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RESEARCH ARTICLE

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Norway spruce responses to drought forcing in areas affected by forest decline

Petr Čermák (Čermák, P)[1], Tomáš Kolář (Kolář, T)[1, 2], Tomáš Žid (Žid, T)[1], Miroslav Trnka (Trnka, M)[2], Michal Rybníček (Rybníček, M)[1, 2]

[1]*Faculty of Forestry and Wood Technology, Mendel University in Brno, Zemědělská 3, 613 00 Brno, Czech Republic;* [2] *Global Change Research Institute of the Czech Academy of Sciences, Bělidla 986/4a, 603 00 Brno, Czech Republic*

Abstract

Aim of study: To assess the crown condition and radial growth of Norway spruce in plots with an increasing frequency and strength of drought during the last decades.

Area of study: Northern Moravia, Czech Republic.

Materials and methods: Crown condition assessment and dendrochronology analysis were used.

Main results: Tree-ring width (TRW) was significantly influenced by previous autumn and current summer climate. The temporal variability of the growth-climate relationship shows that the impact of water sufficiency (precipitation, relative soil water content, drought index) markedly increased mainly during the 2000s and the 2010s. Most climate-growth relationships were significant only in the last two or three decades. The observed crown conditions and their relationships with TRW also indicate stress intensification during the same period. Our results suggest that water availability was the main factor affecting radial growth and the occurrence of negative pointer years and was probably also the factor triggering the decline.

Research highlights: In these current site and climate conditions, the silviculture of Norway spruce is extremely risky in the study area. Our results have also shown that the observed climate change is too dynamic for long-term forest plans, especially with regard to recommended forest species composition.

Keywords: defoliation; *Picea abies*; tree-ring width; precipitation; PDSI; available soil water.

Authors´ contributions: Conceived and designed the experiments: PČ, TK, MR. Performed the experiments: PČ, TK, TŽ and MR. Analysed the data: PČ, TK, MT, MR. Contributed reagents/materials/analysis tools: MT. Wrote the paper: PČ and TK.

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Correspondence should be addressed to Petr Čermák: e-mail cermacek@mendelu.cz

Introduction

Tree mortality usually involves complex processes and multiple interactions among disturbance agents and stress factors occurring at different time scales (Franklin *et al.*, 1987; Trumbore *et al.*, 2015). Tree death can be caused by abiotic stress factors interacting with different biotic factors, resulting in forest decline (Manion, 1991; Manion & Lachance, 1992; Sturrock *et al.* 2011). Drought is an important and frequent causal factor of forest decline; it can function as a predisposing, inciting or contributing factor (Sinclair, 1967). Forest resilience to drought mainly depends on drought intensity, but it may also depend on tree species or specific functional traits (Greenwood *et al.*, 2017); furthermore, it can vary from one individual to another (Gazol *et al.*, 2017; Camarero *et al.*, 2018). *Picea abies* is one of the most drought-sensitive European tree species (van der Maaten-Theunissen *et al.*, 2013; Hartl-Meier *et* *al.*, 2014; Leuschner & Ellenberg, 2017) because it is a water-demanding species often having a shallow root system. During recent decades, drought-triggered forest declines have appeared in different forest types and climate zones. Allen *et al.* (2010) identified 88 episodes of drought and/or heat-induced forest mortality over the past years, and 10 of them affected the *Picea* spp.

One of the last *Picea abies* forest decline episodes started at the beginning of the 1990s in the Polish part of the Silesian Beskids Mts., and after the dry year 2003, it has spread southward to the Czech Republic (Rybníček *et al.*, 2010). The main identified predisposing factors of forest decline were the artificial origin of stands, low content of basic elements in the soil, and mainly drought spells, especially in 2003 and 2007 (Novotný *et al.*, 2008; Šrámek *et al.,* 2008; Rybníček *et al.,* 2010; Cienciala *et al.,* 2017). Severe infestation by fungi *Armillaria* spp. was often an inciting factor for a subsequent attack of bark beetles (*Ips typographus*, *Ips duplicatus* and *Pityogenes chalcographus*) as a contributing factor causing final mortality (Grodzki, 2010; Vakula *et al.,* 2015). Moreover, root decays caused by *Armillaria* spp. and some other primary parasitic wood-destroying fungi increase the host water deficit and predispose it to the invasion of bark beetles (Jankovský *et al.,* 2003; Grodzki, 2007; Holuša *et al.*, 2018).

The stress response of trees in radial growth and crown conditions may occur with varying delays. In some cases, the first observable reaction to a stressor is discoloration or defoliation, and in other cases, the growth reduction is immediate, whereas the change in crown can be observed later. The differences in reaction may be caused by stress intensity, its duration or kind of affecting stressor (Rybníček *et al.,* 2012a). Therefore, the use of both indicators is suitable for a precise description of forest decline processes.

With respect to the recurrent serious drought spells in the last two decades, we assessed the crown condition and radial growth of surviving *Picea abies* trees in northern Moravia (Oderské vrchy or Odra Highlands), an area of Central Europe that is strongly affected by forest decline. Our initial hypothesis was that the changing climate conditions, especially the rapid decrease in soil water availability, considerably affected crown conditions and tree ring width (TRW). Our aims were to i) investigate possible relationships between crown condition parameters and tree-ring width and ii) analyse changes in climate-growth relationships during a period of progressive climate change.

Materials and Methods

Study plots

The study area is a plateau in the submontane belt in the Oderské vrchy, or Odra Highlands. We selected six circular plots (min. r = 32 m) in a forest district with the presence of declining stands. The plots were selected randomly in the prevailing site conditions (i.e., prevailing altitudinal zones and edaphic categories in the study area). More detailed information about the plots is provided in Table 1. All study plots were either Norway spruce artificial monocultures or stands with spruce as a dominant tree species (> 90% in species composition). The assessed stands have a closed canopy. The same silvicultural treatments were used in all plots during the stands' history, repeating thinning from below at ages up to 40 years and eliminating unhealthy trees from older stands. The plots are representative of Norway spruce stands of the study area.

The dominant soils were spodo-dystric cambisols. The soil condition of the area was evaluated by Šrámek *et al.* (2015). Soil profiles were acidified with a median pH ($CaCl_2$) < 4 in the organic layer and the upper 30 cm of mineral soil. The strong deficiency of exchangeable calcium (< 140 $mg.kg^{-1}$) has been found to the depth of 50 cm and magnesium deficiency (< 40 $mg.kg^{-1}$) to the depth of 60 cm. The total nitrogen content is sufficient or good within the soil profile.

Climate conditions

Station climate data covering the period 1961–2014 were derived through interpolation from a set of nearby weather stations using locally weighted regressions, including the effect of altitude. The interpolation was based on the database of the Czech Hydrometeorological Institute and included measurements from 268 meteorological stations and 787 precipitation stations representing the territory of the Czech Republic.

We tested all observed weather variables for outliers and breaks through a detailed homogenization sequence, and missing data were filled using the methods described by Štěpánek *et al.,* (2009 and 2011). We then employed the SoilClim (Hlavinka *et al.*, 2011) model to estimate the daily values of the relative soil water content (AWR) for the top 1.3 m, which was used as one of the water availability proxies, with 0 representing the wilting point and 100 the field capacity. The SoilClim model divided the

Table 1. Parameters of study plots

No.	Position	Altitude (m a.s.l.)	Slope gradient (degree)	Slope orientation	Altitudinal zones *	Edaphic categories **	Age ***
1	N49° 40.129’ E17° 31.458’	520	5°	SE 140°	4-*Fagus*	mesotrophica	85
2	N49° 37.242’ E17° 31.124’	649	5°	NW 286°	5-*Abies-Fagus*	acidophila	100
3	N49° 39.700’ E17° 31.508’	604	5°	N 5°	5-*Abies-Fagus*	mesotrophica	75
4	N49° 38.667’ E17° 29.734’	629	to 2°	NE 41°	5-*Abies-Fagus*	mesotrophica	84
5	N49° 39.733’ E17° 31.694’	580	4°	NE 65°	5-*Abies-Fagus*	mesotrophica	81
6	N49° 37.211’ E17° 31.414’	630	to 2°	SE 110°	5-*Abies-Fagus*	mesotrophica	81

* Forest altitudinal zones according to Czech Forest Ecosystem Classification (Viewegh *et al.,* 2003). The zones are based on the relationship between potential natural vegetation and climatic characteristics. The nine zones are defined. They were named according to potential dominant tree species. The second tree genus name is the main determinant, and the first is codeterminant. ** Edaphic category according to Czech Forest Ecosystem Classification (Viewegh *et al.,* 2003). Edaphic category represents the soil nutrient regime and water impact on the site. Mesotrophica = nutrient-medium soils without significant soil water influence. Acidophila = oligotrophic soils without significant soil water influence. *** Age of stand taken from the forest management plans.

soil profile into 2 layers (0–40 cm and 40 to 130 cm), which were also considered TRW predictors but were found to perform worse than the relative available water content in the entire profile. We also calculated the Palmer drought severity index (PDSI) using the procedure described by Palmer (1965).

The climate conditions changed in the study plots during the observed period (Fig. 1). Average temperatures increased, precipitation totals rapidly fluctuated annually without significant changes in mid-term average totals (Table 2), and AWR decreased, especially the summer AWR (Fig. 1). Severe drought in the growing season (April–September) repeated approximately once every ten years, but the last two dry episodes (2003–2007 and 2012–2014) were multiannual, in contrast to the previous droughts (Fig. 1). The average interval between two drought years was markedly shorter, and the average length of the drought period was longer in the 1991–2014 period compared to the 1961–1990 period (Fig. 2).

Crown condition assessment

The plot design is the same as that of Level I of the ICP Forest network – a circular plot with a fixed number of trees (Eichhorn *et al.* 2010; Ferretti & Fischer 2013). With regard to dendrochronology analysis, we selected twenty trees within each plot. Only living trees without visible specific symptoms of *Armillaria* spp. infestation (presence of mushrooms, intensive resinosis on the base of the trunk near the soil line and noticeable hypertrophy of the base of the trunk) or signs of bark beetle attack were assessed. We visually evaluated the assessable crowns using modified methods of Cudlín *et al.* (2001) and Eichhorn *et al.* (2010) (Table 3). The assessable crown includes recently dead branches but excludes snags that have been dead for many years (i.e., those that have already lost their side-shoots). For the assessment of parameters of the tree parts that are five or more metres above ground, the use of binoculars (10×50) is mandatory. We also evaluated the stress response of all trees (Cudlín *et al.,* 2001). The stress response classification illustrates the stress tolerance and crown structure transformation stage (i.e., rate of substitution of original primary shoots by secondary shoots). Based on the guidelines of Cudlín *et al*. (2001), we applied the following classes: A resistant tree has total defoliation lower than 35% and a proportion of secondary shoots lower than 50%; a resilient tree has total defoliation lower than 35% and a proportion of secondary shoots higher than 50%; a slightly transformed damaged tree has total defoliation higher than 35% and a proportion of secondary shoots lower than 50%; a considerably transformed damaged tree has total defoliation higher than 35% and a pro-portion of secondary shoots higher than 50%.

Categorical tree crown parameters were compared with the mean tree-ring width index (TRWi) for the last

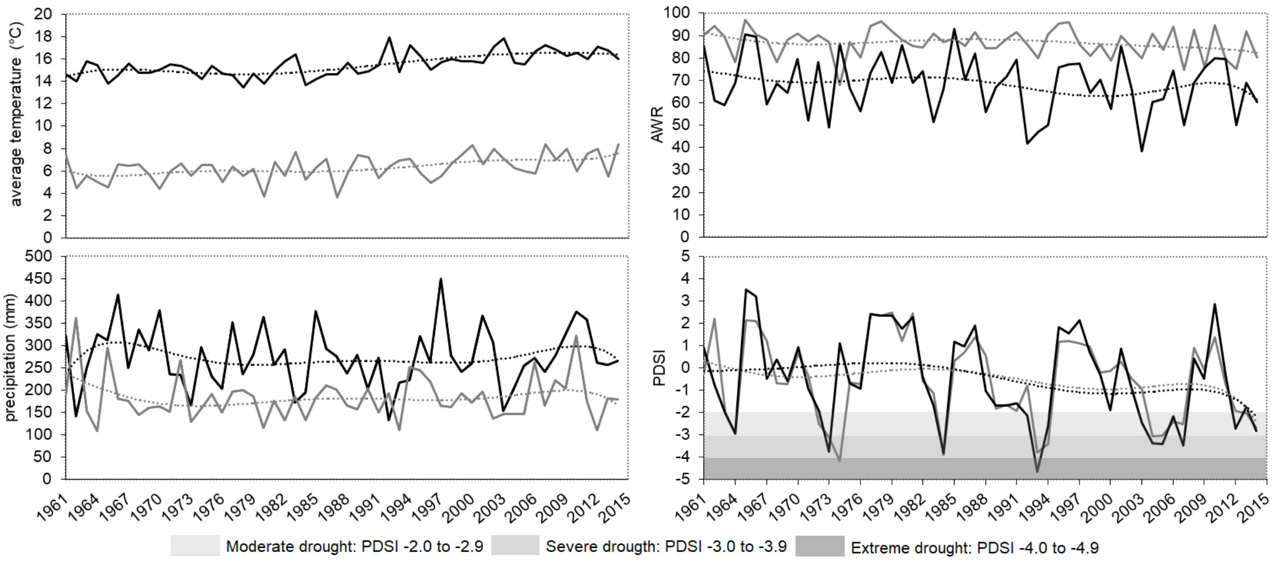


Figure 1. Climate development in the growing season during 1961–2014. The grey lines represent the March–May period, and the black lines represent the June–August period. The dotted lines are polynomial trendlines.

5, 10 and 15 years using one-way analysis of variance (ANOVA). Semi-continuous tree crown parameters were compared with TRWi for the last 5, 10, and 15 years using Pearson correlation. Although crown parameters indicate the current crown state, they also capture the long-term processes; in particular, the proportion of secondary shoots reflects approximately the last ten years of tree growth.

Tree-ring sampling and chronology development

We used the same trees to analyse tree-ring widths as were used for the crown condition assessment. We used the Pressler borer to extract all samples at breast height. To avoid compression wood, the cores were sampled in a direction parallel to the slope. Because the between-tree variability of TRW within a plot is much higher than the within-tree variability around the stem (Bošeľa *et al*., 2014), we extracted one core per tree. We measured the samples using the VIAS TimeTable (Vienna Institute for Archaeological Science, Vienna, Austria) measuring system (with an accuracy of 0.01 mm). Then, we synchronized and cross-dated the tree-ring sequences using PAST4 software (©SCIEM) and COFECHA (Grissino-Mayer, 2001). To assess the degree of similarity between the raw TRW series, we used the t-test according to Baillie & Pilcher (1973) and the t-test according to Hollstein (1980), the coefficient of agreement (called the Gleichläufigkeit) (Eckstein & Bauch, 1969), the correlation coefficient, and a visual comparison of the TRW series, which is crucial for the final dating (Rybníček *et al.,* 2007). Well-correlated TRW series were used to create site (plot) TRW chronologies. Non-climatic size- and age-related growth trends and other factors (e.g., competition) were removed from the individual TRW series by applying negative exponential functions (Cook & Peters, 1981) in the ARSTAN software (Cook & Krusic, 2005). This standardization method best resembles the common growth trend and preserves inter-annual to multi-decadal growth variations. TRW indices (TRWi) were calculated as residuals between the measured TRW and the corresponding fitted values after power transformation (Cook & Peters, 1997). The mean chronologies were calculated using bi-weight robust means, and their signal strength was assessed using the inter-series correlation (Rbar) and the expressed population signal (EPS; Wigley *et al.,* 1984). Principal component analysis (PCA) was applied to capture the main growth variance among site-indexed chronologies for the common period (1961–2014).

Table 2. Average values of temperature and precipitation during the growing season and the entire year.

Period	Average temperature		Total precipitation	
	Growing season (III–IX)	Annual	Growing season (III–IX)	Annual
1961–1990	8.2 °C	6.0 °C	512 mm	769 mm
1991–2014	9.1 °C	7.0 °C	525 mm	782 mm
1961–2014	8.6 °C	6.5 °C	518 mm	775 mm

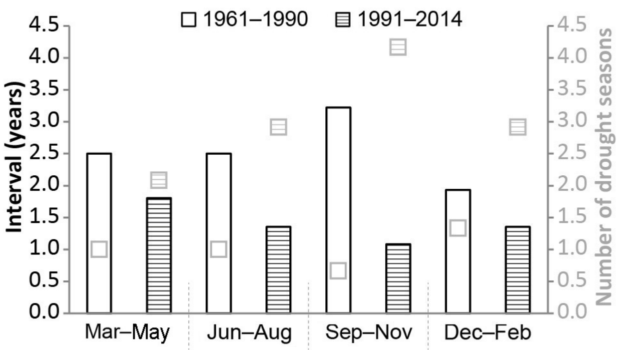


Figure 2. Mean interval between drought seasons (in years) and number of drought seasons per 10 years calculated separately March–May (Mar–May), June–August (Jun–Aug), September–November (Sep–Nov) and December–February (Dec–Feb) and both parts (1961–1990 and 1991–2014) of the study period. A season was considered a drought season when the PDSI values were below -2 during the whole season.

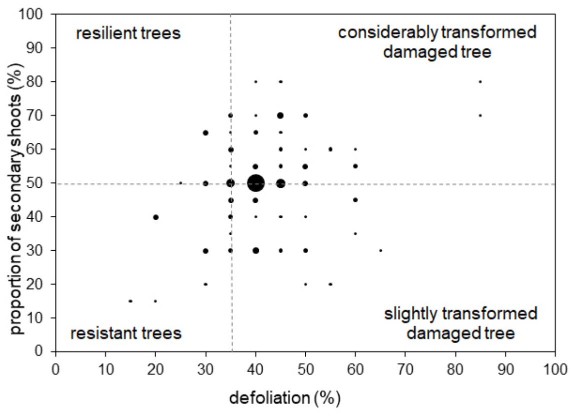
Growth-climate response

To calculate the correlation between radial increments and climate characteristics (temperature, precipitation, AWR and PDSI), we used the residual indexed tree-ring width chronologies (TRWi) in the DendroClim2002 software (Biondi & Waikul, 2004) for the period 1961–2014. Pearson's correlation coefficients were calculated for the seasonal window from May of the previous year to August of the year of tree-ring formation – referred to as "the current year". This interval should have the maximum impact on the TRW in the study area (Gričar *et al*., 2014). In addition, the seasonal means (temperature, PDSI and AWR) or totals (precipitation) of the previous and current years were analysed. Furthermore, we calculated 20-year backward moving Pearson's correlations to explore the expected temporal changes. This window length is a compromise between isolating signal changes with the highest possible temporal resolution and having enough data-points to estimate the signal (Friedrichs *et al.,* 2009). The negative pointer years were analysed for the period replicated by at least 20 TRWi series (from 1930 to the present). The negative pointer years were analysed for years in which residual TRWi chronology dropped below -0.5 standard deviation (SD). The threshold value was arbitrarily defined to yield a sufficient number of extreme years. The relationships between negative pointer years and climate factors were determined using logistic regression (Quinn & Keough, 2002), for which the binary response was coded as a "normal" year (value zero) or a negative pointer year (value 1). Models were verified in the first step using Wald's test for regression parameters and goodness of fit (Quinn & Keough, 2002), and in the second step, using the likelihood ratio test. The model was considered a good fit if both of these tests reached the 0.05 significance level.

Table 3. The evaluated crown condition parameters (Lesinski & Landmann, 1985; Cudlín et al., 2001; Eichhorn et al., 2010)

Social status class (according to Kraft, 1884)		**Branch (crown) form**	
1	dominant	1	comb
2	codominant	1.5	transition from comb to brush
3	subdominant	2	brush
Crown top*		2.5	transition from brush to plate
1	normal	3	plate
2	short – retarded	**Crown shape****	
3	dry	1	normal
4	curved	2	wide
5	broken	3	narrow
Fruiting		4	uneven
0.5	to 5 cones in crown	5	with dry top
1	cones only on the top (to 20 cones)	**Defoliation, Proportion of secondary shoots, Chlorosis, Browning *****	
2	more than 20 cones		
3	high number of cones in whole crown	%	assessed in 5% step

* Short – retarded = top with notably retarded or stopped high increment; dry = top with dry terminal leader; curved =with wilting terminal leader; broken = without terminal leader or with broken terminal leader. ** Wide = broadly conical, with low high increment; narrow = narrow conical or columnar; uneven = irregular, with crown break; with dry top = with dry juvenile part of crown. *** Defoliation, proportion of secondary shoots, chlorosis and browning was assessed as the percentage of the total volume of the living foliage in assessable crowns.



	min–max	Q1–Q3	median	mean	SD
defoliation	15–85%	35–45%	40%	**42%**	10.33
proportion of secondary shoots	18–80%	45–60%	50%	**51%**	13.79

Figure 3. Crown conditions. The bubble size represents the number of trees with the given values of the total defoliation and the proportion of secondary shoots – this is a continuum from the smallest bubble representing one tree to the largest bubble representing 13 trees.

Results

Crown condition and its effect on the mean TRW of the last fifteen years

In total, we assessed 120 Norway spruce trees in the study area. The considerably transformed damaged trees predominated (Fig. 3). The average defoliation was 42%, and the average percentage of secondary shoots was 51%. Thirty-one percent of trees had abnormal crown tops (short – retarded 23%, broken 8%) and 11% had abnormal crown shapes (wide 5%, narrow 3%, uneven 3%); 41% of trees had the branch form changed from comb to brush as a consequence of repeated substitution of original primary shoots by secondary shoots. We observed yellowing only in small parts of the crowns (maximum 20% of crown) of 14% of the trees; browning was not present at all. The trees with changed shape and crown tops, as well as discoloured trees, were dispersed throughout the stand, without recognizable grouping or effects of prevailing wind direction.

The last 5-year, 10-year and 15-year tree-ring widths of the trees with abnormal crown tops and abnormal crown shapes were significantly narrower than in the trees with normal crowns (Table 4). The last 5-year tree-ring width of trees with a lower % of secondary shoots was significantly narrower than in the trees with an unchanged branch form (Table 5).

Climate-growth relationships

Given that residual site TRWi chronologies showed high common variability (Fig. 4, the PC1 axis explained more than 77% of the variance) and were used to compile the regional TRW chronology (Fig. 5A), the regional chronology covering the 1915–2014 period was characterized by an average growth rate higher than 2.5 mm and a high first order autocorrelation (0.77). The length of the TRW series ranged from 50 to 100 years with a mean segment length of 75 years. Reliable values of Rbar (mean = 0.4) and EPS (> 0.95) revealed a robust signal strength of the chronology (Fig. 5B). Although the more recent part of the study period (1991–2014) was shorter compared to the normal period (1961–1990), more negative pointer years were detected in the last two decades.

The months that had significant correlations between TRW and climate parameters in the whole period 1961–2014 are presented (Fig. 6). Tree-ring width was significantly influenced by climate mainly in September and October of the previous year and July and August of the current year. September temperature had a negative effect on TRW. The rest of the observed significant correlations were positive (Fig. 6).

The significance of many observed correlations was not stable over time (Fig. 6). Most relationships were significant only in the last two or three decades. Previous September temperature, precipitation, and AWR became significant in moving intervals ending after 1997 (AWR) and 1999 (temperature and precipitation). Previous August and September PDSI were significant at the beginning and end of the analysed period. Previous October AWR and PDSI became significant in moving intervals ending after 1990 and 2000, respectively. The effects of PDSI in the previous November and December became significant at the end of the analysed period. In contrast, the effect of the previous July precipitation lost its significance in intervals after 1979–1999.

The effects of current July precipitation, AWR and PDSI became significant in moving intervals ending after 1997 (precipitation and AWR) and 1999 (PDSI). August AWR and PDSI became significant in moving intervals ending after 2000 and 1999, respectively. The effects of January and February PDSI became significant at the end of the analysed period. The effects of temperature in March and precipitation in August were only significant in scattered short intervals.

The results of the logistic regression showed that negative pointer years were caused by drought in the 1991–2014 period. Low values of AWR and PDSI during the previous and current years of tree-ring formation significantly correlated with the occurrence of negative pointer years. However, no significant relationship between negative pointer years in the first part of the study period (1961–1990) and climate factors was revealed.

Table 4. Results of the effect of categorical crown condition parameters on the mean tree-ring width (TRWi) of the last 5, 10 and 15 years analysed using one-way ANOVA. Statistically significant values ($p < 0.05$) are in bold.

Source	mean TRWi					
	last 15 years		last 10 years		last 5 years	
	F	p	F	p	F	p
Branch form	0.0978	0.7561	0.4154	0.5229	0.0122	0.9125
Crown top	4.6089	**0.0048**	4.1843	**0.0081**	3.7325	**0.0141**
Crown shape	4.2180	**0.0078**	3.5476	**0.0177**	3.2073	**0.0270**

Discussion

Relationships between crown condition and TRWi

The observed mean defoliation in all stands was higher than the mean defoliation in the Czech Republic (MZe, 2016). We propose that the assessed spruces defoliated and transformed their crown structures in reaction to drought periods after 2012 (Fig. 1) because the research area was one of the Czech land areas where the drought periods were strongest (Zahradníček *et al.*, 2013, 2014).

In general, trees have different drought avoidance and drought tolerance given their abilities to modulate their vegetative and reproductive growth according to water availability and their abilities to maintain (relatively) higher tissue water content despite reduced soil water content. The differences in root morphology, presence of decay, and water conducting element conditions lead to differences in the health status of trees, but not all of the trees show visible symptoms of stress. Defoliation and radial growth can complement each other, but their reactions to stress are usually not synchronous. Drought often affects radial growth almost immediately, while foliage reduction becomes visible months later (Dobbertin, 2006). This reaction asynchronicity could also be the reason we did not identify any relationships between defoliation and the mean TRWi in recent years.

The observed effects of the changed crown shapes and crown tops in the last 5-year, 10-year and 15-year tree-ring widths testified to a longer duration of crown changes. Most of the crown reductions were probably mainly caused by the wind, heavy snow and frost deposits over fifteen years ago. The trees were dispersed throughout the stand, without recognizable effects of prevailing wind direction. On the other hand, the process of crown structure transformation, i.e., the substitution of original primary shoots by secondary shoots probably proceeded in the past few years because the observed percentage of secondary shoots significantly affected only the last 5-year TRWi. We presumed that the crown transformation process was initiated by drought periods after 2012 (see above).

Differences in tree growth response to climate or other environmental factors can also indicate differences in ecotype, provenience or individual predisposition as well as micro-site factors and age-related physiology. The different growth reactivity (growth strategies) can also be grounds for different crown reactivity and resistance to biotic agents. It was found in the declining spruce stands in southeast Norway that trees with dieback symptoms were anatomically predisposed to suffer from hydraulic failure during the drought period because their growth and resource use strategies were different (Rosner *et al.,* 2016). The trees with a provident strategy have a higher wood density, which increased the safety margin for hydraulic failure in years with normal or high water availability. The trees with prodigal strategy invested in growth and increased conductivity rather than hydraulic safety and benefited from it in years with a high water supply but seemed to suffer during dry periods (Hentschel *et al.* 2014). On the other hand, Børja *et al.* (2016) identified disruption in the

Table 5. Results of the effect of semi-continuous crown condition parameters on the mean tree-ring width (TRWi) of the last 5, 10 and 15 years analysed using Pearson correlation. Significant values of the Pearson correlation coefficient are given in bold, significant level: $p < 0.05$.

Source	mean TRWi		
	last 15 years	last 10 years	last 5 years
Defoliation	0.01	0.05	0.10
% of secondary shoots	0.14	0.14	0.22
Chlorosis	0.15	0.17	0.14

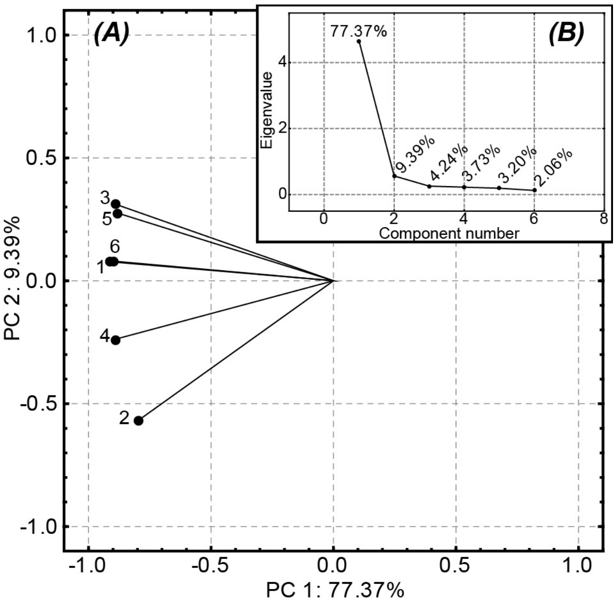


Figure 4. PCA of indexed site TRW chronologies for the common overlap period of 1945–2014 (A) and the scree plot (B).

water transport system in symptomatic trees as well as in spruce trees without visual symptoms, and Čermák *et al.* (2017) did not identify any significant relationships between crown condition and radial growth in the same area affected by a forest decline episode.

Climate-growth relationships

The study of droughts in the Czech lands demonstrates an increasing long-term dryness in the Czech climate. The period 2004–2012 was the most severely dry part of the period with available climatic data (from 1805). Two similar long periods of drought were also recorded in the 19th century, but the drought severity was lower (Brázdil *et al.* 2014). Most of the climatic parameters significantly correlated with TRW mainly after the end of the 1990s (Fig. 6), and the relationships probably primarily reflect the higher frequency and duration of drought periods (Fig. 2). During 1961–1990, only one-year drought periods affected trees; after 2002, two longer drought periods limited growth conditions. The drought-affected growing seasons were 1992–1994, 2003–2007 and 2012–2015 in the research area (Fig. 1, PDSI).

Brázdil *et al.* (2014) demonstrated that the drought episodes in the Czech lands before 1880 may be attributed to a lack of precipitation, whereas the droughts of recent decades (particularly 2004–2012) are more strongly related to high temperatures. The increasing temperature increased the vapour pressure deficit and thereby the transpiration rates. The climatic optimum of *Picea abies* is characterized by a mean annual temperature of 6°C and a growing-season precipitation

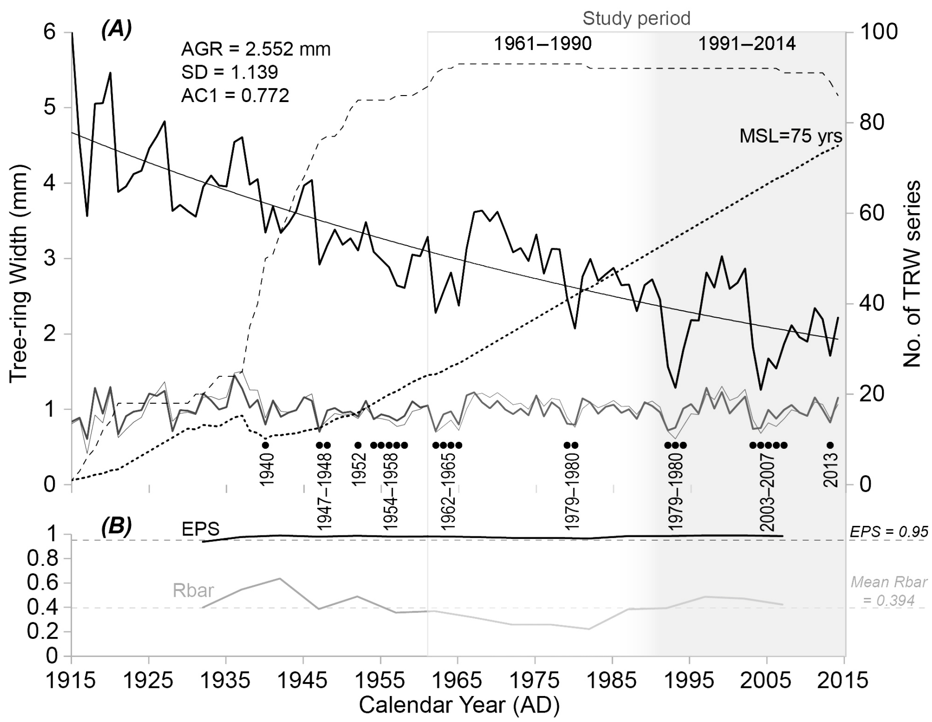


Figure 5. (A) Raw (black), standard (dark grey) and residual (light grey) versions of the regional TRW chronology, its replication (dashed line) and basic dendrochronological metrics (AGR – average growth rate, SD – standard deviation, AC1 – first-order autocorrelation. Black dots indicate negative pointer years. (B) Rbar (mean inter-series correlation) and EPS (expressed population signal) statistics of the regional TRW chronology.

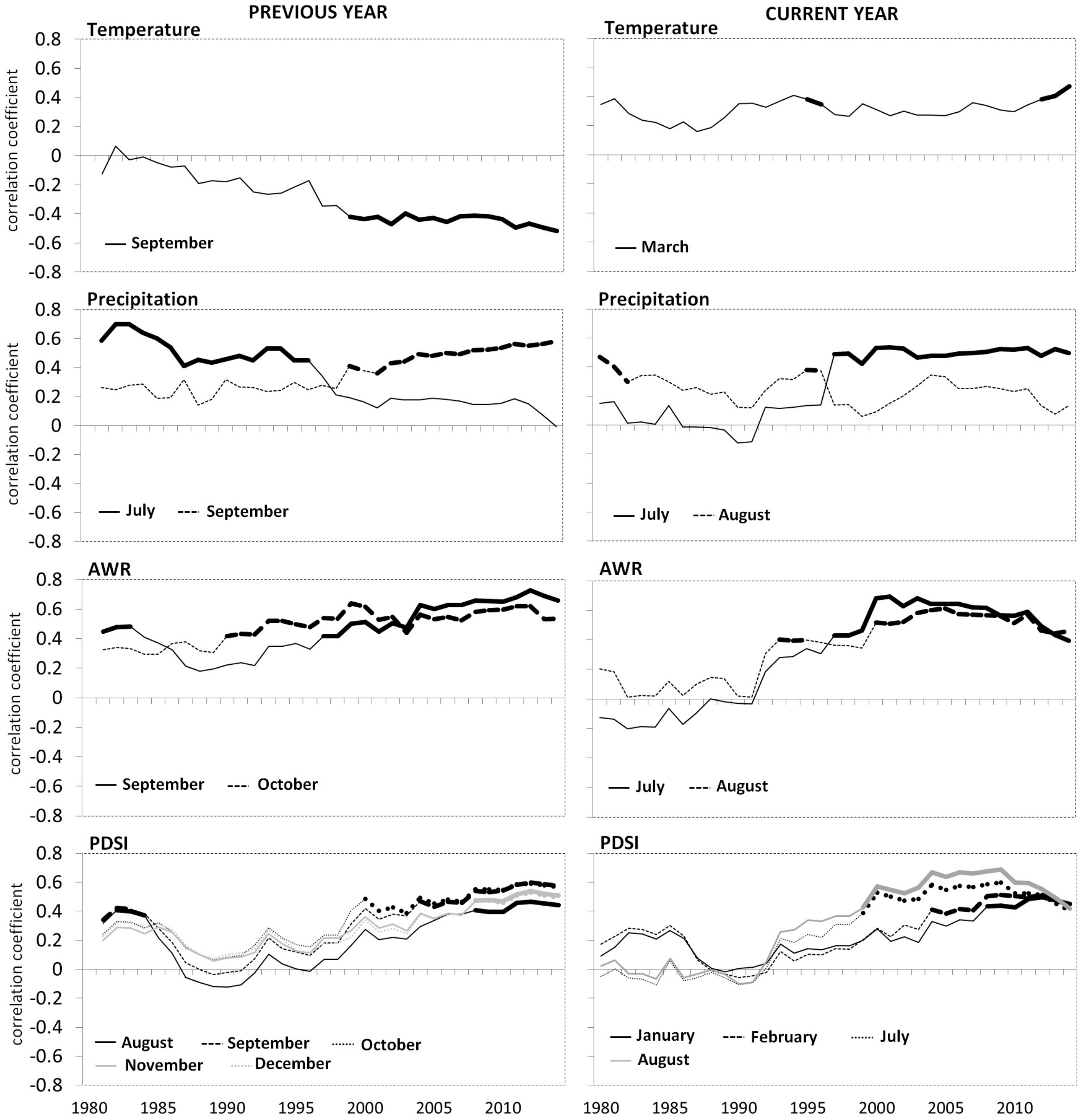


Figure 6. Correlation coefficients calculated between mean monthly temperature, monthly precipitation totals, relative soil water content for the top 1.3 m (AWR), Palmer drought severity index (PDSI) and tree-ring width (TRW) for 20-year backward moving intervals. Significant correlations are indicated by bold lines (Student's t test). Only months that had significant correlations in the whole period 1961–2014 are shown. The years on the x-axis represent the last year of moving intervals.

total of 490–580 mm (Modrzyński, 2007). Although the growing-season precipitation total remained at the bottom edge of the climatic optimum range in our study plots, the temperature increased above the climatic optimum (Table 2). The current climatic conditions are thus not comfortable for *Picea abies* in the study area.

These changes in climate conditions can be clearly seen in the climate-growth relationship. The increasing negative significant effect of previous September temperature to TRW (Fig. 6) validates the described temperature effect of drought on our assessed area. The effects of previous September temperature and precipitation are also reflected in AWR and PDSI effects on TRW in the following autumn months (Fig. 6). A negative effect of temperature in the previous autumn was identified many times across Europe (MZe ČR & VÚLHM, 2004; Andreassen *et al.,* 2006; Bouriaud & Popa, 2009; Affolter *et al.,* 2010; Aakala & Kuuluvainen, 2011; Rybníček *et al.,* 2012b, c). However, a positive effect of precipitation in the previous autumn has also been observed (Bouriaud & Popa, 2009; Rybníček *et al.,* 2010). Higher mean temperatures at the end of the growing season generally negatively affect the availability of soil moisture through increased evapotranspiration (Miyamoto *et al.,* 2010). Conversely, higher autumn precipitation increases soil water content and the amount of available water in the spring. Moreover, September is important for the growth of Norway spruce roots because their second distinct growth period is from August to September (Xu *et al.,* 1997).

In the same period when the previous September precipitation started to be significant, the previous July precipitation stopped being significant (Fig. 6). The relationship between previous summer precipitation and TRW is frequent (Affolter *et al.,* 2010; Aakala & Kuuluvainen, 2011), especially in the conditions of Central Europe (Rybníček *et al.,* 2009, 2010, 2012c). The relationship is also commonly explained as a positive effect on soil water content and production capacity (vitality, distribution and biomass of roots, etc.). However, in the above-described climate conditions, the previous July precipitation effect on growing conditions at the beginning of the growing season is probably minimized.

Our results also show that precipitation in the current summer months (mainly in July) and the related AWR and PDSI are significant mainly in moving intervals ending at the end of the 1990s or the beginning of the 2000s (Fig. 6). The significant positive correlation between July or August precipitation and TRW was identified in the central area of the Czech Republic (Rybníček *et al.,* 2012c), the White Carpathians (Kolář *et al.,* 2017), in northern lowland Poland (Koprowski & Zielski, 2006) and the Alps (Affolter *et al.,* 2010). The observed increase in July and August AWR and PDSI significance is probably also related to the increasing temperature. The mean June temperature increased from 13.9°C in 1961–1990 to 14.9°C in 1991–2014, the mean July temperature increased from 15.4°C to 17.2°C, and the mean August temperature increased from 15.2°C to 17°C. The strong temperature growth increased evapotranspiration and led to decreased relative soil water content for the top 1.3 m.

Intensive and often recurring drought spells (Fig. 2) starting at the beginning of the 1990s caused more frequent spruce growth depression reflected in a higher number of negative pointer years compared to the normal period (Fig. 5A). The results of the logistic regression revealed that the negative pointer years were triggered by a lack of available water, but only in recent decades. Therefore, the expected more frequent drought in the following years can lead to serious growth reductions and possible weakening of tree vitality.

Conclusions

The observed crown condition and its relationships with the last 5-year, 10-year and 15-year TRWi indicate stress intensification during the period starting at the turn of the 21st century.

The soil water content decrease evoked mainly by increasing temperature led to significant changes in relationships between climate parameters and tree-ring width. We suppose that water availability was the main inciting factor (Sinclair, 1967) that triggered the decline event and is currently a contributing factor that significantly intensifies forest decline.

The study area was relatively favourable for *Picea abies* at the time when the stands were planted (from 1915 to 1965), but currently, the climatic conditions at these sites have changed, moving away from the Norway spruce ecological optimum (Modrzyński, 2007). Silviculture of the Norway spruce is extremely risky in such conditions. The conversion from Norway spruce forests managed under systems involving coupes to uneven-aged mixed forest silviculture is needed under such conditions (Temperli *et al.,* 2012). Long-term general forestry planning uses time horizons of 20 years or longer. Our results have shown that the observed climate change is too dynamic for many recommendations included in the plans for the site and climate conditions – recommended species composition, timber-stand improvement models, etc. The recommendations become inadequate in the course of the planning period, let alone during the tree or stand life. New long-term plans should support operational decisions responding to the state of the stands. It is necessary for effective adaptive management.

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