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THE TREE-RING GROWTH RESPONSES TO CLIMATE IN THE TIMBERLINE ECOTONE OF BABIA GÓRA MOUNTAIN

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Abstract

The growth/climate response of Norway spruce in the timberline ecotone of Babia Góra Mountain was examined. Based on a pool of 708 trees from 10 sites, the influence of age, exposure, and method of computing chronology, was assessed. Gridded data and 12 instrumental series were used to study the spatiotemporal relationship of the tree growth and climate. Temperature mainly controls the growth of the Norway spruce in the timberline ecotone at Babia Góra Mountain. The most important factors were the June and July temperatures (r = 0.57) and of the entire growing season April-September (r = 0.52). The precipitation of late winter (March and correspondingly the January-March season) had a positive influence on the tree growth. The previously reported negative correlation with the summer precipitation was found but it was less important. The mature trees growing on the northern slope showed a response to the summer temperature in a stronger manner than all the other groups. The low-frequency SPL chronologies (detrended using the cubic smoothing splines method) performed better than the RCS (regional curve standardisation) of the high-frequency SPL. A strong correlation was found with Obidowa, the nearest located instrumental data (a distance of 35 km), and the Hala Gąsienicowa, the station located at a similar elevation a.s.l. (1508 m a.s.l.), but also with the Krakow located farther away and at a lower elevation (237 m a.s.l.). The TRW/temperature correlation was temporally most stable in the case of Zakopane.

Key words

Babia Góra • Carpathians • climate • dendrochronology • Norway spruce • tree-rings

Introduction

Climate is recognised as the main factor limiting tree growth and causing the formation of the upper timberline and latitudinal timberline (Troll 1973). Authors examining these natural borderlines have emphasised the dominating influence of temperature (Imhof 1900; Marek 1910; Mikola 1962; Stevens & Fox 1991; Grace 1977; Richardson & Friedland 2009; Paulsen & Körner 2014). The studies concerning the time and rate of wood formation underline the role of temperature in the vegetation period as a key factor in tree ring formation (Rossi et al. 2006, 2007, 2008). The maximum vertical range of the timberline is identified with an isotherm of the vegetation period of 5.5-7.5°C (Walter & Medina 1969; Hoch et al. 2002; Körner 2003; Körner & Paulsen 2004; Körner 2012), the isotherm of the warmest month reaching about 10°C (Daubenmire 1954; Holtmeier 1974; Grace 1977) or the annual isotherm of 2°C (Hess 1965). The timberline defined in such a manner has an idealised character. The real course of the timberline is far more complex (Fig. 1A). The real course is a result of the interaction of various factors, explicitly biological (Holtmeier 1973; Ohsawa & Die 2008), geomorphological (Kotarba & Starkel 1972; Bebi et al. 2009), edaphic (Sokołowski 1928; Bednorz 2000), and anthropogenic (Sitko & Troll 2008). Therefore, in detailed studies, the theoretical upper timberline is often replaced with the line or ecotone of the empirical timberline (Fries 1913; Sokołowski 1928; Guzik 2008). In spite of the complexity of that ecotone environment, numerous studies confirm the leading effect of temperature on tree growth (Schweingruber 1996; Rolland et al. 2000; Carrer & Urbinati 2001, 2004; Wilson & Topham 2004; Frank & Esper 2005; Büntgen et al. 2007). The significance of temperature in the summer period is more evident in the case of the trees growing in the timberline ecotone than those trees located lower down (Makinen et al. 2002; Savva et al. 2006; Czajka 2012). Moreover the growth/temperature relationship depends on geoecological character of the sites and the characteristics of the tree, i.e. species, age (Carrer & Urbinati 2004; Büntgen et al. 2008; Esper & Frank 2009), and condition (Wilson & Topham 2004). The aim of this study was to:

- determine the climate influence on the growth of the Norway spruce, the main tree species found in the timberline ecotone on Babia Góra Mountain,
- determine the influence of the exposure and age of trees on the tree-ring growth responses to climate, and
- evaluate spatiotemporal dynamics of this relationship.

Study site

Babia Góra is the north westernmost mountain of the Carpathians where fully developed vegetative-climatic altitudinal zones can be found. The zones are located at a lower altitude, on average, about 60 m lower, than those in the nearby Tatra Mountains. It is an effect of not only the latitude but also the isolation from other mountains and the small size of the massif itself (Zientarski 1985). The asymmetry is the main feature of the Babia Góra relief: the slopes with southern exposure (40% of the surface area) are characterised by a slight inclination and a simple shape and the slopes with northern exposure (40% of the surface area) are steeper and more varied owing to the presence of chutes, landslides, and debris flows (Czajka et al. 2015). The relief is a simple reflection of the geological structure. Babia Góra is a monocline with a southern inclination of the layers of the Magurska nappe flish.

In spite of such unique features of the environment, little is known about the climate of Babia Góra. It is classified as a typical azonal alpine climate remaining, similarly to the entire Western Carpathians, under the influence of air masses of Atlantic origin (69%) (Obrębska-Starklowa 1963; Obrębska-Starkel 2004). The average annual temperature for the period from 1890 to 1910, the only period when actual measurements were previously taken, amounts to 0.5°C near the peak (1616 m a.s.l.) and 2.5°C at timberline zone (Milata 1936, 1937 after Leszczycki 1938). July is the warmest month with the temperature clearly higher in the subalpine forest (12.7°C) than above the timberline (8.7°C). In the same month the precipitation reaches its maxima of 280 mm in the subalpine forest zone and 220 mm montane forest zone. The annual precipitation in the subalpine forest reaches 1409 mm and up to 1226 mm above the timberline (Leszczycki 1938). The length of the vegetation period is dependent on the altitude above sea level and near the timberline lasts 5 months (from the middle of May to the beginning of October). The forests on Babia

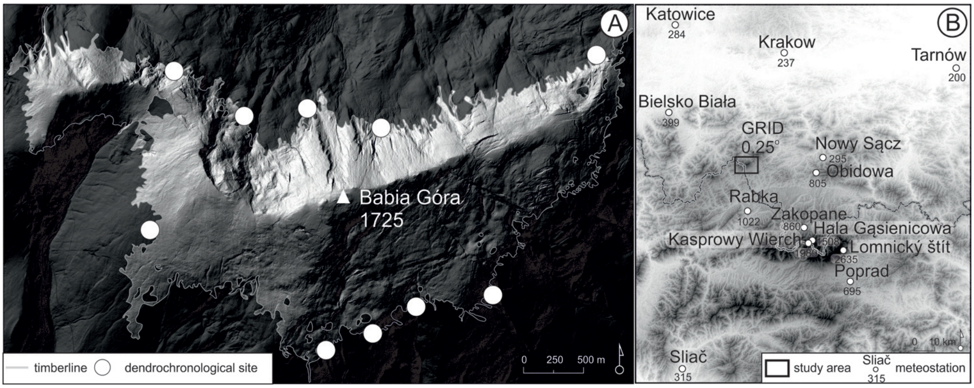

Figure 1. The study site: A – the Babia Góra Mountain, B – the location of the study site and the meteostations in the region

Góra are typical remains of the Carpathian primeval forest predominated in the subalpine zone by Norway spruce (*Picea abies* (L.) Karst.). At the lower altitudes this forest has been considerably changed due to the long period of human influence (Łajczak & Lamorski 2015). In the timberline ecotone, the forest has the most natural character (Bednarz et al. 2009). Timber logging has probably never reached those elevations. The intense pasturing in the 18th and 19th century influenced the upper part of timberline ecotone (Czajka et al. 2015). In the 20th century, the part of Babia Góra became protected (in 1926 as a nature reserve in the Slovakian part, in 1928 in the Southern Polish part, and in 1954 as a national park in the Polish part). For the last few decades mountain hiking has been the main human activity there.

Materials and methods

The study of the climate influence on Norway spruce growth in the timberline ecotone is based on the analysis of samples taken from 708 trees from 10 sites: 5 located on the northern slope and 5 on the southern slope. The samples were collected and prepared for the analysis with the application of standard dendrochronological techniques (Frits 1976; Schweingruber 1996). The width of the tree rings (TRW) was measured with the CooRecorder programme, Cybis Elektronik & Data AB. The measurements were checked by employing the statistics (Cofecha programme) (Grissino-Mayer 2001) and visual cross-dating (CDendro programme, Cybis Elektronik & Data AB) (Larsson 2003a,b). The whole set of time series consisted of 708 trees, covers the period from 1704 to 2012. The time series of the TRW were split and used in four chronologies depending on:

- exposure (north and south),
- age structure of the population (young and mature trees).

The criterion of age division was the median of the series length (MedSL), reaching 131 years in the case of the northern slope and 82 years in the case of the southern slope (Tab. 1). Although this method is not related to any classical system of age-structure defining, similarly relative criteria can be found in other dendroclimatological studies (Carrer & Urbinati 2004; Esper et al. 2008; Büntgen et al. 2012). For all sets of data residual and RCS (regional curve standardisation) (Esper et al. 2003) chronologies were computed employing the Arstan software (Cook & Holmes 1986). The cubic smoothing splines (SPL) with a 50% frequency-response cutoff at *S* years, were chosen as the detrending method (Cook & Peters 1981). To test the strength of the low and high frequency climate signal, the *S* value was calculated as 2xMedSL (low-pass) and 0.5xMedSL (high-pass). The lack

Exposure	Age	Number of samples	Median (MedSL)	S = 2xMedSL	S = 0.5xMedSL	Chronology length	Rbar	EPS
North slope	Mature (>131 years)	148	189	378	95	1704-2012	0.38	0.87
	Young (<131 years)	151	107	214	54	1882-2012	0.40-0.42	0.98-0.99
South slope	Mature (>82 years)	205	122	244	61	1819-2012	0.38-0.40	0.98
	Young (<82 years)	206	66	132	33	1931-2012	0.34-0.42	0.99

Table 1. The characteristics of the developed Norway spruce TRW chronologies with combinations including exposure and age factors. The descriptive statistics including the median of the series length (MedSL), the parameters of the SPL detrending (S parameter), the length of the chronologies after truncation < 5 series, the inter-series correlation (Rbar), and the expressed population signal (EPS)

of a sufficiently long onsite instrumental series led to the employment of the 0.25° E-OBS 10.0 (Haylock et al. 2008) gridded data: monthly mean temperature and monthly sum of precipitation. The available instrumental data from the proximity of the study site were also used to check the spatial autocorrelation (Kaczka & Büntgen 2006) (Fig. 1B).

Results and discussion

The 12 calculated chronologies displayed a clear common signal (Tab. 1), the Expressed Population Signal (EPS) values were above the applied threshold of 0.85 (Wigley et al. 1984). The inter-series correlation (Rbar) ranged from 0.34 to 0.42. The course of the common period of the chronologies (1931-2012) is similar (Fig. 2a). According to the results of the clustering (Ward's hierarchical cluster analysis), two chronologies from the northern slope revealed the highest similarity (Fig. 2b). This cluster was joined by the chronology representing the mature trees (>82 years) from the southern slope and in the last step joined by the young trees with the same exposition. Except for the chronology composed of the old trees (>131 years) from the northern slope, the RCS and low-pass SPL always showed the strongest interconnection.

The spruce growth was significantly influenced by: the spring (April) and summer (June, July), the whole growing period (April-September), and also by the annual temperature (Fig. 3). The correlation analysis of all the 12 TRW chronologies to temperature revealed a rather consistent response to the current-year summer temperatures, especially in July (average $r = 0.42$) and the June-July season (average $r = 0.48$). The low-frequency chronologies of the mature ($r = 0.57$) and young trees ($r = 0.57$) from the northern slope showed the strongest climatic signal (JJ temperature). All low-frequency chronologies independently of the age and location of the trees, demonstrated a similar behaviour. Correspondingly, the growth/climate response for the JJ temperature of all low-frequency chronologies was most coherent (average $r = 0.53$, $SD = 0.07$). The small differences between the performances of the 12 analysed chronologies justify their aggregation into three groups representing:

- all the 10 sites,
- the northern slope,
- the southern slope (Fig. 4).

The correlations reached lower values but they displayed a similar pattern to that of the relationship to the summer temperature (Fig. 4). The temperature of the high summer period remains the main factor controlling tree growth. The SPL chronology representing the entire pool of the TRW series, revealed the

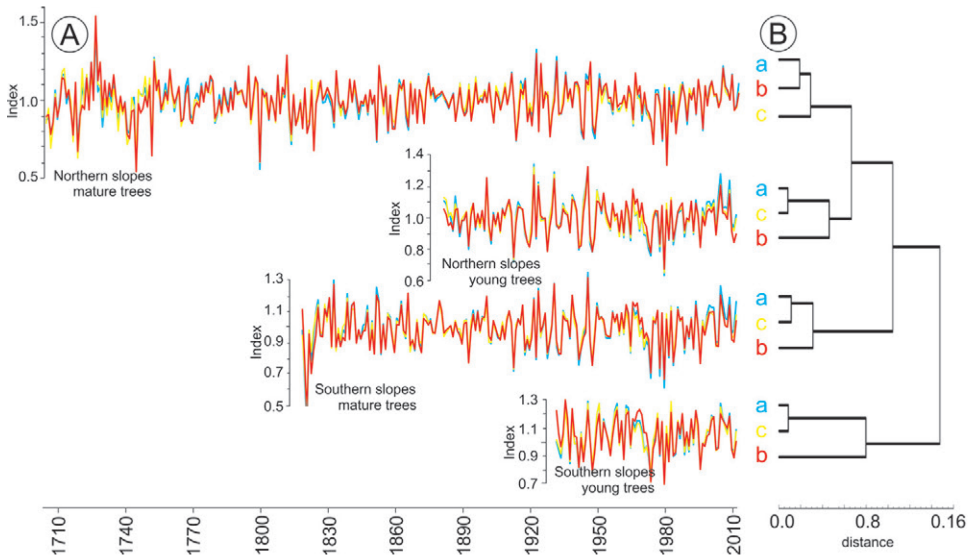

Figure 2. (A) The twelve chronologies developed as concerns the site exposure and the age of the trees. (B) Cluster analysis (Ward's hierarchical cluster analysis, distance measure: 1- Pearson r): a – the high-frequency SPL detrended (with 0.5xMedSL-spline, here ranging from 33 to 95) (blue colour), b – the low-frequency SPL detrended (with 2xMedSL-spline, here ranging from 132 to 378) (red colour), c – the Regional Curve Standardisation (yellow colour)

strongest response (r = 0.43 for June-July) but a pointedly lower response than the 7 chronologies calculated taking into account both the age and exposition differentiation (Fig. 3). A strong response of the Norway spruce to summer temperatures (June-July) is typical for the timberline ecotone sites of the region (Szychowska-Krąpiec 1998; Bednarz et al. 1999; Savva et al. 2006; Kaczka & Büntgen 2006; Büntgen et al. 2007; Czajka & Kaczka 2014) and generally for a cold environment (Briffa et al. 2002). A high correlation between the TRW and the growing season temperature (April-September) is more distinctive for Babia Góra Mt. and similar to the result deriver employing the wood density related

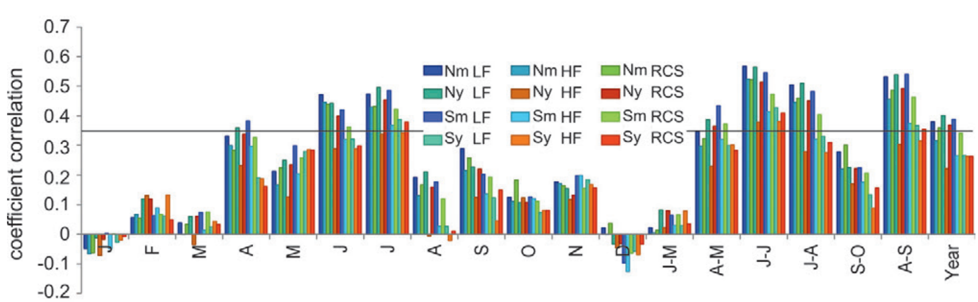

Figure 3. The response of the twelve exposure- and age-dependent chronologies to the monthly and seasonal temperatures obtained from the 0.25 degree E-OBS 10.0 grid (the 1950-2012 period). The abbreviation represents the exposure (N – northern, S – southern), age class (m – mature, y – young) and the type of the chronology (LF – low frequency SPL, HF – high frequency SPL, RCS – regional curve standardisation). The black horizontal line represents the statistical significance at the 99% level

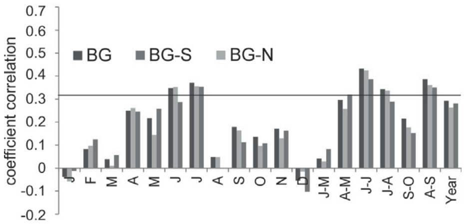

Figure 4. The response of the regional (BG) the northern (BG-N) and the southern (BG-S) exposure SPL chronologies to the monthly and seasonal temperature obtained from the 0.25 degree E-OBS 10.0 grid (the 1950-2012 period). The black horizontal line represents the statistical significance at the 99% level

proxies such as Maximum Wood Density (Büntgen et al. 2007) or Blue Reflectance (Kaczka & Czajka 2014).

The influence of precipitation on the spruce growth was positive in winter (January and March) and negative in summer (June) (Fig. 5). The low-frequency chronology representing the young trees on the northern slope shows the strongest response to the winter precipitation consisting of snowfall (r = 0.53). This is a frequently reported result linking the winter snowfall with the spring importance of snow as a frost protection and water source (Vaganov et al. 1999). The negative effect of the June precipitation is less pronounced than that described in earlier works from the same region (Bednarz 1996). As with the results of the temperature/TRW correlation, the response of all the three chronologies to precipitation reached lower values (Fig. 6). The trees from the northern slope showed the strongest correlation to the winter precipitation (r = 0.45). These findings suggest that the protection effect of the snow cover is more important there. The amassed SPL chronologies demonstrated only a positive response to the winter precipitation.

Independent of the age and exposure, preselection of all the twelve chronologies were dominated by a positive response to the June-July temperatures. Ten of the chronologies also showed a similar correlation to the

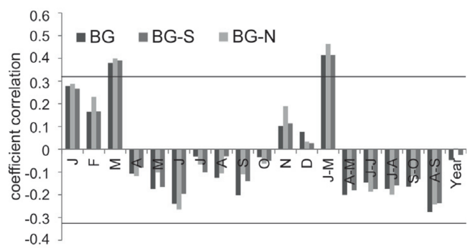

Figure 6. The response of the regional (BG) the northern (BG-N) and the southern (BG-S) exposure SPL chronologies to the monthly and seasonal precipitation obtained from the 0.25 degree E-OBS 10.0 grid (the 1950-2012 period). The black horizontal line represents the statistical significance at the 99% level

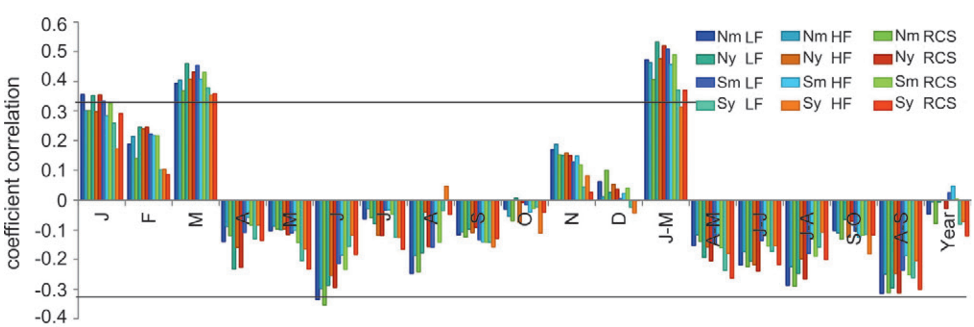

Figure 5. The response of the twelve exposure- and age-dependent chronologies to the monthly and seasonal precipitation obtained from the 0.25 degree E-OBS 10.0 grid (the 1950-2012 period). The abbreviation represents the exposure (N – northern, S – southern), age class (m – mature, y – young) and kind of the chronology (LF – low frequency SPL, HF – high frequency SPL, RCS – regional curve standardisation). The black horizontal line represents the statistical significance at the 99% level

April-September period. The former period was related to the highest growth rate (Rossi et al. 2006, 2007, 2008), the latter represents the whole vegetation period of the subalpine zone at Babia Góra (Obrębska-Starkel 2004). The similarity in the strength of these relations (average r for J-J = 0.48 and for A-S = 0.44) as well as their independence from the age and exposure criteria could result from the homogeneous or oppositely complex climate sensitivity among the 708 trees investigated. For these reasons, the proportion of the trees reacting to the temperatures of different seasons was tested. The whole pool of 708 trees was examined to reveal the correlation between the individual trees against the AS and JJ temperature. Based on the results of that selection ($r > 0.33$, $p < 0.01$, calculated for the 1951-2009 period), two SPL chronologies were computed:

- the *AS chronology* for the trees affected mostly by the April-September temperature (112 trees),
- the *JJ chronology* consisting only of the trees sensitive to the June-July temperature (162 trees).

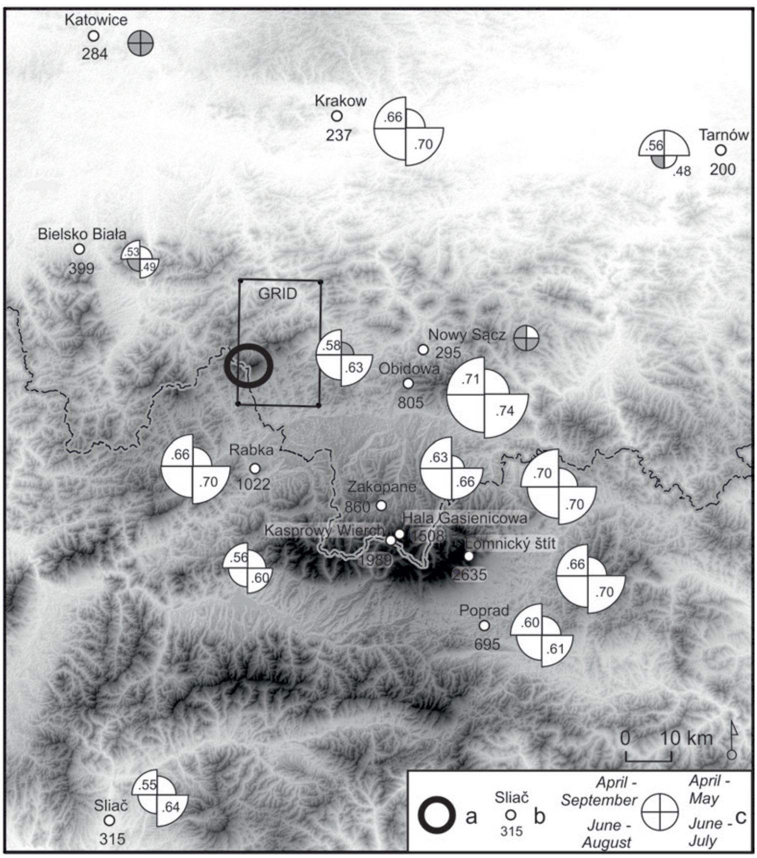

Figure 7. Spatial correlations of the SPL detrended 708 chronology calculated against four different temperature series (the mean of April-September period, mean of April-May period, mean of June-August period, and mean of June-July period), obtained from 13 instrumental measurements and gridded data (0.25 degree E-OBS 10.0) for the 1951-2012 period

Legend: a – the study site, b – the location and elevation (m a.s.l.) of the climatic stations, c – the pie chart representing the TRW and temperature correlation. The grey colour represents the result's insignificance at the 99% level

The age and provenance of the trees included in the JJ chronology and AS chronology were varied. Those two chronologies were joined by the *708 chronology* (the SPL chronology consisting of all the 708 trees) and correlated with the gridded data and 13 instrumental measurements from the region. The *708 chronology* correlates mostly with the JJ temperature of the nearest located climatic stations (Obidowa r = 0.74, Rabka r = 0.70) and the stations near or above the timberline (Hala Gąsienicowa r = 0.70, Lomnický štít r = 0.70). The relatively remote and low located Krakow also revealed a strong correlation with the Babia Góra massif (r = 0.70) (Fig. 7). The correlation between the *AS chronology* and the 13 instrumental measurements showed a similar spatial pattern (Fig. 8). The preselection did not strengthened the climatic signal in a substantial way. The nearest located instrumental data displayed a higher correlation with the JJ than with the AS temperature. The results obtained for the *JJ chronology* showed a noticeable improvement in the strength of the

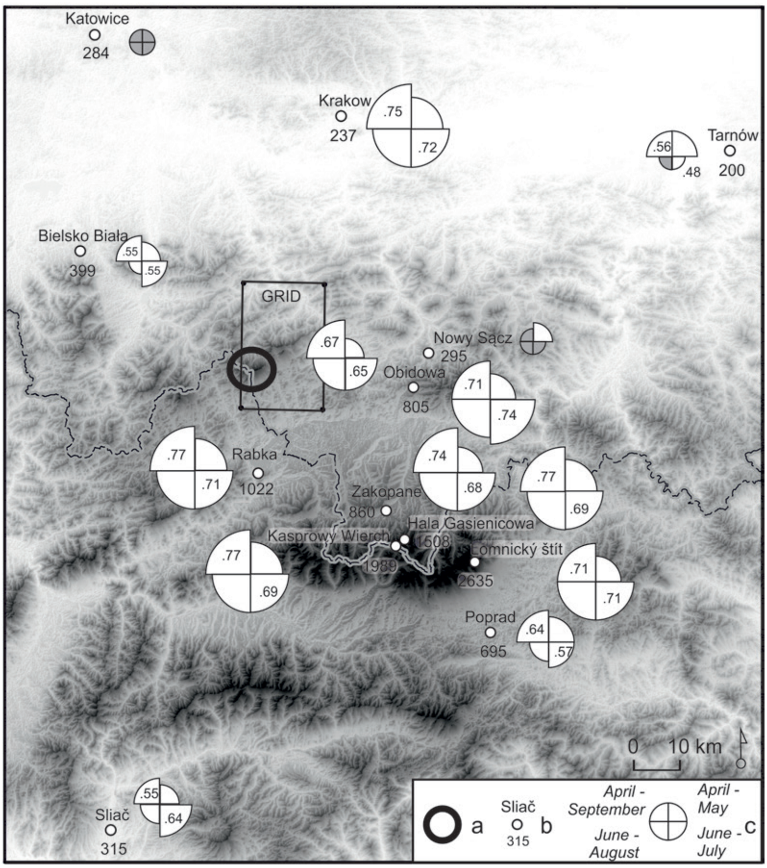

Figure 8. Spatial correlations for the SPL detrended AS chronology calculated against four different temperature series (the mean of April-September period, mean of April-May period, mean of June-August period, and mean of June-July period), obtained from 13 instrumental measurements and gridded data (0.25 degree E-OBS 10.0) for the 1951-2012 period

Legend: a – the study site, b – the location and elevation (m a.s.l.) of the climatic stations, c – the pie chart representing the TRW and temperature correlation. The grey colour represents the result insignificant at the 99% level climatic signal. The trees most sensitive to the temperature of the warmest period of summer are less susceptible to other seasons, e.g spring (April-May) or the whole summer (June-August) (Fig. 9). All three chronologies revealed a similar pattern of the response to the two additional periods: April-May and June-August. The correlations to the instrumental data coming from the direct neighbourhood were always higher than the correlations to the gridded data. Among the 13 stations used in the study, Krakow and Zakopane represented the two longest instrumental time series, and the correlations for the climatic stations were always >0.5. Using the two time series, the temporal variability in the observed growth–climate response patterns was assessed. A fifteen-year correlation between the *JJ*, *AS chronologies* and temperatures for the 1898-2007 period were computed (Fig. 10). Although Krakow showed a higher correlation with both types of chronologies, this relation revealed lower temporal stability. It has only been since the 1950s, that the correlation for

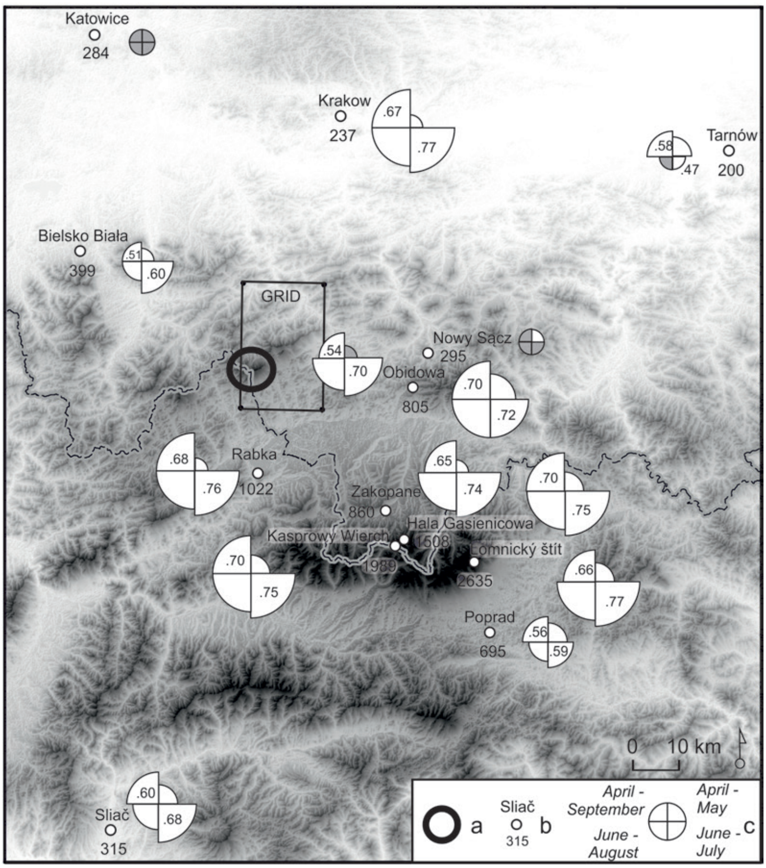

Figure 9. Spatial correlations for the SPL detrended JJ chronology calculated against four different temperature series (the mean of April-September period, mean of April-May period, mean of June-August period, and mean of June-July period), obtained from 13 instrumental measurements and gridded data (0.25 degree E-OBS 10.0) for the 1951-2012 period

Legend: a – the study site, b – the location and elevation (m a.s.l.) of the climatic station, c – the pie chart representing the TRW and temperature correlation. The grey colour represents the result insignificant at the 99% level both AS and JJ temperature has been significant ($p < 0.01$). The tree-ring width response to the AS temperature declined at the turn of the 1960s and 1970s as well as during the last few decades. The latter period is characterised by a decreased sensitivity of the trees to both summer and the growing-season temperature. The relation between the TRW and the temperature in Zakopane exhibited sinusoid-like temporal changes in the first part of the studied period. The correlation for both AS and JJ temperature became significant around the same time as in the case of Krakow, and showed enhanced temporal stability for most of the period. As regards Zakopane, a considerable decline of the correlation was also observed at the end of the 20th century. These findings correspond with the descriptions of the divergence problem (Briffa et al. 1998; D'Arrigo et al. 2008; Büntgen et al. 2008; Melvin & Briffa 2008; Esper et al. 2010; Schneider et al. 2014).

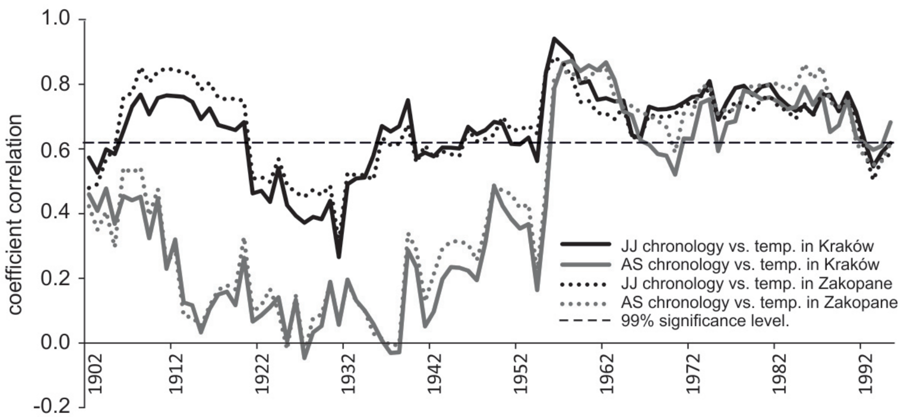

Figure 10. The 15-year running correlation of the SPL detrended 708 chronology calculated against the AS and JJ temperature from Krakow and Zakopane

Conclusion

Temperature controls the growth of the Norway spruce in the timberline ecotone at Babia Góra Mountain. During our study, we found that the most important factors were the temperatures of June and July ($r = 0.57$) and of the entire growing season April-September ($r = 0.52$).

The precipitation of late winter (March and correspondingly the January-March season) had a positive influence on the tree growth. The previously reported negative correlation with the summer precipitation was still noted but it is not so significant.

The pattern of the growth/climate response was homogeneous and factors such as exposition or age did not appear to change the character of this relationship. Certain differences were noticeable in the value of the correlations. The old trees growing on the northern slope responded more strongly to the summer temperature than all of the other groups.

The various methods of computing the chronologies were important for extracting the climatic signal. The low-frequency SPL chronologies perform better than the RSC of the high-frequency SPL.

The established Norway spruce chronologies correlated well with the temperature records of the climatic stations of the region. Strong correlations with Obidowa, the nearest located instrumental data (distance of 35 km), and Hala Gąsienicowa, the station located at a similar elevation a.s.l. (1508 m a.s.l.), but also for Krakow located farther and lower (237 m a.s.l.), were found.

The analyses of the two longest instrumental series from the region, Krakow and Zakopane, revealed a temporal variability of the climate/growth relationship. The response was more temporally stable in the case of Zakopane than Krakow.

The over 310-year-long, well-replicated chronology and the clear summer temperature signal suggest that the examined trees can be applied as a good proxy for climate reconstruction. Considering the length of the series, the strength of the climate/growth responses as well as the temporal stability of these relationships, the instrumental data from Zakopane and Hala Gąsienicowa seem to be the best for that task.

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Editors' note:

Unless otherwise stated, the sources of tables and figures are the authors' on the basis of their own research.

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