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ORIGINAL PAPER

Radial increment and defoliation of *Pinus sylvestris* (L.) on sandy soils relate to summer temperatures and ground water level

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Abstract

The study deals with the analysis of the impact of climate and ground water table level on radial increment and defoliation of Scots pine (*Pinus sylvestris* L.) growing on sandy soils. The research was performed in the area of the Borska nížina (i.e. Borská Lowland, situated in southwest of Slovakia), where a substantial die-back of pine trees has been observed in the last decade. Increment measurements and defoliation assessment were performed at 150 adult trees of Scots pine growing at three permanent monitoring plots within the international network of ICP Forests during the years 1989–2018. We examined the impact of climatic and hydrological factors on selected features of pine using the methods of correlation analysis and linear mixed models. Statistical analyses confirmed that the annual radial increment of Scots pine significantly depended on the mean air temperature from June to August, and mean ground water level in the mentioned months. These two factors also significantly correlated with crown defoliation. The factors explained 26% and 32% of increment and defoliation variability, respectively. From the long-term perspective, our analyses indicated that the decrease of ground water level by 0.5 m in summer resulted in the increase of defoliation by 10%. The obtained results indicate a further increase of Scots pine die-back on easy-to-dry sandy soils in regions with low precipitation totals, particularly considering the ongoing climate change and its inherent factors.

Key words: Scots pine; tree growth; crown condition; ground water; climate change

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1. Introduction

Scots pine (*Pinus sylvestris* L.) is one of the most important tree species of Central and Eastern Europe. It has the widest distribution range from all pine species and can be adapted to many different biotopes (Schutt et al. 1984). Scots pine belongs to the tree species of the continental climate, well adapted to colder and nutrient-poor sites. Its climate envelope covers a temperature amplitude between about −4 and 14 °C and a precipitation range of 400 to 1,300 mm (Kölling 2007; Pretzsch et al. 2020). Scots pine is known for its ability to grow in a wide range of relatively extreme site conditions, such as rocky ridges with different parent rock material, peat soils, and other nutrient-poor soils (Richardson & Rundel 1998; Oyen et al. 2006; Bogino et al. 2009; Pärn 2009), and it is relatively tolerant to drought (Picon-Cochard et al. 2006; Sanchez-Gomez et al. 2006). Pine needles are adapted to deal with drought thanks to embedded stomata and a waxy layer on epidermis protecting from sudden water loss (Ayanz et al. 2016). Another advantage of Scots pine in coping with drought periods is its relatively deep root system (Roberts 1976). Scots pine (often together with oak) is widely considered as a promising tree species that allows forest managers to reduce risks associated with ongoing climate changes having a potential for adaptive forest management in Central Europe (Spellmann et al. 2011).

Climate change together with accompanying phenomena has a significant impact on forest ecosystems, including forest stands containing Scots pine (Lindner et al. 2010). The increase of air temperature can for example modify the beginning of the growing season (Koprowski 2013), its length (Menzel & Fabian 1999), and subsequently the dynamics of annual ring formation during

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a growing season (D'Arrigo et al. 2008; de Luis et al. 2014). Cumulative effect of different climatic parameter can shift the growing period and also can affect the morphology, for example early wood and latewood proportion though the total radial growth may remain same. The relationship between the growth activity of Scots pine and climatic factors was examined in different climatic, environmental and elevational conditions (Eilmann et al. 2006; Bauwe et al. 2013; Panayotov et al. 2013; Bauwe et al. 2015; Sanchez-Salguero et al. 2015). Although the adaptability of Scots pine to various climatic and environmental conditions is in general high, its growth in Central and Southern Europe is assumed to decline due to warming (Reich & Oleksyn 2008).

Impacts of temperature and precipitation on Scots pine growth in different regions of Europe can be seen in dendro-climatic studies focusing on the analyses of growth and climate interactions on the base of tree ring samples (e.g. Henttonen et al. 2014). For example, the study from Poland revealed that wide tree rings are formed in the years with higher air temperatures in February and sufficient precipitation totals during a growing season (Zielski et al. 2010). The works from Hungary show that precipitation in June and July and temperatures from February to March have dominant impacts on Scots pine growth, while summer temperatures play a secondary role (Misi & Nafradi 2016; 2017). Under the conditions of north-eastern Germany, Scots pine forms wide tree rings in the case of above standard moist / warm February and moist and cold June (Bauwe et al. 2013). Dendro-climatological research performed in the Czech Republic showed that temperatures in February and March, and summer precipitation are main factors positively affecting Scots pine growth (Mácová 2008). Similar analyses from Lithuania confirmed that precipitations in May and June are key factors limiting Scots pine radial increment (Vitas & Erlickyté 2008). Scots pine increment reactions to climatic characteristic are substantially modified by a tree growth stage. The study from the Romanian Carpathians suggested that radial increment of young pine trees (particularly in the western part of the Carpathians) had negative correlations with temperature in summer months, while older trees (above 50 years old) were indifferent, or had even positive correlations (Sidor et al. 2018). Several studies jointly confirm that climatic variables are dominant factors affecting tree growth, even in the cases of trees growing on soils with different nutrition conditions (Vitas & Erlickyté 2008; Xenakis et al. 2012).

In Slovakia, Scots pine occurs under varying conditions, at elevations from approximately 200 m to 1,500 m a.s.l., exceptionally also up to 1,800 m a.s.l. (Pagan & Randuška 1987). Its occurrence is concentrated in areas with extreme relief and geological conditions of limestone mountains (so called relict pine forests), but especially in the Borská Lowland. In this region, pine forms continuous forests growing on relatively nutrient-poor sandy soils (Pagan & Randuška 1987). Since the year 2008, a substantial increase of incidental felling has been recorded as a result of repeating wind disturbances, and since 2013 also due to the intense bark beetle damage in the region (Leontovyč et al. 2017). However, problems with pine die-back were observed already before. It was assumed that worsened health conditions of this tree species were linked to climate change and the decrease of ground water level, but relevant connections have not been thoroughly studied. The unfavourable development of pine health state as well as requirements of the forestry practice motivated researchers to perform a more detailed analysis of available information (Leontovyč et al. 2017).

The aim of this study was to analyse and document the impact of climatic and hydrological factors on growth and vitality of Scots pine using long-term monitoring ICP Forests plots in the western part of Slovakia, where the health conditions (manifested as defoliation and discoloration in crowns) of pine have been substantially worsened in recent years.

The Scots pine research under the conditions of the Borská Lowland focused on examining the following hypotheses:

H1/ changes in air temperature in growing seasons during the last 30 years had an impact on radial increments of this tree species,

H2/ the annual radial increment reacts to fluctuations of ground water level,

H3/ crown conditions (loss of foliage) depend on the changing regional climate and hydrological regime in the area of interest.

2. Material and methods

2.1. Study area

The study area is located in the western part of Slovakia, the geomorphological unit of the Borská Lowland, at the border of Austria and the Czech Republic (Fig. 1). It is a part of the West Pannonian Basin and the Záhorská Lowland (Kočický & Ivanič 2011). Most of the area is situated at elevations from 180 to 230 m a.s.l. The highest peak of the Borská Lowland called the Mária Magdaléna Hill is at an elevation of 297 m a.s.l. It is a continuous, geologically, and site-specific area of wind-blown sands with a relief of low hills. The surface is slightly undulating with sand dunes, with closed drainless depressions. It is assumed that average annual sand accumulation in this region is 2.4 cm per year (Šilhán et al. 2021). Soils that developed from the parent rock material in the absolute predominance are classified as Haplic Arenosols (IUSS Working Group WRB 2015). Only locally, more significant manifestations of podsolisation or other soil-forming processes are apparent. Gleysols occur at locations directly affected by ground water. Soil texture (very high sand fraction), and usually also very low amount of alkaline nutrients (nutrient poor) are determining features of these soils.

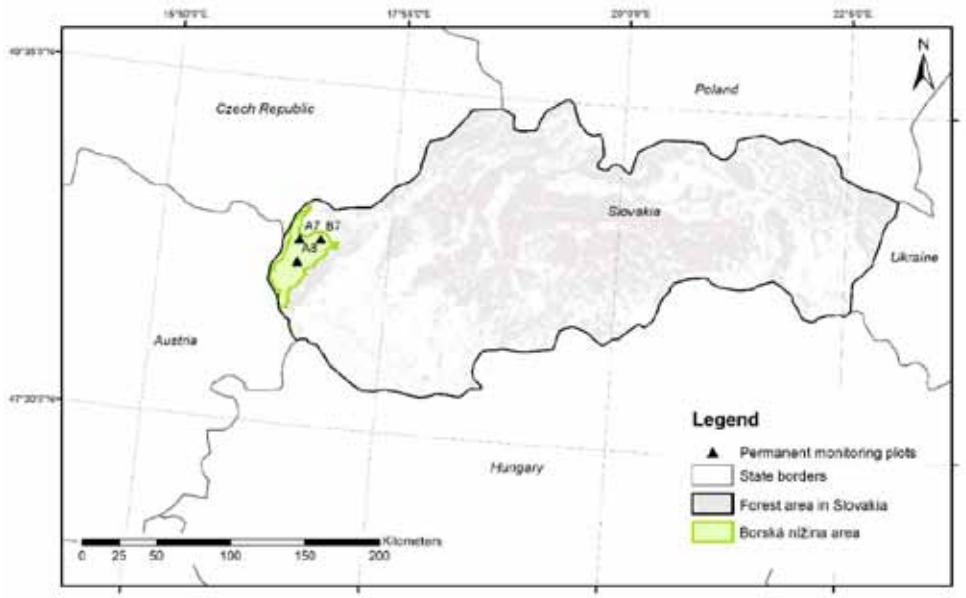


Fig. 1. Location of the study area in the south-western part of Slovakia.

From the point of edaphic conditions, communities belong to the A acidic order. The dominant groups of forest types (according to Zlatník 1976) are *Pineto-Quercetum* (PiQ) and *Quercetum* (Q), followed by *Carpineto-Quercetum* (CQ), and to a smaller extent also *Betuleto-Quercetum* (BQ) and *Betuleto-Alnetum* (BAl). Forests cover around 42% of the Borská Lowland area. From the hydrological perspective, the area belongs to the Morava river watershed affected by local inflows of the Myjava and the Rudava. Climatologically, the area and research plots at Záhorie belong to the warm, slightly dry, lowland climatological district with mild winter (Bochníček et al. 2015). Monthly mean temperature in January exceeds −3 °C and number of summer days exceeds 50. Annual mean air temperature of the area is 9.1 °C, and the long-term annual precipitation total derived from 1961–1990 period is 554 mm (see climate diagram in Fig. 2).

2.2. Climate and ground water data

Climatic data on monthly precipitation totals were obtained from two climatological stations (Senica, Malacky) and one precipitation station (Šaštín-Stráže) that belong to the network of the Slovak Hydrometeorological Institute (SHMI hereinafter). The data on monthly mean air temperatures for individual research plots were extracted from international climatic databases E-OBS v20.0e and CRU TS4.03, which are available in resolutions of 0.25 or 0.5° (Cornes et al. 2018, http://climexp.knmi.nl/). The analysis also used weekly data on the ground water level from the Šaštín-south probe covering the long-term period 1969–2018 (from the SHMI database). This probe is located at an altitude of 183.35 m a.s.l. and its depth is 13.94 m. The surface height of the second ground water probe Tomky lies at elevation of 177.01 m a.s.l. and its depth is 7.25 m. Ground water probe Tomky has only shorter period of observations (since 1994), thus for the analyses we used data from Šaštín-south probe for period 1989–2018, when data about radial increment of measured pines were available. The map in Fig. 3 displays location of both groundwater stations and its approximate distance from the research stands.

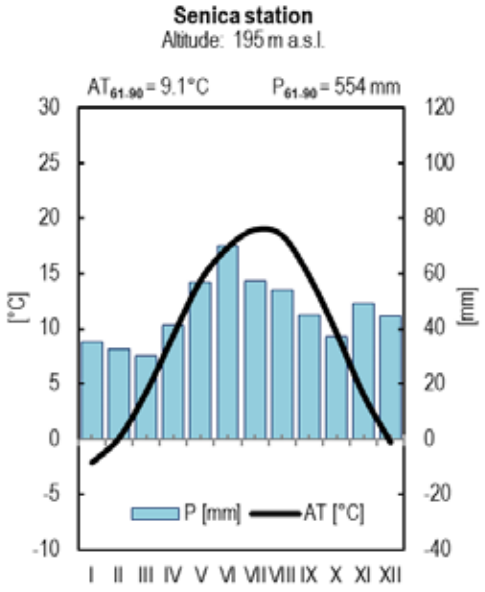


Fig. 2. Climate diagram for SHMI weather station Senica (195 m a.s.l.) valid for the long-term period 1961–1990.

2.3. Tree growth measurements and crown condition assessment

To analyse the impact of climate and ground water level on the radial increment and defoliation of Scots pine at Záhorie we used long-term measurements from three permanent monitoring plots (PMP; A7, A8, B7), which belong to the network of the international extensive forest monitoring ICP Forests (Level I plots) covering a period 1988–2018 (Fig. 3). Basic site and stand characteristics of plots are given in Table 1. The stands growing at the plots are mature forests aged 90–100 years old, with stocking of 0.8, dominated by Scots pine (*Pinus sylvestris* L.) and with minor and only very local admixture of black poplar (*Populus nigra* L.), common oak (*Quercus robur* L.) and common alder (*Alnus glutinosa* L. Gaertn). From the point of site index and hence also nutrient sources in soil, A7 plot is of the highest quality (site index of 30), while B7 plot is of the lowest quality (site index of 24). Hectare wood volumes in these pine stands fluctuate around 218–282 $m^3 ha^{-1}$ (Source: LGIS, © NLC Zvolen, 2020).

Since 1988, defoliation, stem and crown damage, and annual radial increment at a height of 1.3 m have been assessed on 50 permanently marked trees per plot. The methodology of increment measurements is in accordance with the guidelines of ICP Forests (Dobbertin & Neumann 2016). Annual radial increments (i_r) were derived from stem circumferences measured at the end of each growing season. Since trees were of approximately the same age, plot-wise mean annual radial increments were calculated from annual radial increments of individual trees ($\bar{i}_r$) without the need to detrend them. In total, we included and evaluated 150 Scots pine trees. The social status of the monitored Scots pine trees according to Kraft's classification is as follows: 9% of the all trees

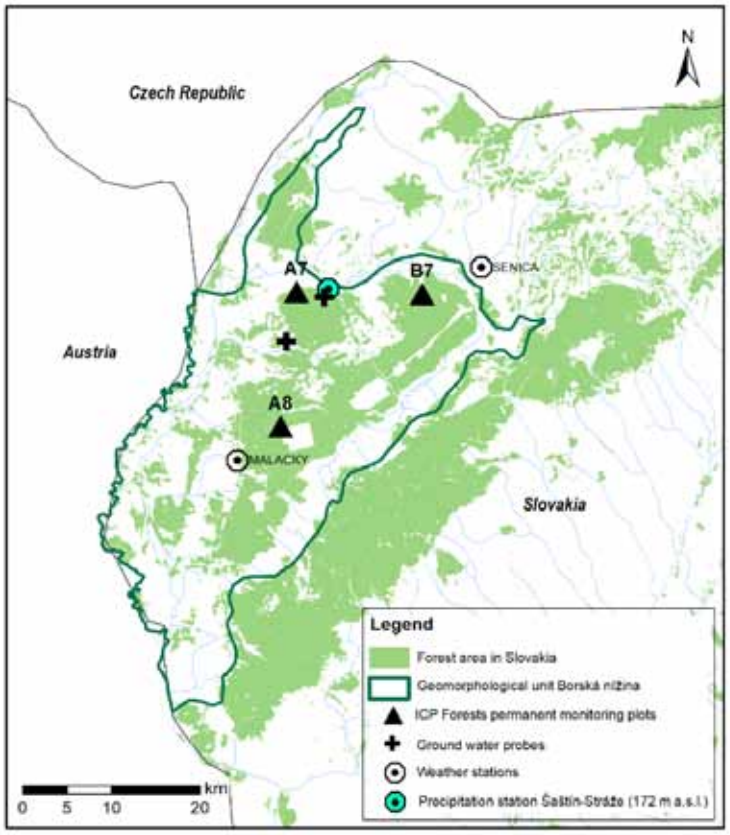


Fig. 3. Location of research plots (formerly ICP Forests monitoring plots with codes: A7, A8 and B7), groundwater probes and the weather and precipitation stations of the Slovak Hydrometeorological Institute (SHMI).

Table 1. Basic characteristics of monitoring plots Šaštín-Stráže (ICP Forests code A7), Studienka (A8) and Šajdíkove Humence (B7).

Plot Characteristics	Measuring unit	Šaštín-Stráže plot	Studienka plot	Šajdíkové Humence plot
Altitude	[m a.s.l.]	170	190	210
Aspect/Slope	[degree]	0	0	0
Stand age*	[years]	100	95	90
Mean height*	[m]	25	24	22
Mean diameter*	[cm]	32	32	33
Group of forest types	—	*Carpineto-Quercetum*	*Quercetum*	*Quercetum*

* Data valid for the year 2018 (according to the Forest management plans, LGIS, © NLC Zvolen, 2020).

cover the pre-dominant social class (1), 88% belong to dominant (2) and only 3 % to co-dominant (3) social class. No suppressed trees (classes 4 and 5) were occurred in the research plots. On this basis, we considered the vertical structure of the forest canopy as homogeneous with a negligible effect on the radial growth.

Defoliation was assessed visually with a precision of 5% following the valid guidelines of ICP Forests (Eichhorn et al. 2016). According to this manual, defoliation is defined as needle/leaf loss in the assessable crown as compared to a reference tree. Absolute reference trees are the best possible trees of a genotype or species, regardless of site conditions, tree age, etc. Defoliation is observed regardless of the cause of foliage loss. It is an important indicator of crown condition, and it is among the indicators of sustainable forest management (Criterion 2: Maintenance of Forest Ecosystem Health and Vitality).

2.4. Development of a dendroclimatic model

Since the mean radial increments did not show any significant temporal trends linked to the biological age in the investigated period, data standardisation (i.e. detrending), which is a part of dendrochronological methods (Fritts 2001), was not necessary. When deriving the model for predicting annual radial increments and defoliation it was first necessary to analyse, which variables affect dependent variables most significantly (Table 2). First, we performed correlation analyses of mean increment chronologies and defoliation development between individual plots (Table 3). Subsequent analyses were performed using data from all three plots together. We calculated correlations between all examined variables listed in Table 2. Afterwards, we applied linear mixed models, in which PMP was used as a random factor (random effect), and climatic variables were used as fixed factors. All analyses were performed using means representing parts of the growing season (n – non, e – early, m – mid, l – late), while the length of individual parts varied between 2 and 4 months depending on the character of climatic and physiological characteristics. Here we assumed that no or minimum increment is produced between November and February (a period named as n – non). The period from March to May represents the beginning of spring, and hence the increasing formation of increment and transpiration, as well as the increase of ground water level. The next period from June to August (m – mid) represents summer, during which evaporation is increased and drought periods occur, while ground water level culminates and begins to decrease. In this period, radial increments culminate, too. The last period covering September and October (l – late) is characterised by the reduction of photosynthetic activity, the tree species preparation for winter, while the ground water level is at its minimum.

Several analyses (steps) that ensure the accuracy of the model are required to derive a linear mixed model. The first model was constructed using the variables that were correlated with radial increment with the correlation coefficient of at least 0.25 (moderate correlation). With the stepwise regression we could select the variables that explained the greatest proportion of the change in the dependent variable. However, these variables need to be subsequently re-evaluated and the variables that are not logical from the physiological point of view or their correlation is only random need to be excluded. In the first step, all variables (i.e. precipitation, temperature, and ground water level in all examined periods) were included in the stepwise analysis. The list of variables used to derive the mathematical statistical model is in Table 2. Selected variables were subsequently re-evaluated, and we searched for a relationship that would explain the maximum proportion of variability and minimum values modified according to Akaike information criterion (AICc). The final model contained variables that were significant and therefore, were not excluded from the model.

Table 2. Description of variables used for correlation analyses and development of the mathematical statistical model.

Variable	Description of a variable
	Tree characteristics
i_r	Mean annual increment [cm]
SAO	Foliage loss – defoliation [%]
Δi_r	Change of mean annual increment ($i_{r(t)} - i_{r(t-1)}$)
	Precipitation characteristics
n_veg_p	Mean precipitation total in months XI – II
e_veg_p	Mean precipitation total in months III – V
m_veg_p	Mean precipitation total in months VI – VIII
l_veg_p	Mean precipitation total in months IX – X
	Temperature characteristics
n_veg_t	Mean temperature in months XI – II
e_veg_t	Mean temperature in months III – V
m_veg_t	Mean temperature in months VI – VIII
l_veg_t	Mean temperature in months IX – X
	Ground water level characteristics
n_veg_gw	Mean ground water level in months XI – II
e_veg_gw	Mean ground water level in months III – V
m_veg_gw	Mean ground water level in months VI – VIII
l_veg_gw	Mean ground water level in months XI – II
gw_climwin	Mean ground water level in months IV – IX
gw_mean	Annual mean ground water level
	Characteristics of ground water level dynamics
w_min	Minimum ground water level per year
gw_max	Maximum ground water level per year
gw_ampl	Change in ground water level per year (*gw_max* – *gw_min*)
gw_ampldif	Inter-annual difference in ground water level change ($gw_ampl_t - gw_ampl_{t-1}$)
gw_velo	Rate of ground water level change (ratio of *gw_ampl* and number of days between *gw_max* and *gw_min*)

3. Results

3.1. Climate and ground water trends

The long-term development of mean annual air temperatures (1961–2018) at the weather station of Senica (195 m a.s.l.) indicates the increasing trend of air temperature in the last decades (R^2=0.40) (Fig. 4). While the long-term mean calculated from the reference period 1961–1990 was equal to 9.1 °C, the mean annual tem-

perature in the last decade 2008–2018 was 10.3 °C, i.e. the temperature increased by 1.2 °C.

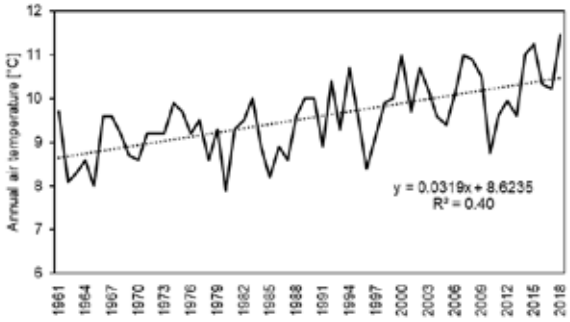


Fig. 4. Temporal trend of mean annual air temperatures at Senica (195 m a.s.l.) weather station of SHMI in the Záhorie region.

A detailed comparison of monthly mean air temperatures in the last decade, during which we observed worsening of pine health conditions (e.g. also of defoliation) at Záhorie region, with long-term monthly means derived from the reference period indicates most profound warming in summer months (July, August by 1.8 °C), but also in April (by 1.6 °C), January (by 1.5 °C), and November (by 1.9 °C). The shift in temperatures is not uniform during the whole year, but relatively differentiated and greater in the growing season than in winter.

However, no obvious increasing or decreasing trend in the long-term development of annual precipitation totals at Šaštín-Stráže precipitation station (172 m a.s.l.) could be seen in the period 1972–2018. Fig. 5 presents the comparison of annual totals with the long-term mean total for the period 1961–1990 (621 mm). The highest annual precipitation total was observed in the year 2010 (894 mm, i.e. 144%), and the lowest one in 2003 (only 373 mm, i.e. 60%). We can see that annual precipitation totals obviously were below-average also in the period 1988–1992, when also ground water level dropped to the lowest values (Fig. 6).

Similarly, as for temperature, we can see differences between months. In the last decade (2008–2018), monthly mean precipitation totals in April, June, and November were systematically deficient, while higher monthly mean precipitation totals were observed in May, from July to September, and in January and February.

The development of ground water level based on weekly elevation measurements (in m a.s.l.) at Šaštín - south probe is presented in Fig. 6 (according to the SHMI hydrological data). Here it is necessary to explain that more substantial changes of ground water level at the western part of the area were linked to the regulation of the Morava river. More specifically, this included

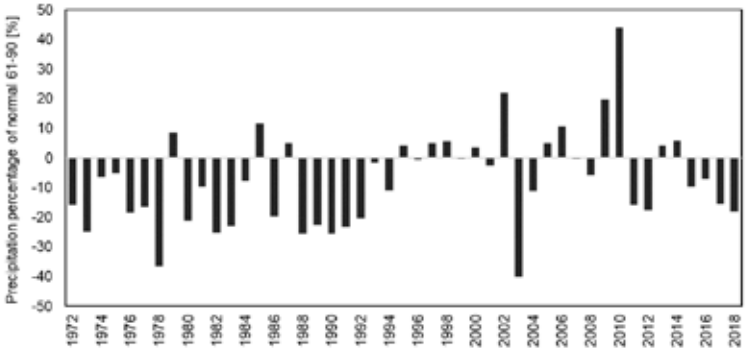


Fig. 5. Long-term development of annual precipitation totals at Šaštín-Stráže precipitation station of SHMI (172 m a.s.l.) compared to the reference precipitation total derived for the reference period 1961–1990 (621 mm).

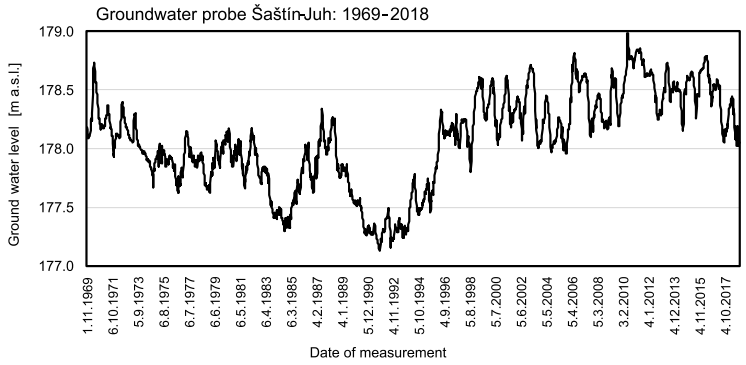


Fig. 6. Development of ground water level on the basis of weekly measurements in the Šaštín-south probe located at an altitude of 183 m a.s.l. (Source: SHMI database).

the construction of the canal collecting water from dead branches of the Morava, as well as widening and deepening of the Porec stream bed in the sixties of the last century. So the ground water level was clearly decreasing since 60´s after regulations of water courses in the region. The depth of ground water table was the lowest in the beginning of 90´s (see Fig. 6). After positive changes between years 1990 and 2010, the ground water table is decreasing again.

3.2. Outputs of correlation analysis

Correlation analysis of mean radial increments and defoliation values between plots showed a moderate relationship between increments, and a strong correlation between plots in the case of the foliage loss (Table 3).

Table 3. Comparison of correlations between individual plots for mean radial increments (i_r) and defoliation.

	Correlation Coefficient	
Variable / Research plots	Radial increment i_r	Defoliation
A7 – A8	0.55	0.89
A7 – B7	0.63	0.84
A8 – B7	0.57	0.83

The final model contained the following variables (r>0.25): spring temperature, summer temperature and precipitation, and ground water level in summer. The analysis showed that summer air temperature and ground water level in summer were most tightly related to the examined dependent variable.

The mathematical form of the final model is as follows:

$$y = b_0 + b_1 * m_{veg_t} + b_2 * m_{veg_{gw}} + \varepsilon \quad [1]$$

y – radial increment (mm) or defoliation (%),
m_{veg_t} – mean air temperature from June to August,
$m_{veg_{gw}}$ – mean ground water level from June to August,
b_0, b_1, b_2 – regression coefficients,
ε – random effect (plot).

The model was primarily derived for radial increment, and subsequently it was also used for modelling defoliation. It is interesting that in the case of a simple correlation analysis summer temperatures did not have a significant impact on defoliation, but in combination with ground water level they were significant.

We can say that variables (factors) included in the model explained 26% and 32% of the overall increment and defoliation variability, respectively. Considering the complexity of living systems, this proportion represents a substantial part of their variability, which is influenced also by other factors (soil, stocking, social position, etc.), measurement errors, or other random factors.

We further revealed a significant correlation between increment and summer temperature (H1), and insignificant effect of precipitation, temperature, and ground water level of other parts of the year (Table 4). Considering the current decreasing trend of the ground water level (Fig. 7a), we can expect a reduction of radial increments (Fig. 7c). The impact of the increasing mean summer temperature (Fig. 7b) was slight at first, but if the temperature exceeded approximately 20 °C the negative

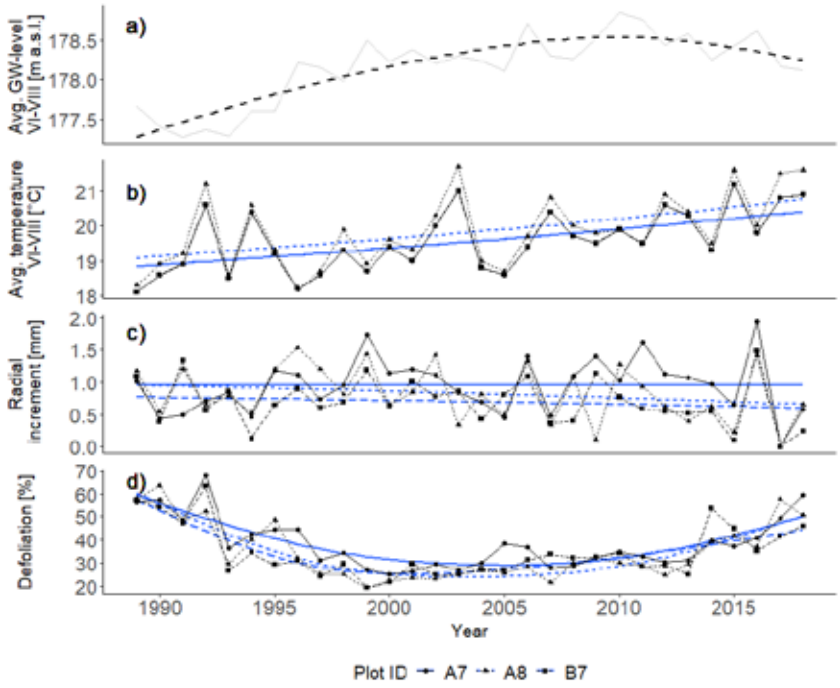


Fig. 7. Temporal development of ground water level (a), mean air temperature from June to August (b), mean radial increment of pine trees (c), and mean defoliation of pine at individual plots in the period 1989–2018 (d).

reaction of radial increment increased (Fig. 7c). Within-plot variability in tree radial increments and sample depth is shown in the Attachment 1.

Defoliation is most closely related to mean ground water level in summer, while higher ground water level resulted in lower defoliation (Fig. 7d). From the long-term perspective, the decrease of ground water level by 0.5 m in summer resulted in the increase of defoliation by 10 %.

Next, we visualised the relationship between the radial increment or defoliation of pine and mean summer temperatures (Fig. 8a and 8b), and ground water level in summer (Fig. 8c and 8d).

Table 4. Statistical characteristics of mathematical models describing the relationship of defoliation or radial increment to mean summer temperature and mean ground water level in in summer. Significance levels: 0 '***' 0.001 '**' 0.01 '*'.

Defoliation [%]					
	Estimate	Std. error	Df	t value	Pr(>|t|)
Intercept (b_0)	2736.046	418.737	85.072	6.534	***
Summer temperature (b_1)	2.601	1.113	86.519	2.336	*
Water level (b_2)	−15.444	2.376	85.11	−6.5	***
Random effects:	Variance	St. dev.			
Intercept	2.513	1.585			
Radial increment i [mm]					
Intercept (b_0)	−50.4201	15.26859	85.03903	−3.302	**
Summer temperature (b_1)	−0.21868	0.04073	85.73386	−5.369	***
Water level (b_2)	0.31178	0.08664	85.05108	3.599	***
Random effects:	Variance	St. dev.			
Intercept	0.01435	0.1198			

Climate-increment statistical analyses confirmed the hypothesis that the ground water level in summer (June – August) had an impact on both defoliation (H3) and radial increment (H2). It needs to be considered that the ground water level depends mainly on precipitation in spring and summer. Under the conditions of the decreasing ground water level, we can expect reductions of radial increments.

The correlation matrix of relationships between individual independent variables in the dendroclimatic model is in Attachment 2.

4. Discussion

To evaluate the influence of climatic factors on tree growth and defoliation of Scots pine, we used data obtained within the long-term monitoring of Slovak forest health in the years 1989–2018. In comparison to classical dendrochronological analyses of tree cores or discs (Speer 2012) or newer ones as automatic band dendrometers (e.g. Leštianska et al. 2020), such an approach was disadvantageous from two aspects. Firstly, only a shorter period of tree life (30 years) could be analysed using such data, and secondly, the accuracy of assessing a tree ring width from tree circumference measurements is lower than that of laboratory measurements of tree ring widths. On the other hand, tree circumference measurements have been performed always on the same permanently marked trees, the number of which is much larger, regularly for a long time, following the internationally calibrated methodologies (Dobbertin & Neumann 2016). This approach allows to capture diameter variability within the stand, which is an advantage over the subjective selection of a few trees for dendrochronological sampling. Several examples from intensive monitoring plots in Switzerland (described in review by Dobbertin 2005), illustrate how tree-growth reactions to environmental stresses may serve as vitality indicators. Crown transparency and growth can complement

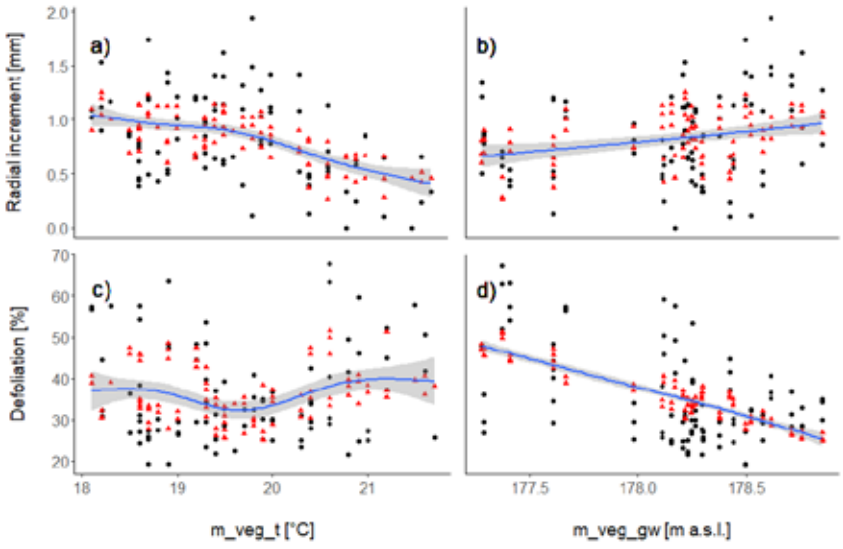


Fig. 8. Relationship of pine radial increment (a, b) or defoliation (c, d) to mean summer temperatures (m_veg_t) (a, c) and mean ground water level in summer (m_veg_gw) (b, d). Black dots represent measured values, red triangles show values predicted with the model [Eq. 1]. The blue line was fitted to predicted values to enable better interpretation, grey areas represent 95% confidence intervals around the lines.

each other. For example, defoliation by insects becomes first visible in crown transparency while stem growth reaction occurs with delay. On the other hand, extreme summer drought as observed in large parts of Europe in 2003 affects stem growth almost immediately, while foliage reduction becomes only visible months later (van der Werf et al. 2007).

The results of our analyses showed a positive reaction of radial increments to summer precipitation. Such a reaction is typical at low and middle elevations in the whole Europe, particularly at dry sites (Spurk 1997; Strumia et al. 1997; Wilczyński & Skrzyszewski 2002; Mácová 2008; Sidor et al. 2018). The analysis also confirmed a negative relationship of radial increment to summer temperatures. A recent study from the Romanian Carpathians showed that younger pine trees can be more sensitive to summer temperatures and summer heatwaves (Sidor et al. 2018). We did not confirm the positive relationship between tree ring widths of Scots pine and mean temperature in February and/or March, which is frequently observed at low and middle elevations in Central Europe (Spurk 1997; Oleksyn et al. 1998; Wilczyński & Skrzyszewski 2002). The paper published by Krakau et al. (2013) showed that Scots pine is well protected against drought, owing to its embedded stomata and a waxy layer on the epidermis, although its sensitivity against increased temperatures is not fully clear yet (Pretzsch et al. 2020). Scots pine can regulate its transpiration at an early stage of drought (Irvine et al. 1998). According to the study of Merlin et al. (2015), Scots pine seems to perform better than other species during spring droughts, e.g. oak showed higher resistance to long-lasting summer drought episodes (Vanhellemont et al. 2019).

Considering the second assessed parameter – vitality or tree crown condition, relevant studies evaluating the impact of climatic factors, or ground water level on tree defoliation are still missing in Europe (see for instance Kath et al. 2014). This is mainly because defoliation cannot be measured accurately and is assessed relatively subjectively. In spite of that, this parameter is frequently used as a basic visual symptom and as a main indicator of health conditions of different tree species (e.g. Rohner et al. 2021). It is a parameter that reflects internal and external impacts of factors affecting a life of an individual (genetics, climate, site, air pollution, etc. Gottardini et al. 2020).

Our study indicated that considering mean summer temperatures the foliage loss is lower in the optimum zone from 19 to 20 °C. However, this relationship is still hypothetical and needs to be proven by further research. Apart from field experiments, we consider also manipulated research activities, i.e. monitoring of pine trees in growth chambers, which allow to set growing conditions including climate (e.g. Basler & Körner 2012).

The obtained results are relevant in the context of expected future development of climatic conditions and linked changes in ground water level, mainly in the southern part of Slovakia currently characterised by the highest temperatures and the lowest precipitation amounts (Bochníček et al. 2015). Under the conditions of Slovakia, intensification of extreme summer heatwaves has already been proven (Lukasová et al. 2021). Similarly, drought indices showed a drying trend typical for the southern regions of Central Europe, besides Slovakia also in the Czech Republic, Hungary, Romania, Moldova and southern Poland (Jaagus et al. 2021). Reich & Oleksyn (2008) assume that in Europe Scots pine will reduce its growth and survival due to climate warming except in the far north, e.g Scandinavia. Therefore, since Scots pine manifested a decline in the south-western part of Slovakia in the last decade, further development of climatic conditions would even worsen this situation. Very probably, ground water level will play an extremely important role in this process. It is generally accepted that climate change may most severely influence ground water table level under the conditions of sandy soils (Lalic et al. 2018), which is the case of the region of our research. The interaction of climatic and hydrological factors with site-specific and geomorphological conditions on windblown sands at Záhorie may have a substantial impact on Scots pine growth and prosperity. The newest study from the Borská Lowland (Šilhán et al. 2021) based on the dendrochronological reconstruction of eolic geomorphological processes showed a substantial reaction of pine trees to sand accumulation events in the years 1990, 1994, 1999, and 2012. After being covered with windblown sand, annual increment of pine trees was reduced by 51.8% on average, and intense anatomic changes and increase of cell size were observed.

When generalising our findings and also those originating from other related works, we may suggest that although Scots pine is considered as a species relatively resistant to weather extremes, its production potential and health conditions (and even its existence) can be endangered by the ongoing climate change. This may be very crucial in the regions with low amount of precipitation and easy-to-dry soils, e.g. sandy ones with a deep ground water level. Besides other measures, groundwater monitoring and implementation of geostatistics analyses for predicting risk of forest decline would help in decision-making processes within forestry management (e.g. Jokanovic et al. 2020).

In fact, our research in the Borská Lowland might be understood as a sort of pilot study bringing just very preliminary results. As for future research activities, it would be interesting to carry out a more extensive analysis of groundwater levels in the study area. Moreover, geostatistical techniques as well as involvement of experts on hydrology and hydrogeology (i.e. using more interdisciplinary approaches) will be necessary.

5. Conclusions

Our research performed on the Scots pines grown under the conditions of the Borská Lowland proved all our initial hypothesis that: H1/ changes in air temperature in growing seasons during the last 30 years had an impact on radial increments of this tree species, H2/ the annual radial increment reacts to fluctuations of ground water level as well as H3/ crown conditions (loss of foliage) depend on the changing regional climate and hydrological regime in the area of interest.

Generalizing these results, we might state that the vitality and production of pine stands in some regions of Central Europe, particularly those with sandy soils, can be substantially reduced with the increasing air temperatures, or the reduction of ground water level due to long-lasting droughts. Hence, further planning and adopting of forestry management measures must be performed with care. As for our studied region, we assume that it is not possible to replace fully Scots pine with alternative species, thus, other options should be sought to keep this tree species in the region under changing climatic conditions. One of possible solutions would be to use the knowledge and methods of forestry genetics by e.g. selecting resistant clones of Scots pine. Another way might be the establishment of mixed forest stands with admixture of xerophilous tree species (including alochtonous ones). However, practical and systematic applications of adaptive management should be preceded by precise research experiments and field testing of methods. Further, we suggest that future research could be focused on the monitoring of health condition in these species, because global climate changes can enable attack of some pathogens such as insects and fungi that may cause forests defoliation and total decline.

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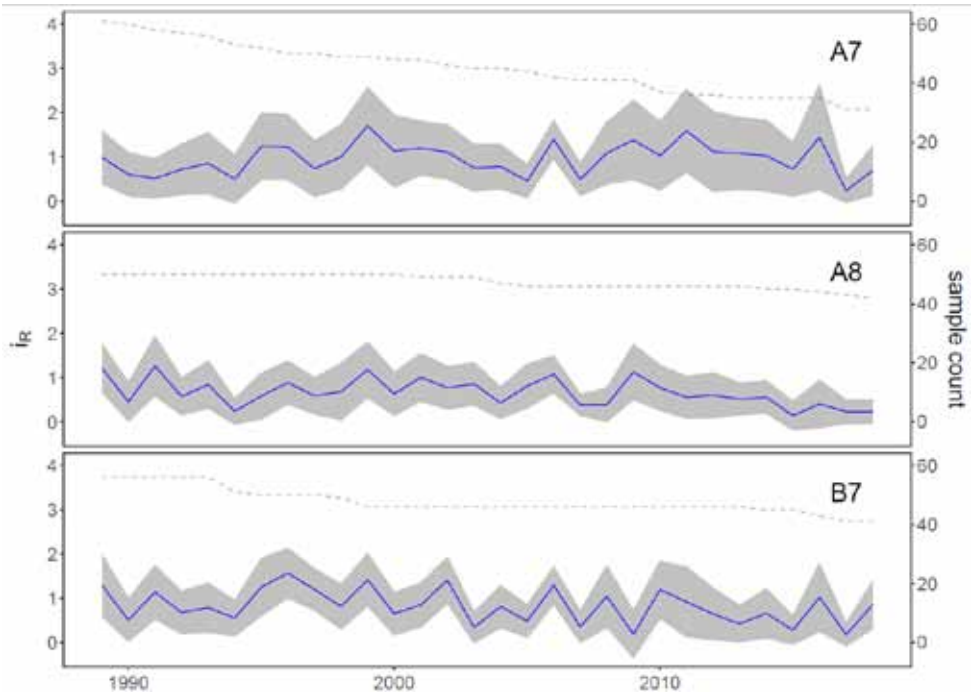
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Attachments

Attachment 1. Within-plot variability in tree radial increments and sample depth. Blue lines represent the mean plot annual radial increment, grey polygons along the mean lines represent mean radial increment ± standard deviation. Dashed lines denote number of measured individuals (sample size).



Attachment 2. Correlation matrix of dependencies of individual variables entering into the models. The values in the cells represent the correlation coefficients. Strikethrough values represent statistically insignificant dependencies considering P>0.05. Abbreviations of all variables are explained in Table 2.

