Dendroecological study of spruce growth in regions under long-term air pollution load

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ABSTRACT: The purpose of this study was to analyse increment cores from spruce growing in the Ore Mountains, Jizerské Mountains, and Giant Mountains, to evaluate the relationship between tree growth, climatic factors, and air pollution load. The sites from which sample cores were extracted were localised along an altitudinal gradient. Analytical methods included single pointer year analysis and simple linear regression. An unambiguous relationship between negative pointer years and climatic extremes was detected for growth increments prior to 1977. After 1977, minimum increment values also reflected the gradient of air pollution levels. In the eastern part of the Ore Mountains, an increased sensitivity of spruce to low temperatures and temperature breaks was evident. The dominant role of temperature during the winter period was confirmed by the results of correlation analysis. From this, I have concluded (indirectly) a long-term deleterious impact of sulphur dioxide, resulting in lower frost resistance of the spruce trees. Recent increment development suggested that the stands in the Giant Mountains overcame the critical period at the end of the 1980's, and regenerated well. By contrast, the ecological stability of the Ore Mountain forests was disturbed due to chronic stress, and the existence of the stands is threatened.

Keywords: growth increment; spruce; climate; air pollution; Ore Mountains; Giant Mountains; Jizerské Mountains

The area comprising the Ore Mountains (Krušné hory), Jizerské Mountains (Jizerské hory), and Giant Mountains (Krkonoše) is the most air polluted region in Central Europe. The Ore Mountains (Mts.), mainly the eastern part, have been exposed to immissions for nearly 150 years.

In the 1950's, the first dendrochronological studies were initiated to examine the impact of smoke emissions on forest stands in the Ore Mountains region (MATERNA 1956). With increasing visible damage to stands the effort to quantify it was intensified. This led MATERNA and VINŠ (1957) to present a proposal for continuous research on "smoke damage" in the Ore Mountains region. A network of permanent plots was subsequently established. During the study of these plots, a detailed methodology for determining increment losses in relation to the extent of stand damage was developed (VINŠ 1962). During 1954–1963, the losses were from 20% in slightly damaged stands to 65% in heavily damaged, dying stands (VINŠ, LUDERA

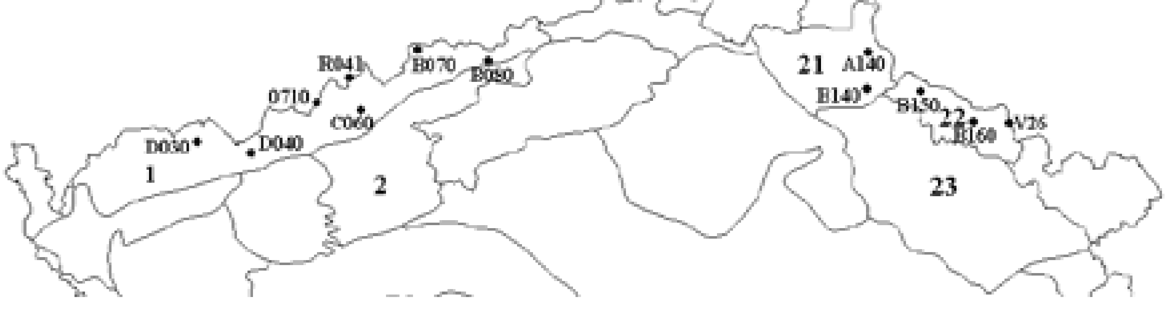

Fig. 1. Location of sample plots

The study was undertaken in conjunction with the Project VaV 620/1/99 of the Ministry of Environment *Causes of Damage to Forest Ecosystems and Prognosis of Further Development, Including Proposal on Remedial Measures in Regions under Heavy Air Pollution Load.*

1967). A similar approach to tree-ring analysis was used in the following years to classify stand productivity losses in other two regions: in Trutnov (VINŠ, TESAŘ 1969), and Jizerské Mts. (VINŠ, POSPÍŠIL 1973).

With increasing damage to the forest stands in the 1970's and 1980's, increment losses were studied less as more attention was given to the study of relationships between growth and environmental factors. For example, SANDER et al. (1995) studied tree growth (tree-ring width and latewood maximum density) in relation to climatic factors and air-pollution in Labský důl locality in the Giant Mts.

This dendroecological study partly continues the work by SANDER et al. (1995). Spruce growth was investigated in the Giant Mts. and in other heavily polluted regions – the Ore Mts. and Jizerské Mts. The dynamics of tree growth and the relation of ring width to climatic factors were studied. In the Ore Mts., for which continuous records of long-term sulphur dioxide (SO_2) concentrations were available, the relationship of tree growth to pollution levels was analysed in detail. The objective of this study was to evaluate the current state of surviving old spruce stands, by using tree-ring analysis in relation to climatic factors and past air pollution levels.

MATERIALS AND METHODS

A plot grid of the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP-Forest) was used for sampling. The plots are shown on the background of a map of Northern Bohemia forest regions (Fig. 1). The basic characteristics of the sample plots are given in Table 1.

Increment cores were taken in 1988, 1992, and 1999. At each plot, 24 sample trees of average diameter at breast height (d.b.h.) 130 cm were selected. From each tree, two cores were taken at breast height. Tree rings were measured with an accuracy of 0.01 mm, and the resulting ring-width series were cross-dated, checked and corrected for missing and false rings. The ring-width series were dated and corrected using the DAS-programme. Dating was verified statistically with the COFECHA-programme (HOLMES et al. 1986).

Critical periods of tree growth were estimated by evaluating the occurrence of irregularities in tree-ring formation (wedging and missing rings).

The method of single pointer years analysis (SCHWEINGRUBER et al. 1990; DESPLANQUE et al. 1999) was used to estimate the influence of extreme climatic events and other abiotic factors on diameter growth. For each tree, the negative event years were defined as extreme narrow ring widths that were 40% or less compared with the average value of ring widths in the previous four years (SCHWEINGRUBER et al. 1990). A negative pointer year occurred when an event year was identified for at least 20% of the trees within the plot.

Ring-width series were standardised to eliminate the age trend with the programme ARSTAN (HOLMES et al.

Table 1. Characteristics of sample sites

Region	Ore Mts.							Jizerské Mts.		Giant Mts.		
	East					West						
Plot name	Krupka	Orasín	Kálek	Fláje	Hora sv. Šebestiána	Mariánská zatáčka	Horní Blatná	Špičák	Smědava	Pec pod Sněžkou	Harrachov	Lysečinský hřeben
Plot code	B 080	C 060	R 041	B 070	0710	D 040	D 030	B 140	A 140	B 160	B 150	V 26
E longit.	13 51 34	13 24 54	13 21 11	13 35 37	13 13 15	13 02 05	12 47 40	15 16 42	15 16 04	15 42 40	15 29 01	15 50 26
N latit.	50 41 50	50 31 58	50 36 33	50 42 02	50 32 06	50 23 19	50 23 49	50 45 13	50 50 30	50 42 09	50 45 50	50 42 42
Aspect	SE	A	N	W	SW	NE	plane	NE	NE	SW	N	SW
Altitude	557	582	600	706	815	990	993	750	850	1,050	1,030	1,130
Age	76	80	108	70	50	90	97	73	70	116	78	90
Forest type	6S6	5K1	6N1	7K4	8G3	8M3	8M3	6S4	7R2	7N4	8F1	
Soil	dystric cambisols	dystric cambisols		cambic podzols			haplic podzols	cambic podzols	umbric gleysols	ferric podzols	haplic podzols	

Table 2. Meteorological stations (Czech Hydrometeorological Institute – CHMI)

Region Meteorological station	Station code (CHMI)	Altitude	Monthly data		Daily data	
			temperature	precipitation	temperature	precipitation
Ore Mts.						
Nová Ves v Horách	U1NOVE02	725	1956–1999	1956–1999	1969–1999	1969–1999
Boleboř	U1BOLR01	640		1961–1999		
Jizerské Mts.						
Bedřichov	U2BEDR01	777	1959–1999	1959–1999		
Desná-Souš	P2DESN01	772	1930–1999	1930–1999	1969–1999	1969–1999
Giant Mts.						
Vysoké nad Jizerou	P2VYSO01	670	1955–1993	1955–1999		
Harrachov	P2HARR01	670	1948–1999	1948–1999	1969–1999	1969–1999

1986). As the first step, the trend was approximated by a negative exponential function or regression line and the index series was obtained. As the second step, the spline was fitted to these index series. The remaining autocorrelation was removed by autoregressive modelling. The resulting index series were aggregated by calculating mean values into the local chronologies.

For the dendroclimatological evaluation, the monthly and daily meteorological data were used (mean monthly temperatures and sum of monthly precipitation, mean daily temperatures and sum of daily precipitation). A list of the stations, together with the periods for which the continuous series of monthly and daily data were obtained, is presented in Table 2.

First the monthly and daily climatic data of the three selected stations (Harrachov, Desná, Nová Ves v Horách) were analysed to determine the seasonal and short-term weather extremities. Given that the intent was to study spruce growth in mountain regions, attention was focused mainly on temperature fluctuations. Seasonal temperature extremes were determined in terms of 99%, 95%, and 90% percentiles of the mean winter temperatures (January–March), and during the growing season (April–September). Similarly, the seasonal precipitation extremes were presented as 1%, 5%, and 10% percentiles of the total precipitation during the growing season. Short-term temperature extremes were computed using the following functions developed by ŠRÁMEK (2000):

Drop of the mean daily temperature in two subsequent days

$$X = T_{d-1} - T_d \quad (1)$$

Drop of the mean daily temperature in four subsequent days (see also AUCLAIR et al. 1996)

$$X = T_{d-3} - T_d \quad (2)$$

Differences in two subsequent ten-day periods

$$X = ((T_{d-11} + T_{d-12} + ... + T_{d-20})/10) - ((T + T_{d-1} + ... + T_{d-10})/10) \quad (3)$$

Cold ten-day periods

$$X = (T + T_{d-1} + ... + T_{d-10})/10) \quad (4)$$

where: X – calculated factor,
T – mean daily temperature of the actual day,
T_{d-1} – mean daily temperature on a previous day,
T_{d-3} – mean daily temperature three days before the day evaluated,
$T_{d-10, 11, 20}$ – ditto.

Factor X (given short-term extreme) was calculated for each day for which climate data were available. Periods for which X exceeded the 99.9% percentile in functions (1–3), or dropped below the 0.1% percentile in function (4), were classified as extreme. Periods during which the

Table 3. SO_2 stations in the Ore Mts. (FGMRI, CHMI)

Station	Station code (CHMI)	Altitude	Mean monthly [SO_2]	Maximum monthly [SO_2]
FGMRI				
Klínovec		1,244	1972–1998	
Suchá		750	1977–1997	
Studenec		660	1972–1998	
CHMI				
Blatno	U1BLAT01	595		1971–1998
Výsluní	U1VYSL02	740		1971–1998

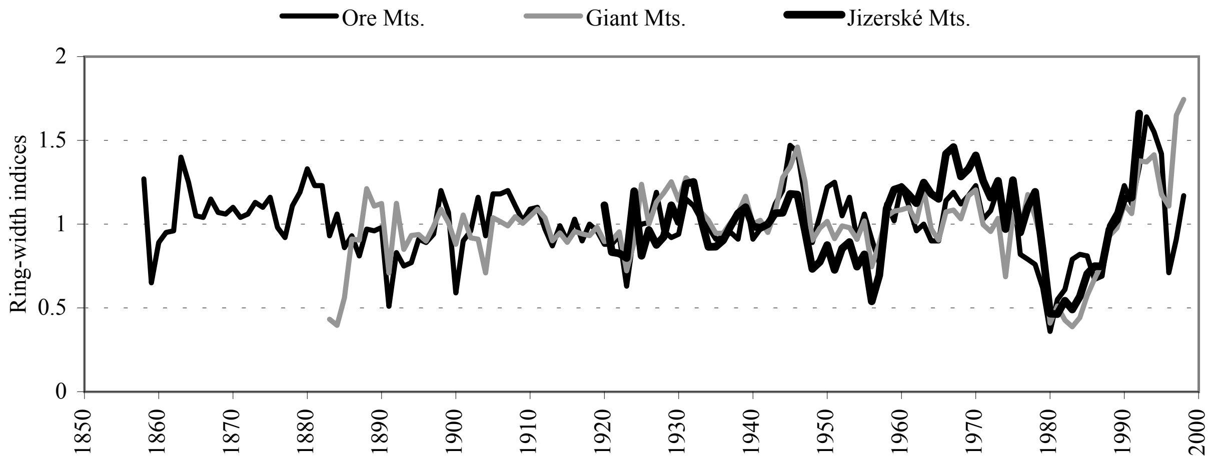

Fig. 2. Regional ring-width chronologies

temperature did not drop below 0°C were not classified as significant. Attention was focused on the periods for which temperature extremes were registered at all the three stations.

The occurrence of both seasonal and short-term weather extremes was used for ecological interpretation of observed negative pointer years. Given that spruce growth in a current year is also strongly affected by the climatic and environmental conditions in the year previous to the year in which the given tree ring formed, data for these years were included in the evaluation.

For the second stage of dendroclimatological evaluation, the monthly climatic data of the stations in Jizerské Mts. and Giant Mts. were checked for homogeneity and then aggregated into the regional climatic chronology. For the Ore Mts. region, the data of the station Nová Ves v Horách was used. The climate-growth relationship was computed by a simple correlation analysis for the period 1956–1998. The residual local chronologies (series of ring-width indices with the autocorrelation removed) were correlated gradually to mean monthly temperatures and precipitation from May of the previous year to September of the current year when the given ring formed (in total 17 months).

For the spruce in the Ore Mts. a correlation analysis of air pollution and tree growth was carried out. The mean monthly SO_2 concentrations were taken from the Forestry and Game Management Research Institute (FGMRI) stations. Maximum monthly SO_2 concentrations were taken from the stations of the Czech Hydrometeorological Institute (CHMI). Both the average and maximum values were summarised in regional chronologies. The stations of the longest continuous time series are presented in Table 3.

The series of ring-width indices were similarly gradually correlated to the mean and maximum values, respectively, of monthly SO_2 concentrations in the given sequence of months. The series of SO_2 concentrations were also analysed to estimate extremities in the pollution values. Given that only monthly data were available, only monthly and seasonal extremes could be determined: 99% and 95% percentiles were calculated for the mean and maximum monthly SO_2 concentrations. The same percentiles were presented for the average winter dor-

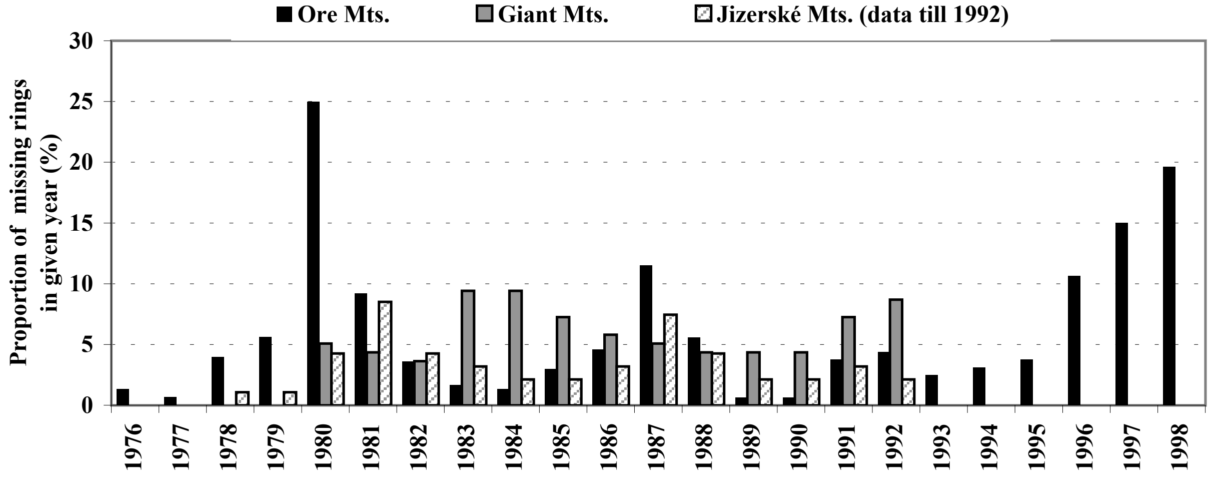

Fig. 3. Proportion of missing rings in tree-ring series

mancy period (October–March), when air pollution usually reached the maximum values.

RESULTS AND DISCUSSION

GROWTH DYNAMICS

Spruce radial growth in the Ore, Jizerské, and Giant Mts. showed similar trends (Fig. 2). An abrupt growth decrease was observed in the second half of the 1970's, enduring until 1983. Thereafter, growth began to improve. The year 1989 marked the end of a severe growth depression. Similar trends are also confirmed by RÖHLE (1999) for spruce in the Saxon region of the Ore Mts., and by SANDER et al. (1995) for spruce in the Labský důl locality of the Giant Mts. At the end of 1980's and in the first half of the 1990's, the stands regenerated, and in 1992–1994 the increments exceeded the values of the mid-1960's. In the Ore Mts., this favourable trend was interrupted by a deep growth decline in 1996.

The beginning of disruptions in tree ring formation at all three localities was evident during the second half of the 1970's (Fig. 3). The highest number of missing rings was identified in the ring-width series in the Ore Mts. A significant increase in the number of missing rings in the Ore Mts. after 1995 indicated a critical period; contrary to the situation in the Giant Mts., where the last irregularities were recorded in 1992.

SINGLE POINTER YEARS

The occurrence of negative pointer years was analysed for the period 1940–1998 (Table 4). The most distinct pointers were 1948, 1956, 1974, 1976–1983, 1986–1987, 1996, and 1997. Tables 5 and 6 summarise results of the analysis of climatic and air-pollution extremities in relation to identified pointer years.

Winter 1946/1947 was very cold (heavy frosts in January and February), with sub-normal precipitation. NĚMEC (1952) believes that low temperatures were the cause of spruce stand damage, observed in spring 1947 near Nová Ves v Horách in the eastern part of the Ore Mts. On the basis of available stand damage descriptive information, SO_2 emission values, and also some results of leaf and soil analyses at that time, MATERNA (1999) concluded that the interaction of low temperatures and air pollution load was the cause of damage. However, according to the single pointer year analysis, in 1947, an abrupt growth change was observed only at two plots in the Ore Mts., situated at the lowest altitudes, which may instead be indicative of extreme drought in that year. With the other higher altitude stands, where precipitation should not be a limiting factor, no stand growth decrease in that year was observed. It seems likely that the air-pollution damage to spruce stands was local, being observed only at the end of Mariánské valley, which was exposed to strong immissions.

By contrast, in 1948, growth decrease was observed at nearly all plots. The analysis of monthly climatic data did not indicate any weather extreme. It seems likely that spruce responded, with some delay, to drought in the previous year. The monthly climate data of Desná and Harrachov show that the dry and very warm weather lasted until October 1947.

The year 1956 had extreme temperatures in the winter period. Growth decrease can be related to heavy frost in February of that year. The fact that the strong decrease was observed at all the plots in the Ore and Jizerské Mts., regardless of the altitude, but not at any of the Giant Mts. plots is of interest. WENTZEL (1956) concluded that serious stand damage after the winter of 1955/1956 was connected with lower resistance to frost combined with the SO_2 effect. From this perspective, different responses of the stands can be explained by higher air-pollution levels in the Ore and Jizerské Mts. However, in comparison with 1947 data, the effect was not of local character. MATERNA (1999) shows that in 1956 all stands in the eastern part of the Ore Mts. and Děčínský Sněžník region were damaged.

Pointer years 1947/1948 and 1956 corresponded with minimum tree growth on a regional scale. In the Czech Republic, minimum pointer years were identified for spruce also in the Beskydy and Orlické Mts. (BÍBA, KROUPOVÁ 2001; KROUPOVÁ, KYNCL 2001). Similar minimum values for spruce were found in the French Alps (DESPLANQUE et al. 1999). Thus it is likely that climatic factors were dominant.

In 1974, extremely low average growing season temperatures were recorded only at the Harrachov station. At the other stations, the 1974 growing season was cold, albeit not extremely. Considering the overall monthly temperature pattern, June and July were among the coldest months of the growing season. These months are normally associated with intensive spruce growth in mountainous regions. Stand response appears to depend on the altitude: a significant growth decrease was observed only in the plots over 1,000 m above sea level in the Giant Mts., and in the highest altitudes in the Ore Mts. – at the sites most sensitive to low temperatures during this period.

The year 1976, together with 1947, were among the driest years of the period under study. However, dry weather in 1976 was not connected with high summer temperatures as in 1947. On the basis of different stand responses at different altitudes, the pointer year 1976 produced evidence to support recognition of a climatic impact on growth in that year. Growth decline was visible in the plots up to 800 m; at higher altitudes normal growth increments were observed. Further evidence to support the climatic impact on stand growth is provided by the observation of no visible damage to the stands in 1974 and 1976, and no increase in salvage fellings due to air pollution (ŠRÁMEK 2000).

The year 1976 marked the beginning of a period of severe growth decline in the Ore Mts.; and, at the same time, it was a year since when the relationship between weather extremities and low growth increments was not unambiguous. In 1977, after a very warm period at the end

Table 4. Negative pointer years

Region	East			Ore Mts.		West		Jizerské Mts.		Giant Mts.		
Plot	**Krupka**	**Orasín**	**Kálek**	**Fláje**	**Hora sv. Šebestiána**	**Mariánská zatáčka**	**Horní Blatná**	**Špičák**	**Smědava**	**Pec pod Sněžkou**	**Harrachov**	**Lysečín**
Aspect	SE	N	N	W	SW	NE	plane	NE	NE	SW	N	SW
Altitude	557	582	600	706	815	990	993	750	850	1,050	1,030	1,130
1940												
1941												
1942												
1943												
1944												
1945												
1946												
1947	21		22									
1948	79		28			36	56	83		45	38	
1949												
1950												
1951												
1952												
1953												
1954	25											
1955	25											
1956	67		89	47		100	48	75	30			
1957	46		50	21		36						
1958												
1959												
1960												
1961												
1962	63	23										
1963			28									
1964			39									
1965			72									
1966			28									
1967												
1968												
1969												
1970												
1971												
1972												
1973												
1974						27	24	25		**41**	**46**	**45**
1975												
1976	75	50	39	50				58				
1977			**78**	**73**	**53**							
1978			67	27	38	32	32					
1979	54	41	56	27	63	27		50				50
1980	92	73	39	27	63	68	84	83	96	77	100	95
1981	79	27				50	52	42	87	68	88	55
1982	54					59	36	21	57	73	46	55
1983						23		25	35	68		45
1984						23						
1985					31	27						
1986		45	39	27	56	32						
1987	25	50	44	45	44	23						
1988												
1989												
1990												
1991												30

Table 4 to be continued

Region	East			Ore Mts.		West		Jizerské Mts.		Giant Mts.		
Plot	**Krupka**	**Orasín**	**Kálek**	**Fláje**	**Hora sv. Šebestiána**	**Mariánská zatáčka**	**Horní Blatná**	**Špičák**	**Smědava**	**Pec pod Sněžkou**	**Harrachov**	**Lysečín**
Aspect	SE	N	N	W	SW	NE	plane	NE	NE	SW	N	SW
1992			22									**35**
1993												
1994												
1995				32								
1996		77	83	77	81							
1997		41	33	68	56							
1998			33	36								

Percentage of trees that show a growth reduction exceeding –40%

0–20 | 21–30 | 31–40 | 41–50 | > 50 | no data

of winter, the temperature dropped suddenly from 8.3°C to –7.5°C. The ensuing frost at the end of March, together with the cold summer, can be considered an important meteorological stress in all the three mountain ridges. While this extreme temperature pattern could be a causal factor for decreasing growth increment, strong growth reduction was, however, observed only in three of the Ore Mts. plots (Kálek, Fláje, Hora sv. Šebestiána). Probably high SO_2 concentrations during the winter 1976/1977 (with maximum extreme SO_2 concentrations occurring in February) were a contributing factor to the growth decline in those three plots. The most affected plots are situated at an altitude of a frequently occurring inversion layer in the eastern part of the Ore Mts., where air pollution was highest. Since 1977, the gradient of pollution load rather than the altitudinal gradient becomes increasingly discernible. According to air pollution levels, the regions can be ranked in the following descending order: eastern part of the Ore Mts., western part of the Ore Mts., Jizerské Mts., Giant Mts.

The summer 1978 was one of the coldest and wettest ones. If stands were impacted only by climatic factors, then the stands at the highest altitudes would be expected to show a significant growth decrease. However, the stands on ridges in the Jizerské and Giant Mts. did not respond. Low growth increments were observed only in the Ore Mts., starting from the medium altitudes. This could partly be attributed to the influence of unfavourable climatic conditions in 1977; however, the SO_2 impact also seems to be an influencing factor.

The year 1979 marks the beginning of a growth depression in the Jizerské and Giant Mts. The critical development was triggered by the temperature break from 31. 12. 1978 to 1. 1. 1979, when the temperature dropped from about 5°C to –18°C. A severe frost period lasted for ten days in all the three regions. Growth decrease of different intensities was visible in all plots during that year. Similarly to the two previous years, the stands in the Ore Mts. were more sensitive to the given meteorological stress that a significant decrease in growth increment was observed.

The years 1977 and 1979 are considered as years of significant change, with respect to stand damage (see also MATERNA 1999). During these years most of the Norway spruce stands in the eastern part of the Ore Mts. died. The rate of spruce mortality due to air pollution resulted in a sharp increase in salvage fellings in the eastern, and also in the western parts of the Ore Mts.; and since 1979, also in the Jizerské Mts. (ŠRÁMEK 2000).

The series of unfavourable years culminated in 1980, towards a very cold summer (the entire growing season was cold), together with high concentrations of air pollution during the winter months. A dramatic decrease in ring width was found in most trees at all plots. The results show a growth reduction along the altitudinal gradient, similar to that found in 1974. The ridge stands were the most affected, which is also indicated by low increments in the next three years. The temperature patterns in the winter 1980/1981, heavy frost in January 1982, together with high pollution levels, all contributed to the extension of a period of minimum growth at the beginning of the 1980's.

In the mid-1980's a minimum increment was recorded at all the plots in the Ore Mts. In 1985–1987, air pollution increased in the Ore Mts., highly exceeding the levels of previous years. The winters 1984/1985 and 1986/1987 were very cold. A frost event in April 1987 (a 10°C to –7°C drop) was another climatic extreme. Given that the weather on all three mountain ridges was similar, the growth reduction in 1986 and 1987, noted only in the Ore Mts., can be attributed to the impact of air pollution and its interaction with weather (low winter temperatures were probably most important). In this context, the relationship of SO_2 concentrations and low resistance of spruce to frost became apparent again. Many authors described and provided experimental evidence for increasing sensitivity of trees to frost stress under the SO_2 impact (FEILER 1985; MICHAEL et al. 1982). Evidence for the manifestation of this phenomenon was supported experimentally in the Ore Mts. by SPÁLENÝ (1980) and RYŠKOVÁ and UHLÍŘOVÁ (1985).

Table 5. Climatic extremes (for current and previous years) in relation to the identified pointer years

		Cold winter		Cold summer		Dry summer		Temperature breaks (winter, spring)		Frost period		Differences of mean temperature in two subsequent ten-day periods	
	Pointers	curr. yr	prev. yr	curr. yr	prev. yr.	curr. yr.	prev. yr.	curr. yr.	prev. yr.	curr. yr.	prev. yr.	curr. yr.	prev. yr.
Ore Mts.	1947					drought[a)]							
	1948						drought[a)]						
	1956	**								February[a)]			
	1974												
	1976					**							
	1977			*				30. 3.					
	1978			**	*								
	1979				**			1. 1.		31. 12. (78)–10. 1.		January	
	1980			***					1. 1. and 12. 12.		31. 12. (78)–10. 1.		
	1981								20. 10., 1. 11., 27. 11.				December
	1982					*		8. 1.		6. 1.–21. 1.			
	1986		*					10. 4.		4. 2.–14. 2.	30. 12. (84)–17. 1.		February
										18. 2.–1. 3.	6. 2.–20. 2.		
	1987	*								4. 1.–21. 1.	18. 2–1. 3.	January	
	1996								27. 1.				
	1997									20. 12. (96)–7. 1.			
Jizerské Mts.	1948		**				**						
	1956	**		*						February[a)]			
	1974												
	1976					***							
	1979				**			1. 1.					
	1980			**					1. 1.				
	1981				**								
	1982					**		8. 1.		6. 1.–18. 1.			
	1983						**		8. 1.		6. 1.–18. 1.		

Table 5 to be continued

		Cold winter		Cold summer		Dry summer		Temperature breaks (winter, spring)		Frost period		Differences of mean temperature in two subsequent ten-day periods	
	Pointers	curr. yr	prev. yr	curr. yr	prev. yr.	curr. yr.	prev. yr.	curr. yr.	prev. yr.	curr. yr.	prev. yr.	curr. yr.	prev. yr.
Giant Mts.	1948						drought[a]						
	1956	***	*	**						February[a)]			
	1974			*									
	1979				***			1. 1.		30. 12. (78)–10. 1.		January	
	1980			**					1. 1.		30. 12. (78)–10. 1.		
	1981				**								December
	1982					**		8. 1.		6. 1.–21. 1.		January	
	1983					*	**				6. 1.–21. 1.		

*** *1% percentile*
** *5% percentile*
* *10% percentile*
a) *lit. data*
(grey) *no data*

The next critical period of the Ore Mts. stands began after 1996. During that year the strongest growth reduction was recorded, along with widespread stand damage. The winter 1995/1996 was cold; however, the seasonal average was not extreme and no frost periods were recorded. Monthly pollution concentrations were higher, but they did not reach the values recorded in the 1980's. This abrupt growth change could not be explained by analysis of meteorological and air pollution data available. According to LOMSKÝ and ŠRÁMEK (1999) the damage may be caused by an interaction between air pollution and the weather patterns in winter 1995/1996. An unusual stable inversion layer lasted for 3 months. Cumulating pollutants and frost deposits were observed with the inversion. Short-duration extreme pollution concentrations caused acute damage to the affected spruce stands. The SO_2 impact was even worsened by mechanical injury of needle surfaces by frost deposits. The damage to stands was so severe that narrow rings were recorded for the two following years. Despite of the diametrically different monthly SO_2 concentrations, stand damage of 1986–1987, and of winter 1995/1996 can be considered attributable to acute air pollution damage. In the Giant Mts., despite of similar weather conditions, no significant decrease in the ring width was recorded. In the Jizerské Mts. only the data of older cores were analysed (1992); therefore, data on growth development during 1996–1998 were not available.

CLIMATE – GROWTH RELATIONSHIP

At all plots in the eastern part of the Ore Mts. with no relationship to the altitude and site conditions, a significant positive correlation ($\alpha = 0.05$) was detected between ring widths and winter temperatures in January and February (Table 7). This result contradicts the common assumption of positive temperature effects on spruce growth in mountain regions during the growing season. As presented by KIENAST et al. (1987), mostly temperatures in July, August and September affect trees growing at sites where temperature is a limiting factor. In some cases spring temperatures may also play a role. High regional levels of air pollution may explain the close relationship between reduced growth and winter temperatures. Long-term impairment of frost resistance due to SO_2 impact may be the underlying reason for statistically significant correlation coefficients for the months of heaviest frost. Similar strong relationships between declining growth and February temperatures were also identified for spruce in Horní Lazy, Slavkovský les region, and spruce near Trutnov (KROUPOVÁ 2001). These two localities are both exposed to long-term air pollution – in Lazy the source of emissions is the Sokolov basin; in Trutnov the local power-plant in Poříčí is an important pollution source. The statistically significant impact of May temperatures in the eastern Ore Mts. suggests tree sensitivity to late frost that can damage flushing trees. The impact of precipitation was of importance only at the lower situated plots in Orasín

Table 6. SO_2 extremes (for current and previous years) in relation to the pointer years – the Ore Mts.

	Mean monthly [SO_2]		Mean [SO_2] Oct prev. – March curr.		Max monthly [SO_2]		Max [SO_2] Oct prev. – March curr.	
Pointers	curr. yr.	prev. yr.	curr. yr.	prev. yr.	curr. yr.	prev. yr.	curr. yr.	prev. yr.
1948	░	░	░	░	░	░	░	░
1956	░	░	░	░	░	░	░	░
1974								
1976						@@ (Oct)		
1977					@@ (Feb)			
1978	@@ (Feb)					@@ (Feb)		
1979	@@ (Feb)	@@ (Feb)						
1980	@@ (Jan, Mar)	@@ (Feb)						
1981	@@ (Feb)	@@ (Jan, Mar)						
1986	@@ (Feb)	@@@ (Jan) @@ (Feb, Mar)		@@		@@ (Jan)		@@@
1987	@@@ (Jan, Feb) @@ (Mar)	@@ (Feb)	@@@		@@@ (Jan) @@ (Feb)			
1996								
1997								

@@@ 99% percentile
@@ 95% percentile
░ no data

Table 7. Climate – growth relationship: summary of correlation analysis

Mean monthly temperature						
Region	Ore Mts. – east				Giant Mts.	
Plot	Orasín	Kálek	Fláje	H. sv. Šebest.	Pec p. Sn.	Harra-chov
May						
Jun						
Jul						
Aug						
Sep					■	
Oct				■		
Nov						
Dec						
Jan	░	░	░	░		
Feb	░	░	░	░		
Mar						
Apr						
May	░	░	░			
Jun						░
Jul						░
Aug		░		░		░
Sep		░				

Sum of monthly precipitation						
Region	Ore Mts. – east				Giant Mts.	
Plot	Orasín	Kálek	Fláje	H. sv. Šebest.	Pec p. Sn.	Harra-chov
May						
Jun						
Jul	░	░				
Aug						
Sep						
Oct						
Nov					■	
Dec						
Jan					■	
Feb						
Mar		░				
Apr						
May		■				
Jun						
Jul						
Aug						
Sep						

░ positive significant correlation (α = 0.05)
■ negative significant correlation (α = 0.05)

and Kálek, where the ring widths responded positively to increased precipitation in July of the previous year.

Spruce growth at the plots in the Giant Mts. was positively affected mainly by summer temperatures of the given year. This relation was evident at the Harrachov plot, where statistically significant correlation coefficients ($\alpha = 0.05$) were obtained for June, July and August of the given year. This strong relationship can be explained by the position of the plot, on the northern slope of the Mumlava river valley. Spruce growth at the plot Pec pod Sněžkou, of SW exposition, showed the highest positive correlation to temperatures in May and June; however, the coefficients were not significant. A similar relationship between ring widths and summer temperatures was found by SANDER et al. (1995) at the locality Labský důl, Giant Mts. Precipitation during the growing season did not affect growth.

AIR POLLUTION – GROWTH RELATIONSHIP

The correlation analysis of the air pollution – growth relationship in the Ore Mts. indicated a significant negative relationship between radial growth and average monthly SO_2 concentrations at all plots studied. The correlation coefficients were negative for all months of a given sequence (May of the previous year to September of the year when the tree-ring was formed). The correlation coefficients reached high values during the dormancy period. The coefficients for November of the year previous to tree-ring formation, and then for February and March of the current year, were statistically significant for most plots.

The relationship between growth and maximum monthly SO_2 concentrations was also negative. The high negative correlation coefficient values were obtained for the spring months of both current and previous years, and also for October of the previous year. Correlation between growth and maximum monthly SO_2 concentrations in May and October of the previous year was statistically significant.

The presented results demonstrate that SO_2 impact on spruce growth is greatest during the autumn months of the year previous to tree-ring formation, and February and March of the current year.

CONCLUSION

The period of 1976–1989 in the Ore Mts., and the period of 1979–1989 in the Jizerské and Giant Mts. were critical for spruce stands, as indicated by extremely low increments (a 50% decrease on average), and by the high frequency of irregularities in tree-ring formations. By 1977, a clearcut relationship between negative pointer years and climatic extremes was obvious – the stands responded more or less according to their position along an altitudinal gradient. Later, the occurrence of pointer years also reflected gradients in air pollution levels. Increased sensitivity of spruce to low temperatures and frost was evident in the eastern part of the Ore Mts. This finding was also supported by the results of correlation analysis between climate and growth, demonstrating a significant impact of January, February and May temperatures on ring widths in the current year. The relationship between ring width and winter temperatures was used to indirectly infer a long-term impact of SO_2, which was manifested by lower frost resistance of the spruce stands.

Despite of heavy damage during the above described critical period, the surviving spruce stands showed high regeneration capacity, demonstrated by a notable growth increase at the end of the 1980's and in the first half of the 1990's. This period was characterised by moderate winters, with no extreme temperature breaks, high temperatures during the growing season, and, also by a decrease in pollution levels. In the Giant Mts. the positive growth trend, with a small decline in 1996, endured until 1998, when the last cores were taken. By contrast, an unfavourable winter in the Ore Mts. during 1995/1996 resulted in an abrupt stand growth decline over the following two years. At the plots in Kálek and Fláje, the ring widths remained reduced until 1998. Recent development thus confirms that the stands in the Giant Mts. have recovered from the critical period at the beginning of the 1980's. The ecological stability of the Ore Mts. stands has been disturbed due to long-term chronic stress and the existence of the stands is threatened.

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Dendroekologické vyhodnocení přírůstu smrku z oblastí pod dlouhodobou imisní zátěží

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ABSTRAKT: Byly analyzovány vývrty smrku z Krušných hor, Jizerských hor a Krkonoš. Odběrová místa byla lokalizována podél výškového gradientu. Pro vyhodnocení vztahu přírůstů ke klimatickým faktorům a imisní zátěži se použila kombinace metod analýzy jednotlivých významných let (tj. roky s významným poklesem přírůstů) a jednoduché lineární regrese. Do roku 1977 je patrná jednoznačná spojitost mezi výskytem významných roků a klimatickými extrémy, po tomto roce výskyt přírůstových minim odráží i gradient v míře znečištění. Byla zjištěna evidentní zvýšená citlivost smrku z východní části Krušných hor k nízkým teplotám a mrazovým zvratům. Dominantní vliv teplot v zimním období dokazují i výsledky regresní analýzy. Takto nepřímo bylo prokázáno dlouhodobé působení SO_2, projevující se sníženou mrazuvzdorností smrku. Vývoj v posledních letech ukazuje, že porosty v Krkonoších po překonání kritického období na počátku osmdesátých let regenerují, zatímco stabilita krušnohorských porostů je vlivem chronického stresu narušena a porosty jsou i nadále ohroženy ve své existenci.

Klíčová slova: růstový přírůst; smrk; klimatické podmínky; znečištění ovzduší; Krušné hory; Krkonoše; Jizerské hory

V rámci studie byly dendroekologickými metodami analyzovány přírůsty 12 smrkových porostů z oblasti Krušných hor, Jizerských hor a Krkonoš (obr. 1). Za odběrová místa byly zvoleny plochy monitoringu zdravotního stavu lesů ICP Forests, uspořádané podél výškového gradientu (557–1 130 m n. m. – charakteristika ploch je uvedena v tab. 1). Cílem práce bylo na základě analýzy přírůstů přežívajících starých smrkových porostů vyhodnotit jejich současný stav ve vztahu k reakci na vývoj klimatických faktorů a imisního zatížení v minulosti.

U všech porostů byla vyhodnocována dynamika vývoje přírůstů, frekvence výskytu poruch v tvorbě letokruhů a vztah šířek letokruhů ke klimatickým faktorům. V Krušných horách, kde byla k dispozici i souvislá dlouhodobá měření měsíčních koncentrací SO_2, byl navíc podrobně analyzován vztah k úrovni znečištění. Pro vyhodnocení vztahu přírůstů ke klimatickým faktorům a imisní zátěži byly použity dva přístupy: 1. analýza výskytu negativních významných roků, 2. jednoduchá lineární regrese. Negativní významný rok je definován jako extrémně úzký letokruh vykazující redukci růstu překračující –40 % v porovnání s průměrnou šířkou letokruhů za čtyři předcházející roky, přičemž silná redukce přírůstů je společná minimálně 20 % stromů z jedné populace/plochy. Analýza výskytu významných roků podél definovaného ekologického gradientu umožňuje odhalit faktory se silným vlivem na přírůsty, ale působící s nižší frekvencí. Naproti tomu metody lineární regrese poskytují informaci o dominantní povaze zkoumaného vztahu v dlouhodobém časovém horizontu. Tyto dva přístupy se tedy vzájemně doplňují.

Období 1977–1989 v Krušných horách a 1979–1989 v Jizerských horách a Krkonoších byla pro smrkové porosty kritická, o čemž svědčí extrémně nízké přírůsty (pokles v průměru o 50 %) a vysoká frekvence poruch v tvorbě letokruhů (obr. 2 a 3). Do roku 1977 je patrná jednoznačná spojitost mezi výskytem negativních významných roků a klimatickými extrémy – porosty reagují víceméně podle své polohy na výškovém gradientu (tab. 4). Po tomto roce výskyt přírůstového minima odráží i gradient v míře znečištění. Evidentní je zvýšená citlivost smrku z východní části Krušných hor k nízkým teplotám a mrazovým zvratům (tab. 5). Toto zjištění je podpořeno i výsledky korelační analýzy vztahu klima – přírůst, prokazující dominantní vliv teplot v lednu, únoru a květnu na velikost přírůstů v daném roce (tab. 7). Vysoké kladné korelace mezi šířkami letokruhů a zimními teplotami tak nepřímo prokazují dlouhodobé působení SO_2 projevující se sníženou mrazuvzdorností dřevin. Podrobný rozbor vývoje znečištění pro oblast Krušných hor potvrzuje spojitost mezi výskytem významných přírůstových minim a extrémními koncentracemi SO_2 na konci sedmdesátých let a v první polovině osmdesátých let (tab. 6). Z výsledků korelační analýzy vztahu imise – přírůst je patrné, že z hlediska působení oxidu siřičitého na přírůsty smrku jsou nejvíce rizikové podzimní měsíce roku předcházejícího tvorbě letokruhu a měsíce únor a březen v daném roce.

Přes silné poškození porostů v popsaném kritickém období prokázaly přeživší porosty smrku vysokou regenerační schopnost demonstrovanou markantním vzestupem přírůstů na konci osmdesátých let a v první polovině let devadesátých. Toto období se vyznačovalo mírnými zimami bez teplotních zvratů, vysokými teplotami ve vegetační době a v neposlední řadě zřejmě příznivě působil i pokles znečištění. V Krkonoších se pozitivní přírůstový trend udržel (s mírným výkyvem v roce 1996) v podstatě až do roku odběru vývrtů – 1998. Naproti tomu v Krušných horách se nepříznivá zima 1995/1996 projevila hlubokým poklesem přírůstů v následujících dvou letech, na plochách Kálek a Fláje byly přírůsty redukovány až do roku 1998. Z vývoje v posledních letech je tedy patrné, že porosty v Krkonoších po překonání kritického období na počátku osmdesátých let regenerují, zatímco stabilita krušnohorských porostů je působením dlouhodobého chronického stresu velmi narušena a porosty jsou i nadále ohroženy ve své existenci.

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