of populations from outplanting. The average air temperature in the vegetation (growing) period, estimated as average temperature in the months of May to August at a nearby reference station, was proved to have a significant influence on year-on-year variability in spruce growth. Based on this finding, it was possible to estimate an increase in the height increment of young spruce (with tree height up to approximately 2 m) caused by warming up since the mid-70s of the 20th century to equal approximately 16% per decade in the spruce altitudinal zone in the Krkonoše Mts.

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