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EXTREME RADIAL GROWTH REACTION OF NORWAY SPRUCE ALONG AN ALTITUDINAL GRADIENT IN THE ŠUMAVA MOUNTAINS

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Abstract: Extreme radial growth reactions were analyzed over a 79-year period (1922-2000) to compare response of Norway spruce (*Picea abies* [L.] Karst.) along an altitudinal gradient (376-1221 m a.s.l.) in the Šumava Mountains, the Czech Republic. Extreme growth events were defined as pointer years, when an average percentage of the site pointer years reached at least 50% strength observed at the relevant altitudinal zone (low < ca. 700 m; middle ca. 700-950 m, high > ca. 950 m). The comparison of the pointer years showed a specific pattern for altitudinal zones (Low: negative pointer years 2000, 1992, 1984, 1976, 1971 and positive 1997, 1975, 1960, 1949, 1932, 1926; middle: negative 2000, 1992, 1976 and positive 1997, 1989, 1978; high: negative 1996, 1980, 1974, 1965 and positive 1989, 1963, 1927). Negative pointer years were usually induced by summer drought at low elevations and by wet-cold summer at high altitudinal zone. These two main limiting factors were probably combined at the middle altitudinal zone. Detailed understanding of the extreme tree ring pattern along the altitudinal and geographical scale may be used as one of the additional indicators of dendrochronological dating and provenance identification of spruce sample among altitudinal zones in the Šumava Mountains.

Keywords: dendrochronology, Picea abies, pointer years, altitudinal gradient.

1. INTRODUCTION

The methods of dendrochronology are an effective tool for analyzing the ecological relationship among tree species and environment (e.g. Fritts, 1976; Schweingruber, 1996). Tree-ring series contain an aggregation of a finite number of signals that represent the sum of the environmental influences on a tree growth (Cook and Kairiukstis, 1990). Climate signal is considered as one of the main controlling factors for the tree growth, and the tree response is modified by tree species, provenience, competition, site conditions etc. (Fritts, 1976; Vitas, 2004; Spiecker, 2002). To understand the relationship between the tree growth and complex actions of climate, correlation and response function analyses have been developed (Fritts, 1976; Cook and Kairiukstis, 1990). This approach ordinarily provides the concept about the average response of trees to the range of climate factors. Such information is very useful for studying climate reconstructions and climate changes over long periods (e.g. Rolland *et al.*, 1998; Solberg *et al.*, 2002; Esper *et al.*, 2002; Wilson *et al.*, 2005a; Wilson *et al.*, 2005b). The above mentioned techniques have not revealed climatic forcing of single extreme years (e.g. Kienast *et al.*, 1987). Analyses of extreme growth events and comparison with instrumental data serve for this purpose (Schweingruber *et al.*, 1990) and could validate the temporal stability of the climate-growth relationship (Neuwirth *et al.*, 2004). When such an event year is detected simultaneously in the majority of trees in the same population, it is named "pointer year". Only these extreme growth changes common for relevant altitudinal zone are comprised in this study. To illustrate the behavioral differences of the Norway spruce to extreme climatic conditions, we analyzed 17 Norway spruce (*Picea abies* [L.] Karst.) popula-

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tions along an altitudinal gradient (370-1315 m) in the Šumava Mountains. The main purpose of this study was to investigate a) the difference and change of frequency and strength of extreme tree rings of Norway spruce with increasing altitude, b) which extremes in the course of climate condition caused pointer years, c) whether such influences differ in various altitudinal zones.

Detailed understanding of the extreme tree ring pattern along the altitudinal and geographical scale may be used as one of the additional indicators of dendrochronological dating and provenance identification of spruce sample among altitudinal zones in the Šumava Mountains. We have repeatedly encountered problems with cross-dating of spruce historical construction timber from higher altitudes of the Šumava Mountains (Beneš *et al.*, 2006).

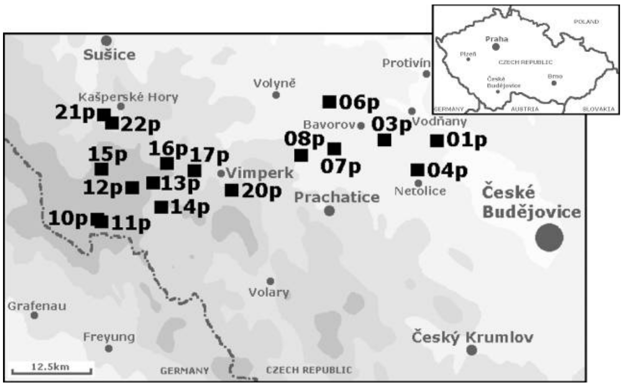

Fig. 1. *Map of 17 study stands of Norway spruce along an altitudinal gradient (370-1 315 m) in the Šumava Mountains.*

2. MATERIAL AND METHODS

For this study, 17 sites of Norway spruce of relatively similar character were chosen along an altitudinal gradient in the Šumava Mountains and its foothills from ca. 375 to 1315m a.s.l. (**Table 1**, **Fig. 1**). Most of the studied sites are plantations, particularly at low and middle elevations. In each stand, 20 dominant trees without visible signs of damage were selected as sample trees. Two increment cores were taken from each tree at the height of 1.3 m above ground.

Tree-ring widths were measured within 0.01 mm accuracy, using the measuring device (TimeTable) and the computer program Past32 (Knibbe, 2003). Tree-ring series with dissimilar growth were not used for the analysis of pointer years.

Pointer years for each stand were determined by the method of "Normalization in a moving window" (Cropper, 1979; this method was also described in Schweingruber *et al.*, 1990 and Meyer, 1999). Extreme growth reaction within a sequence of an individual tree is called an event year, synchronous event years of one site are referred to as pointer years (Schweingruber *et al.*, 1990).

In the first step, event years were calculated using a five-year moving window in each measured tree-ring width series following this formula:

$$z_i = \frac{x_i - mean\left[window\right]}{stdev\left[window\right]} \tag{2.1}$$

z_i – index value in the year *i*
x_i – original value in the year *i*
mean [window] – arithmetic mean of the ring width within the window x_i^{-2}, x_i^{-1}, x_i, x_i^{+1}, x_i^{+2}
stdev [window] – standard deviation of the ring width within the window x_i^{-2}, x_i^{-1}, x_i, x_i^{+1}, x_i^{+2}

Negative and positive event years demand for threshold values of z_i, which were $z_i \geq -1$ and ≥ 1.

In the second step, the site pointer year was determined when the event value recurred in at least 50% of tree-ring width series per population.

The pointer years of the 17 site chronologies were analyzed along an altitudinal gradient for the common time span of 1922-2000. The whole period of individual chronologies is longer (from 83 to 275 years, **Table 1**), but the common interval with sufficient numbers of measurements for every stand started in 1922. In our previous study (Čejková and Kolář, 2005) we identified three categories of altitudinal zones (low < ca. 700 m; middle ca. 700-950 m, high > ca. 950 m). Common altitudinal pointer years were determined for each of these altitudinal zones, and they were recognized when the average percentage of site pointer years reached at least 50%.

For the climatic interpretation of pointer years meteorological data from České Budějovice (mean temperature and monthly sum of precipitation) were used. This series were used for its longer time period and relatively close distance of the study area.

3. RESULTS AND DISCUSSION

Pointer years on the altitudinal gradient

The analysis of pointer years found out five negative (2000, 1992, 1984, 1976, 1971) and six positive pointer years (1997, 1975, 1960, 1949, 1932, 1926) for the low altitudinal zone, three negative (2000, 1992, 1976) and three positive pointer years (1997, 1989, 1978) for the middle altitudinal zone and four negative (1996, 1980, 1974, 1965) and three positive pointer years (1989, 1963, 1927) for the high altitudinal zone (**Fig. 2**).

The highest tree responses to the changes of the environmental factors are often observed at low altitudes and particularly on the southern slopes (Rolland *et al.*, 2000). The same trend was determined for populations of Norway spruces at the low altitudinal zone of the Šumava foothills where the trees reacted more frequently than at the high altitudinal zone. Spruces had extreme growth reactions along the whole altitudinal gradients only since the 1960s and eminent abrupt reductions were higher than positive increments (**Fig. 2**). It could be a consequence of the negative correlation between the tree age and its tree-ring width. Schweingruber (1986) demonstrated that younger trees were unable to react whereas the reactions of the mature individuals were obvious (Schweingruber, 1986). Another and probable explanation is the negative influence of air pollution (above all SO_2) in central Europe (e.g. Visser and Molenaar, 1992; Wilson and Elling, 2004 – Bavarian forest-Germany; Sander *et al.*, 1995 – Giant Mountain-Czech Republic). In the first part

Table 1. *Climatic interpretation of pointer years: - negative, + positive pointer year, L – low altitudinal zone (< ca. 700 m), M – middle altitudinal zone (ca. 700-950 m), H – high altitudinal zone (> ca. 950 m).*

altitudinal zone	Sand code	Location	Altitude (m)	chronology time span	mean age	No. of radii (trees)	Site description
low	001p	49°06´35,8"N 14°13´36,6"E	376	1908-2002	86	30 (17)	plain, mixed forest: *Picea abies*, *Pinus sylvestris* with *Rubus sp*.
	003p	49°06´08,1"N 14°07´24,4"E	537	1900-2001	94	29 (20)	plain, spruce forest with *Calamagrostis epygejos*
	004p	49°04´26,1"N 14°11´24,9"E	480	1883-2002	105	27 (17)	plain, mixed forest: *Picea abies*, *Pinus sylvestris* with *Avenella flexuosa*
	006p	49°09´03,8"N 14°00´29,0"E	624	1884-2002	91	27 (16)	west gentle slope (5°) mixed forest: *Picea abies*, *Abies alba* with *Calamagrostis arundinacea*
	007p	49°05´11,4"N 14°01´07,9"E	520	1908-2002	81	23 (17)	plain, mixed forest: *Picea abies*, *Pinus sylvestris*, *Larix decidua* with *Carex brizoides*
	008p	49°04´16,9"N 13°55´53,2"E	698	1910-2002	81	18 (14)	plain and gentle slope, mixed forest: *Picea abies*, *Abies alba*, *Pinus sylvestris* with *Calamagrostis arundinacea*
high	010p	48°58´45,2"N 13°33´02,7"E	1 313	1857-2002	118	26 (14)	summit site, spruce forest with *Calamagrostis villosa*
	011p	48°58´38,2"N 13°33´29,0"E	1 255	1865-2002	111	23 (15)	small plain in east slope (10°), spruce forest with *Calamagrostis villosa*
	012p	49°02´16,4"N 13°34´54,3"E	1 118	1839-2002	110	28 (17)	plain, spruce forest with *Avenella flexuosa*
	013p	49°02´22,7"N 13°37´08,1"E	1 218	1837-2002	136	27 (15)	summit site, spruce forest with *Calamagrostis villosa*
	014p	49°00´10,8"N 13°37´51,2"E	1 047	1858-2002	124	28 (16)	southwest slope (5°), spruce forest with *Calamagrostis villosa*
	015p	49°00´10,8"N 13°37´51,2"E	1 221	1729-2002	177	32 (19)	plain in southwest slope (10°), spruce forest with *Calamagrostis villosa*
	016p	49°03´12,8"N 13°39´54,7"E	979	1736-2002	190	30 (17)	plain, spruce forest with *Calamagrostis villosa*
middle	017p	49°03´32,2"N 13°42´54,9"E	946	1901-2002	93	29 (15)	southeast gentle slope (5°), spruce forest with *Avenella flexuosa* and *Vaccinium myrtillus*
	020p	49°01´54,8"N 13°48´29,8"E	835	1910-2002	86	19 (10)	gentle slope and plain, spruce forest with *Avenella flexuosa* and *Vaccinium myrtillus*
	021p	49°08´09,5"N 13°30´45,6"E	842	1879-2004	105	34 (19)	plain, mixed forest: *Picea abies*, *Pinus sylvestris*, *Abies alba* with *Vaccinium myrtillus*
	022p	49°06´43,4"N 13°33´25,2"E	760	1849-2004	110	28 (18)	east gentle slope (5°), mixed forest: *Picea abies*, *Abies alba*, *Fagus sylvestris*, *Tilia cordata* with *Calamagrostis villosa*

of the analyzed time span (1922-1960), the trees reacted only extremely positively in the low altitudinal zone, weakly in the high altitudinal zone and no reaction was found by means of this calculation method in the middle altitudinal zone. Most positive growth responses are caused by a local combination of favorable climatic factors rather than simple extreme events, and therefore they are less efficient for wood dating (Rolland *et al.*, 2000).

Pointer years were specific in the low and high altitudinal zones. The middle altitudes comprised a transition area with pointer years identical with the above-mentioned zones (particularly with low altitudes), but pointer years differ in intensity, i.e. trees reacted less frequently and the response was weaker (**Figs. 2** and **3**). This situation probably shows the ambiguous reaction of trees to external environmental conditions that switch from those limiting either for high or low altitudes. The influence of climatic conditions on tree growth becomes stronger with the ecological limits of the species (Fritts, 1976). In this case, the abiotic ecological limit of the spruce is at low altitudes; the centre of the occurrence of *Picea abies* is the mountainous (750-1100 m a.s.l.) and above all the supramountainous zone (1000-1370 m) in the Czech Republic (Skalický and Skalická, 1988). Trees growing in average climatic conditions react in a weaker way to the changes of climatic factors and the relationship between radial increment and climatic conditions may be more complex in average conditions. The factors that affect radial increment may change from year-to-year (Mäkinen *et al.*, 2003).

Climatic interpretation of pointer years and the large-scale comparison for Europe

In the low altitudinal zone, the expression of negative pointer years (years: 1971, 1976, 1984, 1992, 2000;

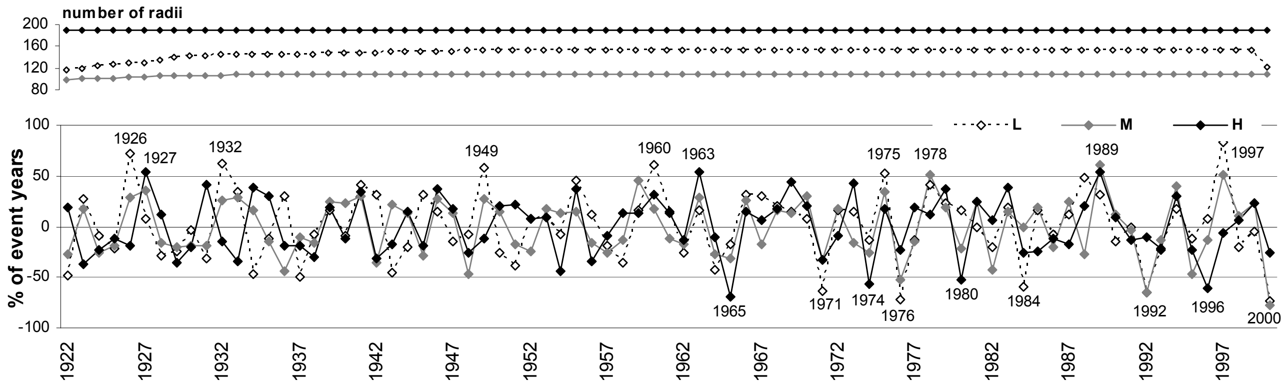

Fig. 2. *The curves represent averaged percentage of site pointer values for the low (L), middle (M) and high (H) altitudinal zones. Labelled pointer years are only obtained when average percentage of site pointer years reached at least 50% strength of observing.*

Fig. 3a, **Table 2**) is probably connected with an insufficient amount of precipitation during the vegetation period (above all in May and June) and with the drought during a part of the vegetation period of the previous year. The lack of water usually interacts with warm temperatures in spring and summer that increase dehydration of the tree and result in a negative relationship between ring-width and temperature (Dittmar and Elling, 1999). The strong impact of drought coincided above all with the beginning of vegetation; mainly during tree-ring formation (Rolland *et al.*, 1999; Vitas, 2001).

Positive pointer years are, to the contrary, connected with enough precipitation during the growing season (1926, 1932, 1949, 1960, 1975, 1997; **Fig. 3**, **Table 2**). It corresponds with the findings that in central Europe the annual growth of the Norway spruce was mainly related to precipitation (e.g. Koprowski and Zielski, 2006; Mäkinen *et al.*, 2002; Wilson and Hopfmueller, 2001), and dry summers were connected to lower growth rates (cf. Eckstein *et al.*, 1989; Spiecker, 1991). A typical positive pointer year of low elevations was 1932. The initiation of tree-ring formation was positively influenced by high precipitation and below-average temperature above all in May; similar situation with a rainy but warmer than usual summer led to larger ring widths in Southern French and Italian Alps (Rolland *et al.*, 2000) and the north foothill of the Alps in Switzerland (Schweingruber *et al.*, 1991).

On the other hand, the drought period from May to August induced the highest growth reduction (Schweingruber, 1986). The Norway spruce is very sensitive to drought due to its superficial root system (Chmelař, 1986). This is the cause of the negative pointer year of

Table 2. *Climatic interpretation of pointer years: - negative, + positive pointer year, L – low altitudinal zone (< ca. 700 m), M – middle altitudinal zone (ca. 700-950 m), H – high altitudinal zone (> ca. 950 m).*

2000	-	L-M	dry and hot spring and early summer, dry previous spring to autumn (1999)
1997	+	L-M	rainy summer, warm and wet end winter and early spring
1996	-	H	severe winter, rainy spring and cold summer
1992	-	L-M	dry and hot spring and summer
1989	+	H-M	mild winter and early spring and relatively dry late spring and summer
1984	-	L	dry almost entire period - May 1983 to August 1984
1980	-	H	extremely cold growing season and after warm December cold January in combination with relatively small precipitation in this period
1978	+	M	cold vegetation season
1976	-	L-M	extremely dry late winter to early summer and relatively hot in summer, after warm January cold February and March
1975	+	L	wet summer and wet summer in previous year (1974) and mild winter
1974	-	H	cold and rainy growing season, dry autumn in previous year (1973) and dry and warm period at the winter
1971	-	L	relatively dry late spring and summer in previous year (1970), dry and cold January and May, dry July
1965	-	H	cold wet year
1963	+	H	relatively hot summer with low precipitation but severe winter – relationship unclear
1960	+	L	wet and relatively cold year, above all summer and rainy late spring and summer in previous year (1959)
1949	+	L	rainy spring and summer
1932	+	L	rainy May and July and warmer than usually in July and August
1927	+	H	mild winter and early summer, wet summer and autumn in previous year (1928)
1926	+	L	wet and cold late spring and summer, mild winter and wet previous summer (1925)

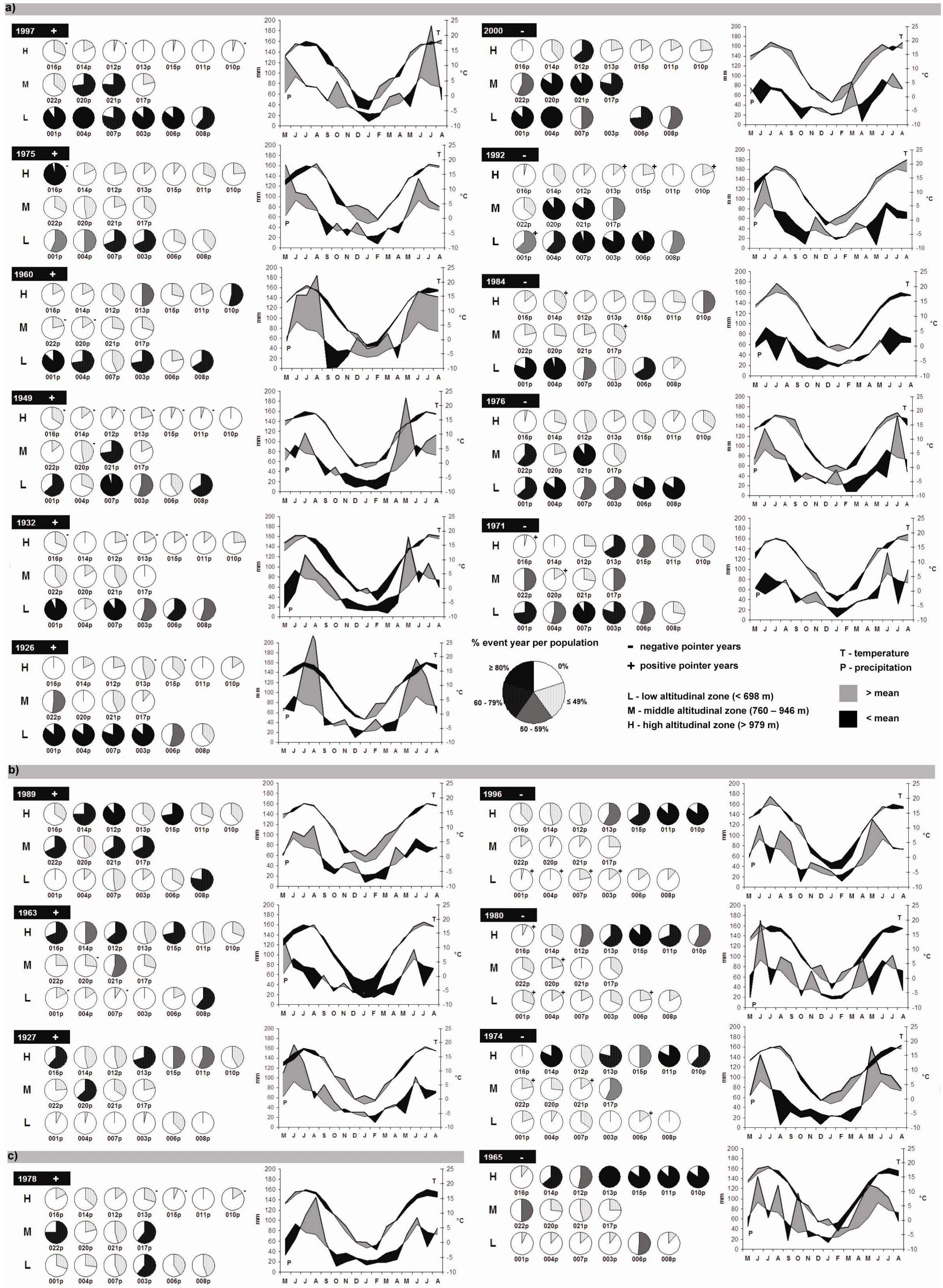

Fig. 3. *Altitudinal variability of pointer years with temperature (T) and precipitation (P) data (mean long term data 1921-2000 and monthly values) for previous vegetation season and current year (from May of previous to September current year). Pie charts show in colored part the percentage of event years per population (The pointer year was determined, when event value was detected at least by 50% of tree-ring width series per population). a) Low altitudinal zone, b) high altitudinal zone, c) middle altitudinal zone.*

1992 in the low and middle altitudinal zones in the Šumava Mountains. This drought year also had a negative impact on spruce growth in the southern French and Italian Alps (Desplanque *et al.*, 1999, Rolland *et al.*, 2000), in Swiss Alps (Neuwirth *et al.*, 2004) or in the whole Lithuania on wet sites (Vitas, 2004). The most important negative year occurred in many regions of Europe in 1976, especially at lower elevations (Swiss, French and Italian Alps – Lingg, 1986; Schweingruber *et al.*, 1991; Desplanque *et al.*, 1999; Rolland *et al.*, 2000, Neuwirth *et al.*, 2004; Germany - Becker *et al.*, 1990; Mäkinen *et al.*, 2002; Southern Norway and Finland – Mäkinen *et al.*, 2002). It was also detected at the elevation bellow 950 m a.s.l. in the Šumava Mountains and the foothills. 1976 was dry and warm, which prolonged the water deficit. This situation was repeated in the other sites in the Czech Republic, specifically in the Ore and Giant Mountains, but growth depression was detected in the trees bellow 800 m (Kroupová, 2002).

Generally, it is assumed that in the mountainous areas, the main driving factor of the tree growth is the temperature (Tranquillini, 1979; Rochefort *et al.*, 1994; Rolland *et al.*, 1998; Desplanque *et al.*, 1999; Koprowski and Zielski, 2006). At high elevations in southern Germany, spruce chronologies (>800-900 m) are more influenced by the temperature rather than precipitation (Dittmar and Elling, 1999). In the Czech part of the Šumava Mountains, the temperature could not be the main driving factor of ring-width formation, because this region does not reach the upper tree-line limit (Moravec, 1964; Skalický, 1998) and the trees from higher sites may not therefore demonstrate as strong response to the temperature as they would at a temperature of upper tree-line (Wilson and Hopfmueller, 2001). Positive pointer years are usually caused by low sums of precipitation and the average temperature or slightly higher temperature during the growing season (1927, 1963, 1989; **Fig. 3b**, **Table 2**) and negative pointer years with the cold especially in July and wet vegetation season (1965, 1974, 1980, 1996; **Fig. 3b**, **Table 2**). The intensive growth of the Norway spruce is connected with the summer months of June and July in the mountains (Kroupová, 2002, Savva *et al.*, 2006) and the excessive June rainfall that are unfavorable for the ring formation at high elevations (Despalnque *et al.*, 1999).

For instance, the stronger negative pointer year 1965 was very rainy and cold. This year was detected at the majority of sites and also in the other part of the Šumava Mountains (Trojmezná forest – Svoboda and Tichý, 2004), in Europe, for example in the French and Swiss Alps (Desplanque *et al.*, 1999; Neuwirth *et al.*, 2004). A similar response to extremely cold summer was observed in the high altitude zone in 1980, which is in a good agreement with the observations from Trojmezná (Svoboda and Tichý, 2004), the northern foothills of Swiss Alps (Schweingruber, 1986; Schweingruber *et al.*, 1991) and wet sites in Lithuania (Vitas, 2004). Kroupová (2002) also connected the negative pointer year 1980 with the high concentration of air pollution during winter for localities above 1000 m in the Giant and Ore Mountains (Czech Republic).

Negative pointer year 1996 seems to be untypical; growth reduction was probably induced by a harsh winter in combination with a wet and cold vegetation season (Savva *et al.,* 2006). Furthermore, the frozen soil may have prevented trees from absorbing soil water in March (Roland *et al.*, 1999). The same reduction was noted in the Ore Mountains (Kroupová, 2002), where it was connected with winter frosts and high SO_2 concentrations. Frost resistance of Norway spruce is decreased by long-term high concentrations of SO_2 during winter (e.g. Spálený, 1980). A relatively similar coincidence could also occur in the Šumava Mountains, because the highest SO_2 concentrations in this decade was recorded for Prachatice region in 1996 (Hruška and Cienciala, 2003).

The occurrence of pointer years could be a consequence of other effects, e.g. defoliation caused by insect, mast year etc. (Schweingruber, 1996). In southern Finland, the low growth of the Norway spruce has often coincided with the production of a rich seed crop, which requires large amounts of photosynthetic products (Mäkinen *et al.*, 2002). For example, negative pointer years 1974 or 1976, usually connected with dry years, and are also related with mast years (Selås *et al.*, 2002). This is a probable explanation also for the negative pointer years 1980, 1971 and 1992 because they represented mast years of the Norway spruce for the whole Czech Republic.

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REFERENCES

Becker M, Bräker OU, Kenk G, Schneider O, Schweingruber FH, 1990. Kronenzustand und Wachstum von Waldbäumen im Dreiländereck Deutschland-Frankreich-Schweiz in den letzten Jahrzehnten (Crown condition and tree growth in the border areas of Germany, France, and Switzerland in the last century). *Allgemeine Forst Zeitschrift* 62(11): 267-274 (in German).

Beneš J, Kolář T and Čejková A, 2006. Xylotomic and dendrochronological analyses in archeology: Changes in the composition type of wood in Prague an in Southern Bohemia. *Ve službách arceologie* VII: 159-169.

Chmelař J, 1986. *Dendrologie s ekologií lesních dřevin* (Dendrology with ecology of tree species). Brno, Vysoká škola zemědělská: 119pp (in Czech).

Cook ER and Kairiukstis LA, 1990. *Methods of Dendrochronology, Applications in the Environmental Sciences*. Dodrecht, Boston, London, Kluwer Academic Publishers: 394pp.

Cropper JP, 1979. Tree-ring skeleton plotting by computer. *Tree-Ring Bulletin* 39: 47-60.

Čejková A and Kolář T, 2005. Dendrochronological Investigations of the Šumava Mountains and the Šumava Foothills, Czech Republic. *EuroDendro 2005, International Conference of Dendrochronology, Conference Abstract, Viterbo, Italy*: 44-45.

Desplanque C, Rolland C and Schweingruber FH, 1999. Influence of species and abiotic factors on extreme tree ring modulation: Picea abies and Abies alba in Tarantaise and Maurienne (French Alps). *Trees* 13: 218-227.

Dittmar C and Elling W, 1999. Jahrringbreite von Fichte und Buche in Abhängigkeit von Witterung und Höhenlage (Radial growth of Norway spruce and European beech in relation to weather and altitude). *Forstwissenschaftliches Centralblatt* 118(4): 251-270 (in German).

Eckstein D, Krause C and Bauch J, 1989. Dendroecological investigation of spruce trees (Picea abies (L.) Karst.) of different damage and canopy classes. *Holzforschung* 43(6): 411-417.

Esper J, Cook ER and Schweingruber FH, 2002. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* 295: 2250-2253, DOI: 10.1126/science.1066208.

Fritts HC, 1976. *Tree Rings and Climate*. New York, Academic Press: 567 pp.

Hruška J and Cienciala E, eds., 2003. *Long-term acidification and nutrient degradation of forest soils – limiting factors of forestry today*. Praha, Ministerstvo životního prostředí: 189pp (in Czech).

Kienast F, Schweingruber FH, Bräker OL and Schär E 1987. Tree-ring studies on conifers along ecological radients and the potential of single-year analyses. *Canadian Journal of Forest Research* 17: 683-696.

Knibbe B, 2003. *Past32 Build 700 User Manual*. Wien, Sciem: 90pp.

Koprowski M, Zielski A 2006. Dendrochronology of Norway spruce (Picea abies (L.) Karst.) from two range centres in lowland Poland. *Trees - Structure and Function* 20(3): 383-390.

Kroupová M, 2002. Dendroecological study of spruce growth in regions under long-term air pollution load. *Journal of Forest Science* 48: 536-548.

Lingg W, 1986. Dendroökologische Studien an Nadelbäumen im alpinen Trockental Wallis (Schweiz). *Berichte der Eidgenössischen Anstalt für das forstliche Versuchswesen* 287: 3-81.

Mäkinen H, Nöjd P, Kahle H-P, Neumann U, Tveite B, Mielikäinen K, Röhle H and Spiecker H, 2002. Radial growth variation of Norwey spruce (Picea abies (L.) Karst.) across latitudinal and altitudinal gradients in central and northern Europe. *Forest Ecology and Management* 171: 243-259.

Mäkinen H, Nöjd P, Kahle H-P, Neumann U, Tveite B, Mielikäinen K, Röhle H and Spiecker H, 2003. Large-scale climatic variability and radial increment variation Picea abies (L.) Karst.) in central and northern Europe. *Trees* 17: 173-184.

Meyer FD, 1999. Pointer year analysis in dendroecology: A comparison of methods. *Dendrochronologia* 16-17: 193-204.

Moravec J, 1964. Vegetační poměry Šumavy (Vegetation conditions of the Šumava Mountains). *Ochrana přírody* 19: 66-69 (in Czech).

Neuwirth B, Esper J, Schweingruber FH, Winiger M, 2004. Site ecological differences to the climatic forcing of spruce pointer years from Lötschental, Switzerland. *Dendrochronologia* 21(2): 69-78.

Rolland C, Petitcolas V, Michalet R, 1998. Changes in radial tree growth for Picea abies, Larix decidua, Pinus cembra and Pinus uncinata near the alpine timberline since 1750. *Trees* 13: 40-53.

Rolland C, Michalet R, Desplanque C, Petetin A and Aimé S, 1999. Ecological requirements of Abies alba in the French Alps derived from dendro-ecological analysis. *Journal of Vegetation Science* 10: 297-306.

Rolland C, Desplanque C, Michalet R, Schweingruber FH, 2000. Extreme tree rings in spruce (Picea abies [L.] Karst.) and fir (Abies alba Mill.) stands in relation to climate, site, and space in the southern French and Italian Alps. *Artic, Antarctic, and Alpine Research* 32: 1-13.

Rochefort RM, Little RL, Woodward A, Peterson DL, 1994. Changes in subalpine tree distribution in western North America: Effects of climate and other environmental factors. *The Holocene* 4: 89-100.

Sander C, Eckstein D, Kyncl J and Dobry J, 1995. The growth of spruce (Picea abies (L.) Karst.) in the Krkonose-(Giant) Mountain as indicated by ring width and wood density. *Annales des Sciences forestières* 52: 401-410.

Savva Y, Oleksyn J, Reich PB, Tjoelker MG, Vaganov EA, Modrzynski J 2006. Interannual growth response of Norway spruce to climate along an altitudinal gradient in the Tatra Mountains, Poland. *Trees - Structure and Function* 20(6): 735-746.

Selås V, Piovesan G, Adams JM and Bernabei M, 2002. Climatic factors controlling reproduction and growth of Norway spruce in southern Norway. *Canadian Journal of Forest Research* 32(2): 217 – 225.

Schweingruber FH, 1986. Abrupt growth changes in conifers. *IAWA Bulletin n. s*. 7(4): 277-283.

Schweingruber FH, 1996. *Tree Rings and Environment Dendroecology*. Birmensdorf, Swiss Federal Institute for Forest, Snow and Landscape Research. Berne, Stuttgart, Vienna, Haupt: 609pp.

Schweingruber FH, Eckstein D, Serre-Bachet F and Bräker OU, 1990. Identification, presentation and interpretation of event years and pointer years in dendrochronology. *Dendrochronologia* 8: 9-38.

Schweingruber FH, Wehrli U, Aellen-Rumo K and Aellen M, 1991. Weiserjahre als Zeiger extremer Standortseinflüsse (A dendrochronological study on trees near an incineration dump). *Schweizerische Zeitschrift für Forstwesen* 142: 33-52 (in German).

Skalický V 1998. Fytogeografický rozbor květeny Šumavy a přilehlých území (Phytogeographical study of flora of The Šumava Mountains and the closed regions). *Zprávy České Botanické společnosti*, 32: 117-121 (in Czech).

Skalický V and Skalická A, 1988. *Picea A. Dieter – smrk*. In: Hejný S and Slavík B, eds., Květena ČR 1, Academia, Praha: 317-322 (in Czech).

Solberg BO, Hofgaard A and Hytteborn H, 2002. Shifts in radial growth responses of coastal Picea abies induced by climatic change during the 20th century, central Norway. *Ecoscience* 9(1): 79-88.

Spálený J, 1980. Vliv kouřových imisí na mrazuvzdornost smrku ztepilého (Influence of fumous immisions on frost-tolerance of Norway spruce). *Lesnická práce* 59: 411-414 (in Czech).

Spiecker H, 1991. Growth variation and environmental stress:long-term observations on permanent research plots in southwestern Germany. *Water Air Soil Pollution* 54: 247-256.

Spiecker H, 2002. Tree rings and forest management in Europe. *Dendrochronologia* 20(1-2): 191-202.

Svoboda M and Tichý T, 2004. Struktura a dynamika lesních porostů a kvantitativní a kvalitativní charakter odumřelé dřevní biomasy v oblasti Trojmezenského pralesa (Structure and dynamics of forest and quantitative and qualitative character dead woody biomass in the area of Trojmezná forest). AOPK, Praha. *Příroda*: 299-310 (in Czech).

Tranquillini W, 1979. *Physiological Ecology of Alpine Timberline, Tree Existence at High Altitudes with Special Reference to the European Alps*. Ecological Studies 31. Berlin, Heidelberg, New York , Springer-Verlag: 137pp.

Visser H and Molenaar J, 1992. Estimating trends and stochastic functions in dendroecology with an application to fir decline. *Forest Science* 38(2): 221-234.

Vitas A, 2004. Tree rings of Norway spruce (Picea abies (L.) Karsten) in Lithuania as drought indicators: dendroecological approach. *Polish Journal of Ecology* 52(2): 201-210.

Wilson RJS and Hopfmueller M, 2001. Dendrochronological investigations of Norway spruce along an elevational transect in the Bavarian Forest, Germany. *Dendrochronologia* 19(1): 67-79.

Wilson R and Elling W, 2004. Temporal instability in tree-growth/climate response in the Lower Bavarian Forest region: implications for dendroclimatic reconstruction. *Trees - Structure and Function* 18(1): 19-28.

Wilson RJS, Luckman BH and Esper J, 2005a. A 500 year dendroclimatic reconstruction of spring-summer precipitation from the lower Bavarian Forest region, Germany. *International Journal of Climatology* 25(5): 611-630.

Wilson R, Frank D, Topham J, Nicolussi K and Esper J, 2005b. Spatial reconstruction of summer temperatures in Central Europe for the last 500 years using annually resolved proxy records: problems and opportunities. *Boreas* 34(4): 490-497.