The effect of different stand density on diameter growth response in Scots pine stands in relation to climate situations

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ABSTRACT: The effect of stand density on the resistance of Scots pine (*Pinus sylvestris* L.) to climatic stress and subsequent response of diameter increment were investigated using data gathered from six long-term experimental series located in the typical pine regions of the Czech Republic (sandy nutrient-poor soils on the *Pineto-Quercetum oligotrophicum-arenosum*). Diameter growth of dominant individuals (with the largest diameter at the age before the first thinning) was measured in all variants of experimental series (control and thinned). Monthly average temperature and total precipitation were taken from the nearest climatological stations and, additionally, three climatic factors (precipitation and temperature ratio in different periods) were calculated. Diameter growth responses were analyzed in connection with long-term deviations of climatic characteristics. The effect of different stand density on diameter growth response in relation to climate situations was evaluated by cluster analysis and the variability of diameter growth response to climate situations was interpreted by the variance of correlation coefficients in groups of sample trees. The investigation confirmed the significant negative effect of meteorological drought on diameter increment of studied pine stands in the period of the last 30 years. At the same time, we observed a significant positive influence of higher spring (February, March) air temperatures on the annual diameter growth of dominant trees. The effect of stand density (in thinned stands) on the relation between diameter growth and climatic characteristic was not significant.

Keywords: diameter growth; *Pinus sylvestris*; precipitation; temperature; thinning

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) referred to the strong influence of climate change and other global changes on forest ecosystems in Europe (Alcamo et al. 2007). Annual mean temperatures in Europe are likely to increase more than the global mean (Christensen et al. 2007). Annual precipitation is very likely to increase in most of northern Europe and decrease in most of the Mediterranean area. In central Europe, precipitation is likely to increase in winter but decrease in summer. The risk of summer drought is likely to occur in central Europe and in the Mediterranean area.

Therefore, the question "How will forest tree species respond to these rapid changes?" is essential for current forestry management. The greatest risk will supposedly be in the lowlands where current precipitation is low and air temperatures are high. Additionally, forest stands under these conditions are located on sandy nutrient-poor sites mainly. Not only in central Europe, Scots pine (*Pinus sylvestris* L.) even-aged monocultures often occur in these localities.

Current pine forests had to undoubtedly cope with frequent drought in the last decades. The main effect of drought stress on pine stands is growth depression, poorer health condition or even high mortality. This is supported by many studies across Europe (e.g. Memelink 1951; Krecmer 1952; Koch 1956; Landa 1959; Orlov et al.

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1974; Tessier 1986; Hill 1993; Barsch et al. 1994; Beker 1996; Cech, Tomiczek 1996; Augustaitis 1998; Irvine et al. 1998; Makkonen, Helmisaari 1998; Linderholm, Molin 2005; Ozolincius et al. 2005; Davi et al. 2006; Eilmann et al. 2006; Weber et al. 2007). On the other hand, pine seemed to be more drought-tolerant than other common species (e.g. Vitas, Bitvinskas 1998; Cienciala et al. 1999). Consequently, the historical growth response of current pine stands to drought stress can contribute to prediction of future development of these stands.

However, information from common dendrochronology studies is mostly affected by the unknown complete history of investigated stand. But silvicultural measures performed in the stands can strongly influence observed growth responses (Sabaté et al. 2002).

Therefore, the objective of the present study was to find out answers to the following questions:

(1) What was the diameter growth response of current Scots pine stands to mentioned climate situations with respect to drought cases characterised by the interaction of precipitation deficiency and high temperature?

(2) Did the thinning regime have any effect on the diameter growth response of Scots pine stands to climate situations?

(3) What is the effect of thinning on variability of diameter growth response in pine stands?

In the Czech Republic, where pine stands take up 18% of the forest area, a relatively wide collection of long-term thinning experiments is available for this research. Some of the experiments are located on sandy nutrient-poor sites where possibilities of pine monocultures conversion are limited (we have no choice of favourable tree species). Despite limited conversion possibilities, we consider silvicultural management used to increase drought resistance of these pine stands as appropriate measures.

MATERIALS AND METHODS

Experimental stands design and site

In the present study, we used six long-term thinning Scots pine (*Pinus sylvestris* L.) experiments established in 1957–1992 by the Forestry and Game Management Research Institute (Table 1). The elevation of stands varied from 190 m to 260 m a.s.l. All stands are located on sandy nutrient-poor soils (arenic Podzol). The forest type was classified as *Pineto-Quercetum oligotrophicum* (*arenosum*) – *Musci* on experiments Bedovice I and II and Tyniste and as (*Carpineto-*)*Quercetum oligo-mesotrophicum – Calamagrostis epigeios*) on experiments Straznice I, II and III. According to data from the Czech Hydrometeorological Institute for the period 1961–2000, mean annual precipitation varies from 550 mm (experiments Straznice I, II and III) to 600 mm (experiments Bedovice I and II and Tyniste) and mean annual temperature from 8.5°C (experiments Bedovice I and II and Tyniste) to 9.0°C (experiments Straznice I, II and III).

Experimental stands were planted with the initial density of 6–15 thousand trees per ha with the exception of Bedovice I experiment, which was regenerated naturally, i.e. with the unknown initial density (Table 2).

According to the age of the first thinning, experiments are divided into two groups (Table 1): older (i.e. experiments with thinning that started at the age of 25–38 years) and younger (i.e. experiments with thinning that started at the age of 7–10 years). Prior to the first thinning, the stand characteristics were comparable on included variants (Table 2) without statistically significant differences. In "older" stands, density varied from 2,600 to 3,800 trees per ha before thinning, with the exception of naturally regenerated Bedovice I experiment, where a higher density was found (ca 9,000 trees·ha^{-1}). In younger experiments, stands were relatively similar in density before the first thinning (9,300–10,300 trees·ha^{-1}).

Experiments consist of two to three treatments, which in total comprised three thinning variants (2a, 3b, 4t) and unthinned control (1c). Variant 2a represents high thinning, i.e. positive selection from above and variant 3b represents low thinning. The intensity of thinning was set to account for 15–10% of the basal area during the first half of the rotation period (up to the age of 50 years) and for 10–6% of the basal area in the second half of rotation period. Full stocking and a five-year thinning interval were assumed. Where stocking was not full, the thinning intensity decreased to 30–50% of the original amount.

On the variants 4t in young stands, special treatments based on a combination of geometric thinning and individual selection were done. In Bedovice II experiment, variant 4t started by geometric thinning with 50% reduction (scheme 2+2, i.e. two rows were left and two rows were removed) at the age of 10 years. The schedule was followed by low thinning in the 5- and 10-year period. In Tyniste experiment, variant 4t started at the age of 7 years with a combination of geometric thinning (scheme 4+1, i.e. four rows were left and one row was re-

Table 1. Basic data about experiments and data collection

	Thinning experiment	Geografical location* of stands	Established (year)	Age of establishment (years)	Elevation of stands (m a.s.l.)	Variants	Increment core collection (date)	Climatological station	Geografical location* of station	Elevation of station (m a.s.l.)	Used climatological data (period)
Older	Straznice I	48°56'40" 17°12'16"	1962	33	207	1c, 2a, 3b	December 2003	Straznice (CHMI)	48°53'57" 17°20'17"	176	1970–2002
	Straznice II	48°56'37" 17°15'02"	1962	25	205	1c, 2a	April 2003				1970–2002
	Straznice III	48°57'44" 17°15'02"	1962	38	190	1c, 2a, 3b	April 2001				1970–2000
	Bedovice I	50°11'47" 16°02'08"	1957	27	260	1c, 2a, 3b	April 2003	Hradec Kralove (CHMI)	50°10'34" 15°50'19"	278	1971–2002
Younger	Bedovice II	50°11'47" 16°02'08"	1972	10	260	1c, 4t	#	Hradec Kralove (CHMI)	50°10'34" 15°50'19"	278	1972–1998
	Tyniste	50°11'35" 16°03'46"	1992	7	260	1c, 4t	#	Tyniste (FGMRI)	50°11'35" 16°03'46"	260	1992–2006

*in WGS 84 system, #without cores – diameter increment was detected from the annual measurement (see methods), CHMI – Czech Hydrometeorological Institute, FGMRI – Forestry and Game Management Research Institute, Variants: 1c – control unthinned plot, 2a – plot with positive selection from above, 3b – plot with low thinning, 4t – plot with combination of geometric thinning and individual selection

Table 2. Summary of the stand characteristics

	Older											Younger			
Thinning experiment	Straznice I			Straznice II		Straznice III			Bedovice I			Bedovice II		Tyniste	
Variant	1c	2a	3b	1c	2a	1c	2a	3b	1c	2a	3b	1c	4t	1c	4t
Area (ha)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.10	0.10	0.10	0.12	0.12	0.09	0.09
Original density planted (per 1 ha)	6,000	6,000	6,000	9,000	9,000	9,000	9,000	9,000	ca 12,000–15,000*			15,000	15,000	10,000	10,000
Initial before thinning (year – age)	1962 – 33 years			1962 – 25 years		1962 – 38 years			1957 – 27 years			1972 – 10 years		1992 – 7 years	
Number of trees (per 1 ha)	3,384	3,528	3,508	3,744	3,840	2,724	2,696	2,600	8,770	8,794	9,334	10,340	9,720	9,289	9,889
Basal area ($m^2 \cdot ha^{-1}$)	37.6	38.3	37.4	27.3	28.4	37.9	39.9	38.6	29.6	27.7	29.0	6.6	6.7	6.4	6.3
Final (year – age)	2002 – 73 years			2002 – 65 years		2002 – 78 years			2000 – 70 years			1998 – 36 years		2006 – 21 years	
Number of trees (per 1 ha)	788	744	852	800	760	696	588	620	1,210	1,320	840	3,017	2,025	5,211	3,600
Basal area ($m^2 \cdot ha^{-1}$)	36.8	35.8	37.7	33.3	36.8	39.2	37.0	37.4	37.0	42.3	37.1	45.6	39.4	34.6	29.4

*natural regeneration, – unknown density. For explanation of variants see Table 1 moved) and individual negative selection in the left rows (totally 50% reduction). The schedule was followed by individual positive selection in the 10-year period.

At the end of the observation period used for this study, the experimental stand showed the following characteristics (Table 2): in older stands, density varied from 620 to 1,320 trees per hectare. It represents basal area from 33.3 to 42.3 $m^2 \cdot ha^{-1}$. In younger experiments, the stands density varied from 2,025 to 5,211 trees$\cdot ha^{-1}$ with basal area from 29.4 to 45.6 $m^2 \cdot ha^{-1}$.

Data collection

Diameter increment data

The experimental stands were measured annually (younger stands) or every five years (older stands). Among others, diameter at breast height was measured to the nearest millimetre on all trees using a calliper. For further investigation we selected from 18 to 24 dominant individuals with the largest diameter before thinning from each variant of experiments (Table 3). Diameter increment data for the analyses were taken using two methods:

In older stands, one core sample was extracted with an increment Pressler borer at 1.3 m from identical direction of each tree from selected group, mounted on a wooden holder and the surface was prepared with belt sander. Ring widths were measured to the nearest 0.01 mm using a DIGI-MET (Bohrkernmeßgerät) which was made in Preisser Messtechnik, Grube KG Forstgerätestelle, Germany. The dating of tree ring series was checked again by existing chronologies from the regular measurement of diameter at breast height.

In younger stands, where stem cores were unacceptable because of smaller diameter (< 15 cm), diameter increment data were calculated from the annual measurement of diameter at breast height.

Age-related trends in diameter increment series of individual trees can be evaluated by different methods. For example, the method of moving averages was successfully used for oak stands (Petráš et al. 2007). In our study, we used the recommended growth function (Smelko, Dursky 1999) – the equation by Korf (1939, 1972) in the increment form:

$$Y = A \cdot \frac{k}{t^n} \cdot e^{\left[\frac{k}{(1-n) \cdot t^{n-1}}\right]}. \qquad (1)$$

where:

A, k, n – coefficients ($k \neq 0$, $n > 1$).

The outputs of analysis were residual chronologies (calculated from measured and modelled data) of all individual trees.

Climate data

Mean monthly temperatures (measured at a height of 2 m above the ground) and total monthly precipitation were available from nearby meteorological stations (two stations in total) operated by the Czech Hydrometeorological Institute (Table 1). Additionally, climatic data from a NOEL automatic station were used. This station is situated directly in Tyniste experimental stand and operated by the Forestry and Game Management Research Institute.

We calculated the long-term mean of monthly average temperatures and total monthly precipitation in accordance with the period of observation (Table 1). Additionally, average temperature and total precipitation from the vegetation period (April–September) and total monthly precipitation and average temperature from the spring period March–August were computed. Furthermore, long-term means of three climatic factors were determined using the following equations:

$$F1 = \frac{\text{total precipitation from February to June}}{\text{average temperature from April to August}}. \qquad (2)$$

Precipitation from several months before the growing season (February, March) can contribute to sufficient soil moisture when growth begins. The precipitation amount from the second half-year was not included. Temperatures characterised almost the whole vegetation period.

$$F2 = \frac{\text{total precipitation from November to June}}{\text{average temperature from April to September}}. \qquad (3)$$

The sum of precipitation in the first half-year is increased via the amount of precipitation in the last two months of the previous year (accumulation of winter precipitation). Temperatures characterised the whole vegetation period.

$$F3 = \frac{\text{total precipitation from April to June}}{\text{average temperature from April to June}}. \qquad (4)$$

This factor characterised the ratio of precipitation and temperature in the spring season only. Diameter increment of forest tree species is maximal in this period.

Finally, for each year from the period of observation we calculated deviations between mean values and measured values of presented climatic vari-

Table 3. Characteristic (diameter $d_{1.3}$) of group of observed trees for particular variants and experiments

		Older											Younger			
Thinning experiment		Straznice I			Straznice II		Straznice III			Bedovice I			Bedovice II		Tyniste	
Variant		1c	2a	3b	1c	2a	1c	2a	3b	1c	2a	3b	1c	4t	1c	4t
Number of trees (*N*)		20	20	20	20	20	20	20	20	20	20	20	24	24	18	18
Initial (year – age)		1962 – 33 years			1962 – 25 years		1962 – 38 years			1971 – 41 years			1972 – 10 years		1992 – 7 years	
$d_{1.3}$ (cm)	Mean	18.8	18.3	18.9	14.9	14.3	19.8	19.6	20.5	18.4	18.3	18.6	8.1	8.5	5.1	4.8
	SD	1.32	1.16	1.44	1.35	0.68	0.59	1.74	1.35	1.44	1.75	1.18	1.13	0.92	0.47	0.33
Final (year – age)		2002 – 73 years			2002 – 65 years		2002 – 78 years			2000 – 70 years			1998 – 36 years		2006 – 21 years	
$d_{1.3}$ (cm)	Mean	29.1	31.6	31.3	26.5	30.2	32.5	32.7	32.7	25.3	25.8	24.9	23.1	20.5	14.1	14.3
	SD	1.81	2.44	2.12	3.35	2.51	2.91	3.72	4.88	3.18	3.20	1.65	2.08	3.21	2.30	2.29

SD – standard deviation. For explanation of variants see Table 1

ables (monthly values, vegetation period, spring season and factors *F*1, *F*2 and *F*3).

The construction of climatic factor equations was supported by some studies. Fritts (1976) reported that growth–climate relationships must also be computed between ring indices and climate variables for several months before the growing season, because the width of the annual ring is an integration of climatically influenced processes taking place over a longer period. Diameter growth of coniferous trees started usually in April and subsided in the period of August–September. Therefore, temperatures in the period of April–June and precipitation in the period of June–August are of great significance in the driving diameter growth process in the stands (Smelko et al. 1992, Riemer , Sloboda 1991). A shorter but similar period (July–August) in relation to the negative drought effect on diameter increment was reported by Cienciala et al. (1997) in the 50-year-old pine stand. On the other hand, no effect of climate variables at the end of growing season on diameter growth of current year was found (Graumlich 1991). However, climate characteristics of the last months can influence growth of trees in the following year.

Data analyses

Data analyses were performed using the statistical software package UNISTAT®(version 5.1) and 3 steps included in total:

(1) Diameter growth response was determined using correlation coefficients characterising the long-term relationship between diameter growth (data from residual chronologies) and climate (long-term deviations between mean values and measured values of climatic variables). All sample trees were described using coefficients calculated and determined at the 95% confidence level. If 25% of trees within a group showed a significant correlation coefficient at the 95% confidence level (evaluated by summary statistics – lower and upper quartile), the growth response of the tree group was considered important.

(2) For the Principal Components Analysis all variables demonstrating a significant effect on diameter growth were applied for each experiment. We used a standard procedure of the multivariate data analysis method (Meloun, Militky 2002). Through the procedure, the number of variables was reduced according to Scree plot results. Two or three clusters (in accordance with the number of variants in individual ex-

periments) were determined. The Hierarchical Cluster Analysis method was used with distance measure as Euclid and linking method as Average Between Groups. We calculated the proportion of individuals by thinning variants for each cluster. This approach was used in order to support or disprove the hypothesis that a group of dominant trees from individual variants of thinning had the identical growth response to climate variation, i.e. differences between thinning variants in diameter growth response of dominant trees to climate variation significantly exist.

(3) Evaluation of growth response variability within the group of trees in the experiments was the last step of data analyses. Variability was determined by variance of correlation coefficients for detected significant relationships (see the first step of data analyses). We compared the variability of growth response in control unthinned variants against thinned variants.

RESULTS

The effect of drought on diameter increment of pine stands

In our study, drought is predominantly represented by three climatic factors *F*1, *F*2 and *F*3, which were calculated as the ratio of precipitation and temperatures in selected periods (for more details see the Method). It means that lower values of these factors showed a possibility of drought in the period of the last ca 30 years. Dominant pine trees showed positive diameter growth responses to higher values of climatic factors (Table 4). However, a significant relationship was observed for neighbouring experiments Bedovice I and II only.

There is a possibility that drought might also be caused over a long period with low precipitation or higher temperatures. This is important mainly during the growing season. In the observed experiments, climate variations in the spring season from April to June (A–J) and in the vegetation period from April to September (A–S) were important for diameter growth of pine stands (Table 4). A negative effect of higher temperature in spring (A–J) and in vegetation period (A–S) on annual diameter increment was observed on experiment Tyniste and Bedovice I, respectively. On the other hand, we found a positive effect of the higher sum of precipitation in the spring season (experiments Bedovice I and II) and in the growing season (experiments Straznice II, Bedovice II and Tyniste) on diameter growth of dominant trees.

At the same time, we observed a significant positive influence of higher air temperatures in early spring (February, March) on annual diameter growth of dominant trees on four experiments (Straznice

Table 4. Significance (for explanation see Methods) of growth response to climate variables according to experiments and variants

Experiment	Variant	Climatic factors			Temperature										Precipitation							
		*F*1	*F*2	*F*3	A–J	A–S	J	F	M	A	M	J	J	A	A–J	A–S	J	M	A	M	J	J
Straznice I	1c							+	+								–					
	2a							+									–					
	3b							+	+													+
Straznice II	1c															+						
	2a												–	–								
Straznice III	1c							+			+	–					–					
	2a							+														
	3b																					
Bedovice I	1c							+	+						+		–		+			
	2a	+		+				+									–		+			
	3b					–		+	+				–				–					
Bedovice II	1c	+	+	+				+							+	+	–		+		+	
	4t	+	+	+											+				+		+	
Tyniste	1c									–								–		+		
	4t				–					–						+						

For explanation of variants see Table 1. *F*1, *F*2, *F*3 – climatic factors (for definition see Methods), A–J – April–June, A–S – April–September, Single letters mean particular months continually in the current year

I and II, Bedovice I and II). Mean temperatures in May also had a positive effect on diameter growth on Straznice III experiment. For the other months (April, June, July and August), a negative influence of higher air temperatures on diameter growth was found on some experiments (Table 4).

Mainly positive effects of higher sums of precipitation in the particular months on annual diameter growth were detected (for April, May, June and July). On the other hand, the higher sum of precipitation in January (four experiments) and in March (one experiment) had a negative influence on annual diameter growth. This result (negative influence of higher sum of precipitation on growth) might be surprising. We can find an explanation within the climate series: the sum of precipitation in January correlated negatively (at the 95% confidence level) with the sum of precipitation in April and mean temperature in March (Hradec Kralove station) and/or with mean temperature in February and March (Straznice station).

Finally, for the relationship between climate and diameter growth, the most important (statistically significant) climate variables were: (a) in "older" stands mean temperature in February (Straznice I, Straznice III and Bedovice I) and sum of precipitation in the vegetation period from April to September (Straznice II); (b) in younger stands climate factor *F*1 (Bedovice experiment) and mean temperature in April (Tyniste). The effect of these variables on diameter growth of dominant pine trees was positive in three cases (factor *F*1, temperatures in February and precipitation in the vegetation period) and negative in one case (temperatures in April) (Figs. 1 and 2).

Effect of stand density (thinning) on pine resistance to drought stress

All variables that showed significant (positive or negative) effects on diameter growth (Table 4) were subjected to Principal Components Analysis (PCA). During the procedure, the number of variables was reduced (according to Scree plot results) to 2–4. In Straznice I experiment, three variables were separated via the analysis: sum of precipitation in July and mean temperature in January and February. Only two important variables – sum of precipitation in the vegetation period (from April to September) and mean temperature in July – were found in Straznice II experiment. For Straznice III experiment we separated three variables using the PCA analysis: mean temperature in February, May and June.

Four variables in total were found for neighbouring experiments Bedovice I (climatic factor *F*1, sum of precipitation in April and mean temperature in February and in the vegetation period from April to September) and Bedovice II (climatic factors *F*1 and *F*2, sum of precipitation in the vegetation period from April to September and mean temperature in February). Finally, for Tyniste experiment four variables were chosen: sum of precipitation in March, May and in the vegetation period (April–September) and mean temperature in the spring season from April to June.

Two or three clusters (in accordance with the number of variants in individual experiments) were determined subsequently and we calculated the proportion of individuals by thinning variants within

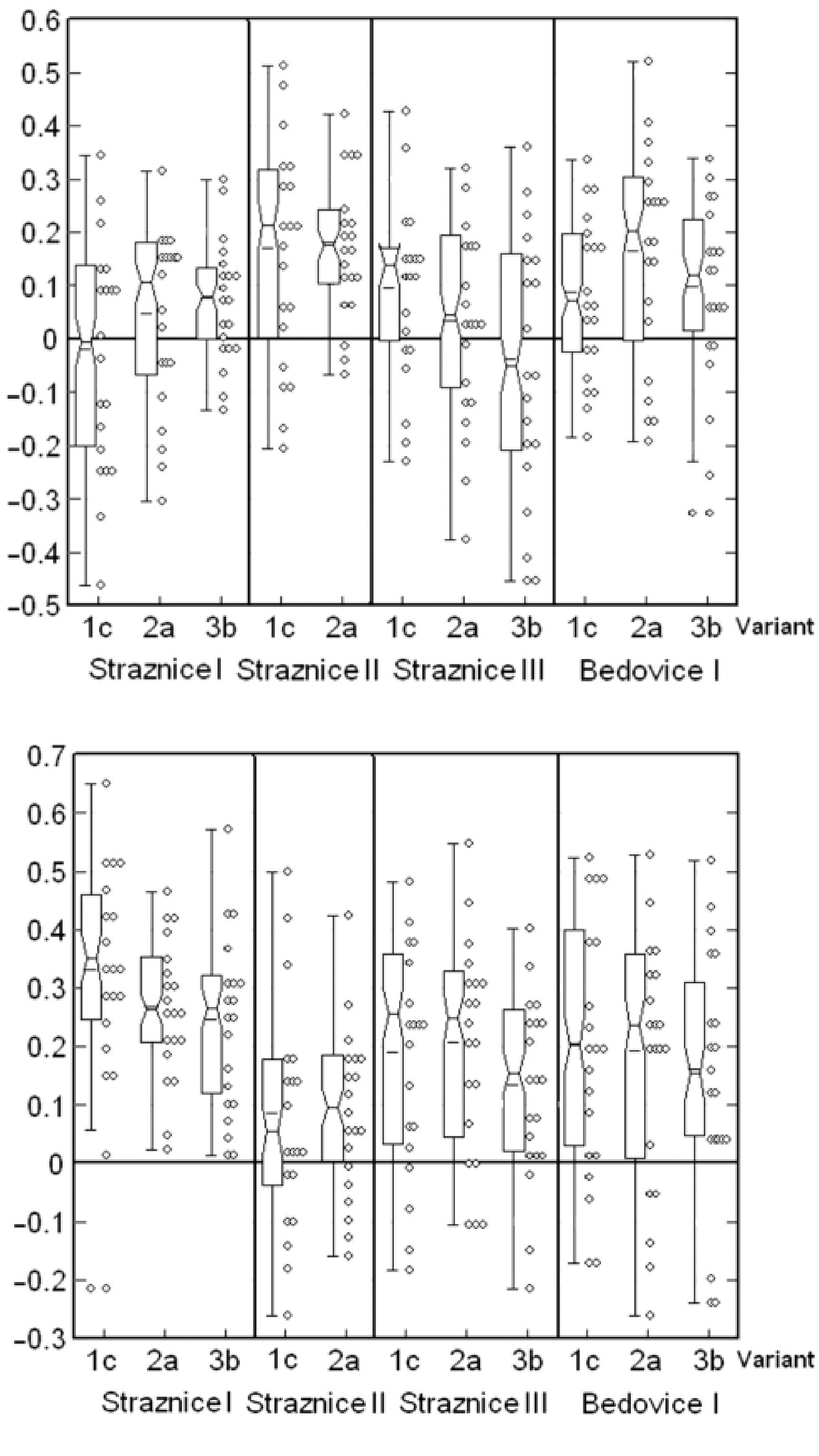

Fig. 1 Comparison of growth response to climate variables (mean temperature in February – above, sum of precipitation in the period of April–September – below) in older experiments Straznice I, II and III and Bedovice I. Variants: 1c – control unthinned plot, 2a – plot with positive selection from above, 3b – plot with low thinning.

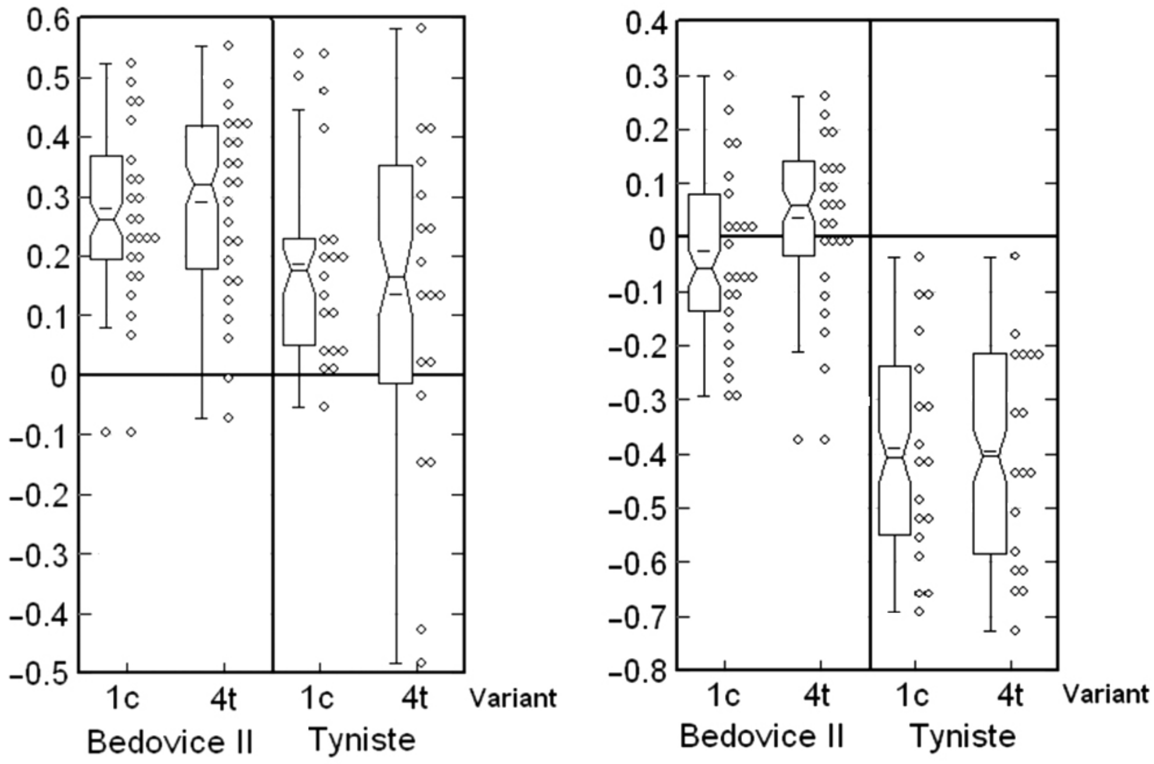

Fig. 2. Comparison of growth response to climate variables (climate factor F1 – left, mean temperature in April – right) in younger experiments Bedovice II and Tyniste. Variants: 1c – control unthinned plot, 4t – plot with combination of geometric thinning and individual selection

each cluster (Fig. 3). The results showed that groups of dominant trees from the particular variants of thinning did not have the identical growth response to climate variation. Each cluster included trees mostly from all variants that were observed in the particular experiments. Straznice III experiment is the only exception. Small proportions of trees (15% in variant 2a with positive selection from above and 20% in variant 3b with low thinning) responded similarly and no individuals from the control unthinned plot belonged to their cluster. In all the remaining experiments, trees from thinned variants (2a, 3b, 4t) were included in the clusters together with trees from unthinned control plots 1c.

Variability of growth response of pine stands to climate characteristic in relation to thinning

Variability of growth response was determined by the variance of correlation coefficients for variables detected using PCA during the previous steps. The effect of thinning on the variability of diameter

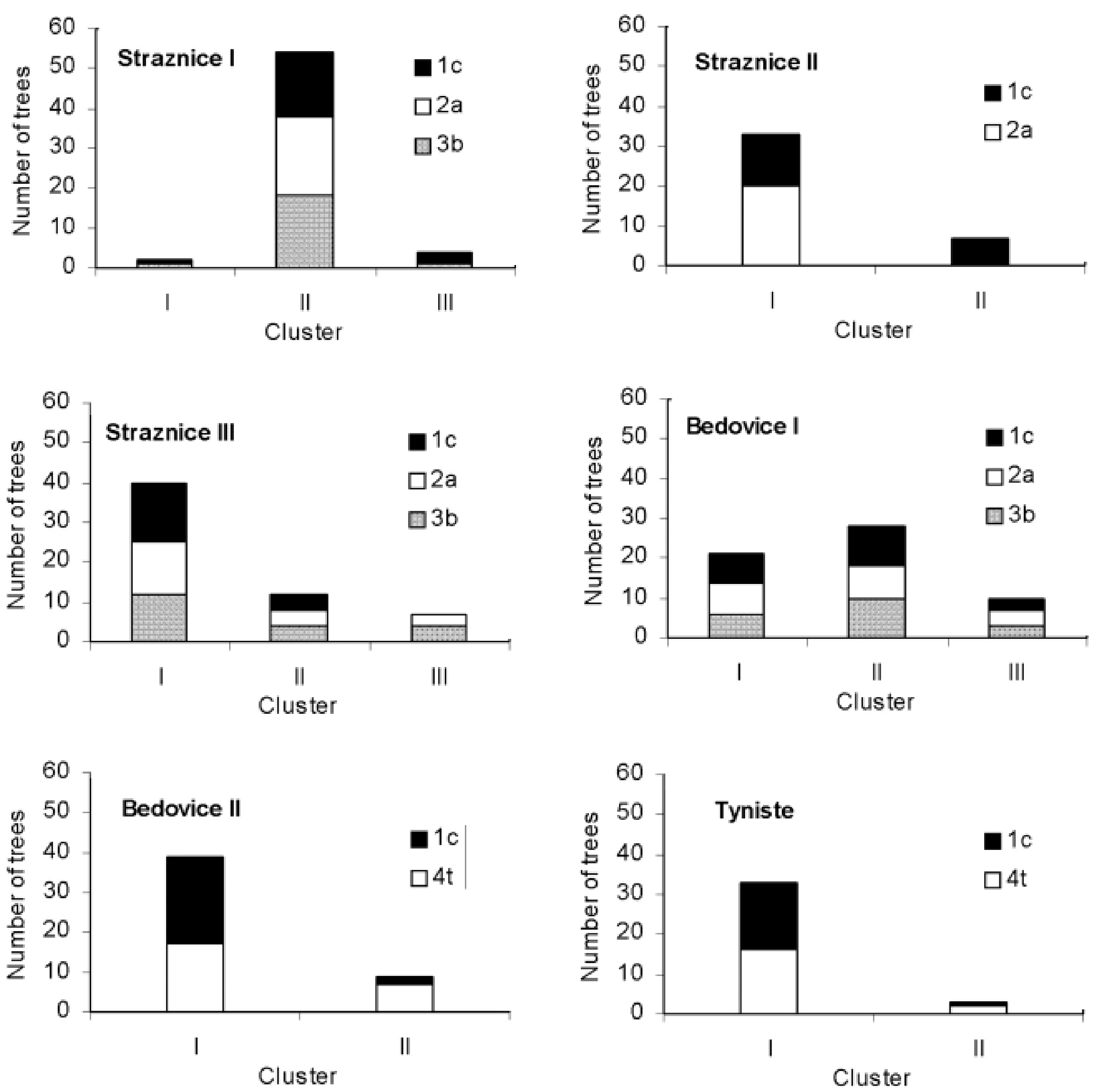

Fig. 3. Clusters resulting from the analysis figured according to particular experiments. Variants: 1c – control unthinned plot, 2a – plot with positive selection from above, 3b – plot with low thinning, 4t – plot with the combination of geometric thinning and individual selection

growth response to climate situations was not uniform (Table 5). When we labelled the variance of correlation coefficients on the control unthinned plot as 100%, the results showed that dominant trees from thinned stands demonstrated in some cases higher (> 105%), comparable (95–105%) and lower (< 95%) variability of diameter growth response in comparison with those from control stands.

However, some trends are obvious. In two experiments (Straznice I and II), dominant trees from variants 2a with positive selection from above had either lower or comparable (in one case in Straznice I experiment) variability of growth response in comparison with relevant control stands. On the other hand, in Straznice III experiment, trees from this variant of thinning (2a) showed either higher or comparable (in one case) variability. In the younger stands (Bedovice II and Tyniste experiments) the results were quite uncomplicated. Nearly in all cases, dominant trees from thinned stands (variant 4t) showed the higher variability of diameter growth response in comparison with those from control stands.

DISCUSSION

The response of Scots pine to climatic conditions has been extensively discussed over the last few decades. Pine is considered a species that is highly tolerant to climate change (Vitas, Bitvinskas 1998; Barbéro et al. 1998), and has been grown under a variety of environmental conditions across Europe and Asia (Richardson, Rundel 1998). Nowadays, forestry science faces the problem of tree species behaviour under conditions of climate extremes suggesting possible climate changes. The Scots pine response to a predicted shift in climate seems to be dependent upon particular site condi-

Table 5. Variability of growth response – determined by variance of correlation coefficients for detected significant relationship (see Methods for detailed explanation)

Experiment	Variant	Variance of correlation coefficients (control plot = 100%)							
Climate variables		prec. July		temp. February		temp. March			
Straznice I	1c	0.0253	100%	0.0376	100%	0.0244	100%		
	2a	0.0242	96%	0.0148	39%	0.0127	52%		
	3b	0.0286	113%	0.0228	61%	0.0283	116%		
Climate variables		prec. April–Sept.		temp. July					
Straznice II	1c	0.0416	100%	0.0203	100%				
	2a	0.0175	42%	0.0093	46%				
Climate variables		temp. February		temp. May		temp. June			
Straznice III	1c	0.0380	100%	0.0133	100%	0.0326	100%		
	2a	0.0355	93%	0.0340	256%	0.0385	118%		
	3b	0.0253	67%	0.0400	301%	0.0211	65%		
Climate variables		*F*1		prec. April		temp. April–Sept.		temp. February	
Bedovice I	1c	0.0273	100%	0.0208	100%	0.0271	100%	0.0479	100%
	2a	0.0177	65%	0.0199	96%	0.0427	158%	0.0475	99%
	3b	0.0264	97%	0.0271	130%	0.0435	161%	0.0460	96%
Climate variables		*F*1		*F*2		prec. April–Sept.		temp. February	
Bedovice II	1c	0.0219	100%	0.0300	100%	0.0163	100%	0.0304	100%
	4t	0.0254	116%	0.0304	101%	0.0338	207%	0.0435	143%
Climate variables		prec. March		prec. May		prec. April–Sept.		temp. April–June	
Tyniste	1c	0.0423	100%	0.0400	100%	0.0342	100%	0.0450	100%
	4t	0.0427	101%	0.0603	151%	0.0995	291%	0.0829	184%

Temp. – temperature, prec. – precipitation. For explanation of variants see Table 1, *F*1, *F*2 – climatic factors (for definition see Methods) tions as noted by Dursky and Pavlickova (1998), when they reported a positive growth response to the expected change. The only negatively responding trees were found at the poorest sites (acidic oak wood with pine). However, the question is which climatic variable is the driving variable for the relationship between pines and growth conditions. Grace and Norton (1990) reported temperature more important than rainfall in influencing growth; a significantly positive correlation between the ring width and both late winter (January–February) and summer (July–August) temperatures was found. The importance of late winter/early spring temperatures was confirmed in the study from Poland (Feliksik, Wilczyński 2000) where a positive relationship between January–March temperatures and wide rings was found. In addition to warm spring (February, March), the autumn temperatures are also considered to be positively affecting the radial growth of pine (Rundel, Yoder 1998; Vitas 2004). Consistently with reported information on the positive effect of higher spring temperatures, we found the positively influenced radial growth of dominant trees in relation to February–March temperatures on four experimental plots (Straznice I and II, Bedovice I and II). On the other hand, summer droughts influence the radial growth of pines rather adversely (Tessier 1986; Riek et al. 1995; Feliksik, Wilczyński 2000; Rigling et al. 2002; Pichler, Oberhuber 2007; Vitas 2004). In accordance with these results, the spring/late spring and summer temperatures were found to negatively influence the diameter growth in our experiments.

Besides early spring temperatures, a positive effect of the higher sum of spring precipitation on the radial growth was found in Bedovice I and II experiments; a similar response was observed for vegetation season precipitation in experiments Straznice II, Bedovice II and Tyniste. Some studies also pointed out the current early spring (Linderholm 2001) and vegetation period (Riemer, Sloboda 1991) precipitation as an important climatic factor influencing Scots pine. Feliksik and Wilczyński (2000) also reported the high summer rainfall as related to wide growth rings. From the season aspect, our results confirm the positive effect of precipitation on annual diameter increment detected in April, May, June (Miller et al. 1977; Oberhuber et al. 1998; Oberhuber 2001) and July. In contrast with Rigling et al. (2002), January (four experiments) and March (one experiment) temperatures proved a negative influence upon annual radial growth.

Based on the results of our study, no significant effects of thinning (stand density management) on the relation between diameter growth and climatic characteristics were detected. Using the methods of increment evaluation (growth function) can be a reason for our ambiguous results. A different method (moving averages) was applied in other similar studies (e.g. Petráš et al. 2007).

On the other hand, Biryukova et al. (1989) reported similar results that thinning did not increase the resistance of pine stands to drought. The dependence of drought resistance on the geographical location of pine provenances was not found in Poland (Przybylski, Malecki 1993). The effect of thinning on dominant trees seems to be negligible from the production aspect (Varmola, Salminen 2004). However, increased variability in the young thinned stands (Bedovice II and Tyniste experiments) confirmed higher growth response variability of pine stands in relation to precipitation (Dursky, Pavlickova 1998; Palmroth et al. 1999). The effect of thinning on growth characteristics is obviously greater in the early thinned pine stands compared to older ones (Eder 1999; Hartig 1999; Huss 1999).

The growth response of thinned young stands is likely to be related to increased availability of water (lower interception) and generally better growth conditions (temperature, radiation). Chroust (1977) confirmed the importance of early thinning of pine stands as highly favourable at sandy and permeable sites in low-precipitation areas.

Consequently, our results support the hypothesis that silvicultural management is likely to result in an increase in drought resistance only in the young pine stands. Subsequently our study suggests that the thinning of older pine stands leads to an insignificant change in drought resistance.

CONCLUSION

On the basis of the study aimed at the effect of stand density on Scots pine resistance to drought stress and subsequent response of diameter increment, carried out in six long-term experimental series with thinning located in the Czech Republic, we conclude:

The investigation confirmed the significant negative effect of meteorological drought on diameter increment of studied pine stands in the period of the last 30 years. At the same time, we observed a significant positive influence of higher spring (February, March) air temperature on the annual diameter growth of dominant trees.

Dominant trees from the particular variants of thinning did not show the identical growth responses to climate variation, except for one experiment (Straznice III), where a small proportion of trees (15–20%) from thinned variants responded similarly and both were different from unthinned individuals on the control plot. Trees from thinned variants in all the other experiments responded similarly together with trees from unthinned control plots.

In the younger pine stands (Bedovice II and Tyniste experiments) dominant trees from thinned stands (variant 4t) showed higher variability of diameter growth response in comparison with those from control stands. In the older stands this result was not significant.

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