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Response of Norway spruce (Picea abies (L.) Karst) to warming climate: a case study from Bulgaria, Southeastern Europe

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Abstract. Climate change, with its increasing frequency and intensity of extreme weather events, poses challenges for tree growth. We investigated the response of Norway spruce at its southernmost distribution point in the Western Rhodope Mountains, an area expected to experience significant changes in temperature and precipitation. Using a dendroecological approach and resilience indices, we analyzed the impact of extreme summer events on annual tree-ring widths. Our data indicate a surprising degree of tolerance by Norway spruce to drier and warmer summers in "Beglika" Reserve. However, temperatures have a cumulative negative effect, with September temperatures exerting the strongest influence. Precipitation, on the other hand, has a consistently positive impact on radial growth regardless of the month. Recovery from hot summers takes 1-2 years under normal conditions, but extends to 3-4 years after very hot and dry summers. The response of Norway spruce to climate change will vary across its range, depending strongly on local microclimates. Our findings provide valuable insights for sustainable management of Norway spruce under changing environmental conditions.

Key words: climate change, tree resilience, tree resistance, dendroecology, forest management, growth dynamics, Rhodope Mountains.

Introduction

Norway spruce (*Picea abies* (L.) Karst) is one of the most important tree species of the Eurasian forest ecosystems (Jansen et al., 2017). The species is shade-tolerant and prefers rich soils, cool and moist climates (Tjoelker et al., 2007). Its wood has valuable qualities and the ability to be grown in monocultures makes it a widely grown and preferred species (Johann et al., 2004) in central and northern Europe. Due to these reasons, there are between 5,7 to 7,3 million ha of natural and artificially planted pure spruce forests in Europe (von Teuffel et al., 2004).

The relatively shallow root system makes the species susceptible to drought (Schlyter et al., 2006; Hanewinkel et al., 2013) and increases the risk of damages during strong winds (Pretzsch et al., 2013). In addition, Norway spruce is often subject to insect outbreaks by spruce bark beetle (*Ips typographus* L.) (Seidl et al., 2011). These mass attacks are often the result after wind throws or severe summer droughts (Stadelmann et al., 2014; Seidl et al., 2016).

Bulgaria does not make an exception with numerous wind throws in the past. One recent example was the wind throw in „Bistrishko Branishte" Reserve in Vitosha mountain in 2001, when strong winds knocked down 60 ha of spruce forests and three years later a severe spruce bark beetle outbreak started and in the following years covered additionally more than 200 ha of mature forests (Panayotov et al., 2015).

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The Earth's climate has undergone an unprecedented change in human history over the past few decades. The average global temperature has risen by 0.85°C over the period 1880-2012 (IPCC, 2022), and the decades from 1980 to the present have been declared the warmest in the last 1400 years (NOAA, 2023). In 2021, the Intergovernmental Panel on Climate Change (IPCC) sent out a warning that our planet was on track to pass the critical warming threshold of 1.5°C by 2030, a decade earlier than previous projections, and 2022 was officially declared the sixth warmest year since the beginning of weather observations (NOAA, 2023). The average summer temperature (June-July-August) of 2023 in the Northern Hemisphere reached 16.77°C, which is 0.66°C above the climate norm based on the period 1991-2020 (Copernicus Climate Change Service). According to the National Institute of Hydrology and Meteorology at the Bulgarian Academy of Sciences, the deviation from the long-term average temperatures in October 2023 in some places in Bulgaria has reached more than 5-6°C. High temperatures in the autumn period of 2023 were combined with drought. According to Forzieri et al. (2021) Europe's forests show increasing vulnerability to climate change: 40% of forest biomass is threatened by wind throws, 34% by fires and 26% by insect outbreaks. The situation is particularly worrying for Southern European forests, where climate change-induced "vulnerability hotspots" could create serious storm risks in the Alps, Balkans and Carpathians, as well as increasing risk of large-scale fires (Eberle and Roa, 2022).

The concept of resilience in ecology usually refers to the capacity of an ecosystem (in this case – a forest) to absorb and recover after disturbances whilst maintaining its basic functions. Although there may not be a specific index called the 'tree resilience index', researchers use a variety of indicators and approaches to assess the resilience of trees or forest ecosystems. Despite decades of research (Allen et al., 2019; Ingrisch and Bahn, 2018), quantifying the resilience of forest ecosystems is still challenging due to the need for long-term observations. Dendrochronology gives the opportunity for providing such data (Panayotov et al., 2020). Annual tree-rings can give information on the status, respectively growth before, during and after an event. For this reason, in recent years, the concept of Lloret et al. (2011) of determining resilience based on three indexes, has been widely applied in dendroecology, which on their own are based on older studies (Abrams et al., 1998; Martín-Benito et al., 2008; Kohler et al., 2010). The original Lloret indices are as follows:

- ***resistance*** **(R)** – it reflects the decline in productivity during a critical event; it is calculated as the ratio between the increment at the time of the event and the average increment over the previous reference period. An index lower than 1 indicates a decline in radial growth;
- ***recovery*** **(Rec)** – it reflects the ability to recover from an event. It is calculated as the ratio between post-event growth and growth at the time of the event. Values above 1 are indicative of an increase in increment and therefore faster recovery;
- ***resilience*** **(Rs)** – reflects the capacity of the tree to restore growth levels after an adverse event. It is calculated as the ratio between growth after and before the abnormal event. Values below 1 reflect an inability to recover or a very slow recovery rate.

Over the years, this three-level concept has been further developed by adding new indexes, allowing the Lloret resilience indexes to now be widely used for the purpose of quantifying the response of different tree species to different types of disturbances (Schwarz et al., 2020). Additional indexes have been introduced such as "*recovery period*" (growth recovery time), which refers to the time needed for growth to reach pre-disturbance (event) levels, and "*total growth reduction*", reflecting the cumulative reduction in growth in the year of the disturbance as well as in all years associated with the recovery period (Thurm et al, 2016). Schwarz et al. (2020) also introduced the index "*average recovery rate*" (the average recovery rate during the recovery period) and "*average growth reduction*" (the total growth reduction in relation to the length of the recovery period). In addition to the three most used indexes, Lloret et al. (2011) also introduced "*relative resilience*", which reflects growth during the event.

Climate change requires adaptive measures to ensure the long-term sustainability of the services provided to society by forest ecosystems (Lindner et al., 2014). In this context, it is important to study the response of Norway spruce after disturbances, as a major species not only for

Europe (San-Miguel-Ayanz et al., 2016), but also for Bulgaria (Panayotov et al., 2016). In the Rhodope Mountains, where Norway spruce is the dominant species in the range of 1300-1900 m a.s.l., no studies have been conducted so far to establish the species' response to future climate change. Therefore, the aim of this paper is to track the response of Norway spruce after recurring extreme events (hot and dry waves) using different resilience indices.

Materials and methods

This study was conducted at Norway spruce forests located on the territory of "Beglika" Reserve, Bulgaria (Fig. 1).

The Reserve is situated in the Dospat-Batak region, Western Rhodope mountains. The total area of the Reserve is 1463.9 ha, 80% of which are covered by pure spruce forests and 20% - by Scots pine (*Pinus sylvestris* L.) stands in the altitude range from 1650 to 2050 m.

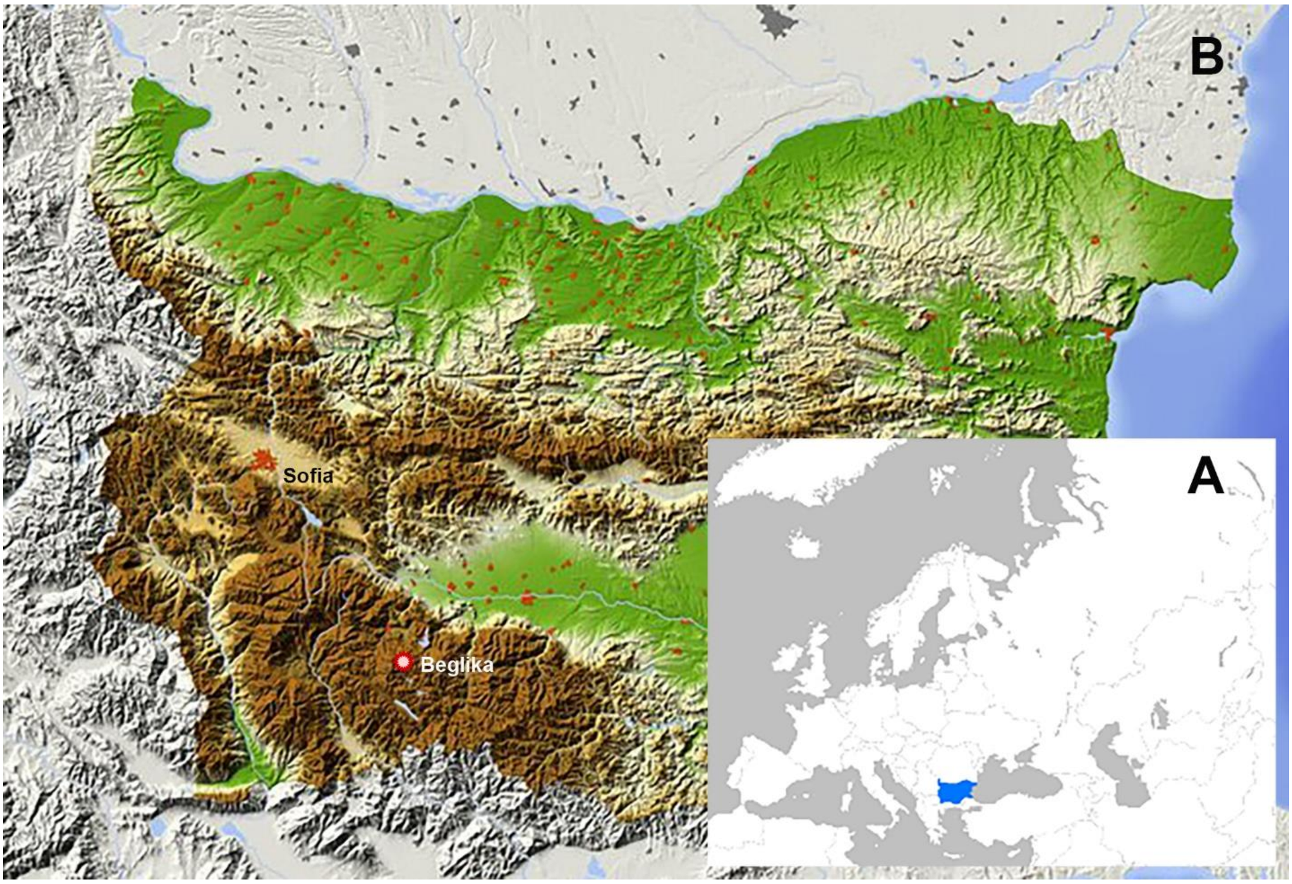

Fig. 1. Location of Bulgaria on the map of Europe (A) and study area location - "Beglika" Reserve is marked with a red dot (B).

The climate in the studied area is slightly warmer, but similar to other spruce-dominated forests in Eastern and Central Europe (Zielonka et al., 2010; Svoboda et al., 2012, 2013; Trotsiuk et al., 2014). The average annual temperature is 8.4°C and the annual precipitation is about 950 mm with no pronounced drought period in the summer months (Fig. 2). These mean values are based on extrapolated data from climate stations located up to 20 km from our study area. For this reason, we installed our own temperature data loggers. Our data shows annual average temperature of 3.0°C at 1700 m a.s.l. and 1.0°C at 2000 m a.s.l. within the studied forest (Panayotov et al., 2015).

Soils are Umbric and Eutric Cambisols, usually moist except of during very dry summer periods.

Five transects with a length of 550 to 850 m and a width of 40 m were laid out in a previously prepared grid in ArcGIS (Esri Inc) (for details, see Panayotov et al., 2015).

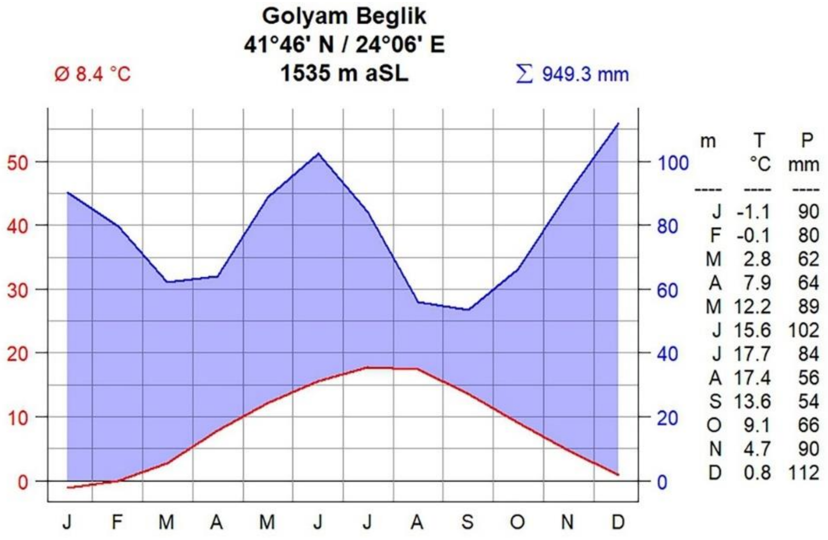

Fig. 2. Walter and Lieth (1967) climate chart for the study area.

A total of 100 tree-ring cores were collected in the transects with an increment borer at breast height (1.3 m). The tree-ring cores were air-dried, mounted on wooden holders and sanded with progressively increasing grit of sandpaper (from 80 to 600).

The prepared cores were scanned with Epson Expression 11 000 XL scanner at resolution of 1200 dpi and then the tree-ring widths were measured on the scanned images with CooRecorder 9.3 software (Cybis Elektronik and Data AB, Sweden). Cross-dating was performed with CDendro 9.3 software (Cybis Elektronik and Data AB) and standardized with a 67%n cubic smoothing spline for each tree-ring series length (Cook and Peters, 1981) using ARSTAN software (Cook et al., 2017). EPS value of 0.85 was used as a threshold for the reliability of our chronology (Wigley et al., 1984). Tree-ring width chronology covers the period from 1736 to 2012 (Fig. 3).

Statistical and descriptive parameters of the chronology are presented in Table 1.

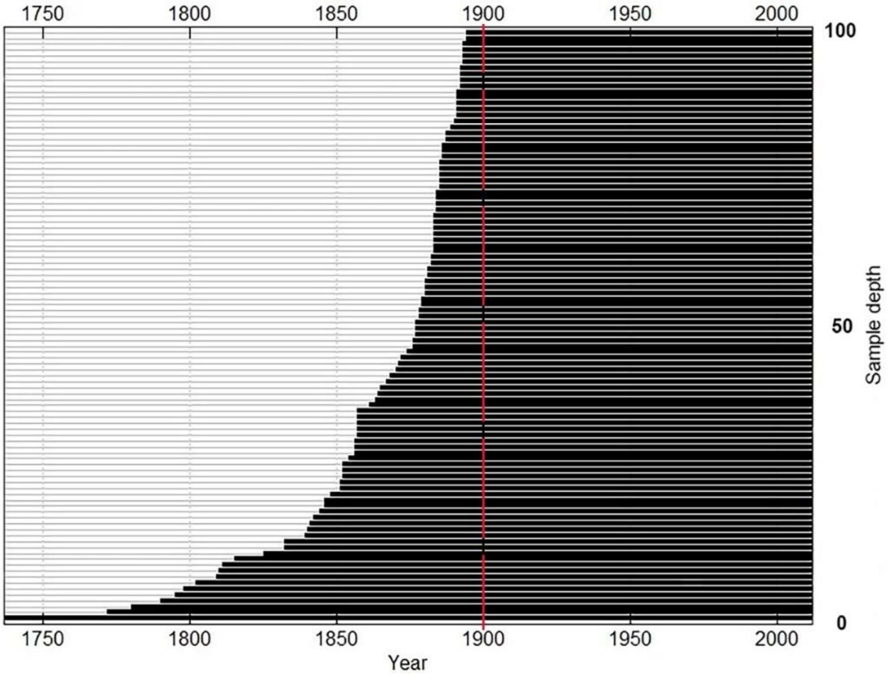

Fig. 3. Sample depth for Beglika site. Time coverage A.D. 1736-2012. We limited our analysis to the period with an EPS of at least 0.85, which was reached in 1900 (marked with a red line).

Table 1. Statistical parameters of the raw tree-ring width chronology from Beglika site.

	year	mean	stdev	sens	ac (1)
arithmetic mean	148	1.408	0.736	0.212	0.840
standard deviation	31	0.471	0.285	0.041	0.085
median (50th quantile)	135	1.390	0.690	0.204	0.860
interquartile range	33	0.528	0.308	0.047	0.110
minimum value	118	0.432	0.257	0.140	0.585
lower hinge (25th quantile)	127	1.131	0.542	0.183	0.793
upper hinge (75th quantile)	160	1.659	0.851	0.230	0.903
maximum value	276	2.562	1.572	0.328	0.964

Legend: stdev – Standard deviation; sens – Sensitivity; ac (1) – 1st order Autocorrelation.

We used the variation in annual tree-ring widths in years that could be classified as climatically extreme, as a model of the response of the trees to unusual events. Data from the meteorological station at Golyam Beglik Dam and our own local data were used to define them. The mean values for the full period with available data from the respective meteorological station were calculated, as well as the deviations with more than 1.5 times the value of the standard deviation of the mean values (1.5*STD) (Fig. 4). Values above or below this interval were considered abnormal. Years in which there was a coincidence of extreme situations of different kind (e.g. a cold winter and an unusual summer in the same year) were ignored as it is possible that two different causes for an event could be mixed. Years with short-term extreme events and a simultaneous other kind of extreme event were also ignored. For example, in 1944, 1952, and 1962 there were very strong short cold spells in May or early June that caused frost rings (Panayotov et al., 2020) and we avoided these years even though later there could be summer drought.

Our analysis was concentrated on hot summer periods and dry summer periods. Climate models show that exactly these types of anomalies are expected to increase in frequency and severity in the region and therefore potentially may have significant effect on woody plants. In addition to the data gathered by meteorological stations, data from the Royal Netherlands Meteorological Institute (KNMI) datasets were also used. For the purposes of our study we have used the variation of the drought indices scPDSI and SPEI. These indices have the advantage of accounting for the cumulative effects of high temperatures and low precipitation, which better reflect prolonged droughts. In turn, they have more significant effects on woody plants than short-term droughts. The E-OBS dataset, widely used for observations and validation of numerical models across Europe (Cornes et al., 2018), was used to define years with unusual events using the scPDSI and SPEI indices.

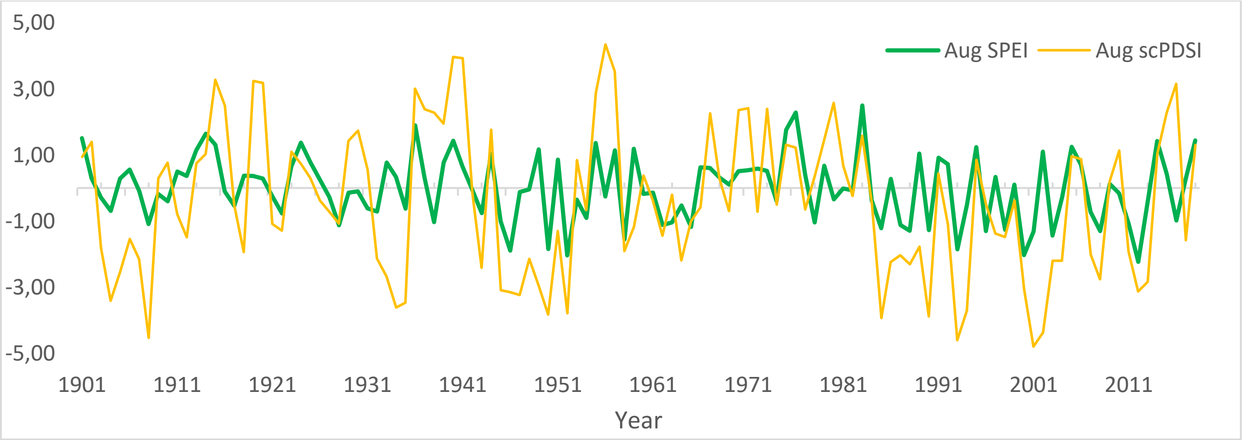

Fig. 4. Mean values of scPDSI (Barichivich et al., 2021) and SPEI (Beguería et al., 2014) for August extracted from the KNMI Climate Explorer dataset for the mountainous region of Southern Bulgaria.

Two types of key years with extreme weather events were selected:

- **hot summers without noticeable drought** - hot summers are increasing, especially in mountainous regions. Meteorological data show that in the period from 1930 to 2012 (82 years), 14 summers were recorded in which the average temperature for the June-August period exceeded the long-term average (1930-2012) by + 1.5 times the standard deviation value (1932, 1934, 1936, 1937, 1947, 1950, 1994, 1998, 2001, 2003, 2007, 2009, 2010, 2012). Some years are both unusually hot and dry and therefore are not analyzed for a response to these types of unusual events.

The years 2003 and 2007 were selected as extreme for the analysis. In these years there was no unusual drought, but at the same time temperatures exceeded the defined threshold by deviating from the long-term average by more than 1.5 times the standard deviation value.

- **dry and hot summers** - this type of event could potentially have the most significant impact on woody plants as usually there are high temperatures and lack of rainfall in the meanwhile. This causes high evapotranspiration and drying out of the soil moisture reserves. The years 1946, 1993 and 2000 were chosen for our analysis.

In 1946, there were normal rainfalls in the mountains in June, as opposed to a significant drought in the period July-August. Temperatures for July-August were higher than usual. August was particularly dry. The SPEI value for June-August was -1.66, which was the second lowest value for the period 1901-2018. The value for August was -1.89. The scPDSI value was -3.14 (Fig. 4).

In 1993, there was a general drought from June to August. Distinctive for this year was a more severe drought in early summer, but a less drastically dry July. The temperature was higher than usual but did not rank among the most extreme values. August was dry, with SPEI value for the mountains of -1.85. The scPDSI for August was -4.60.

In 2000, there was relatively normal rainfall in June, but severe drought in July and August. Temperatures were higher than normal but did not exceed the defined threshold of average +1.5*STD. The SPEI index for June-August had a value of -2.08. The value for July was -2.28, which is record low. The scPDSI index for August was -3.07.

The values of the three classic indices of Lloret et al. (2011) and the subsequently developed ones "*total growth reduction*" and "*recovery period*" (growth recovery time) (Thurm et al., 2016) were calculated using the pointRes 2.0 library (van der Maaten-Theunissen et al., 2021) of the R software program (R Core Team, 2019).

It is to be noted that even though using all indices, the impact of a given key year may be underestimated if the reference period prior to the event was also low in growth (deviations for the "normal" growth). The integrated algorithm of the pointRes 2.0 library a 5-year pre- and post-event period was used and a maximum post-event recovery period length was set to 7 years. The pointRes 2.0 library algorithm is set for a recovery period of 10 years by default. However, some studies have shown that for a period between 5 and 10 years, the results are comparable (Pretzch et al., 2013; Sohn et al., 2013; Schwarz et al., 2020).

Unprocessed data (raw) for the width of the annual tree rings was used in the resilience indices calculations. In this way the possibility of introducing additional effects, by mathematically processing the data, is eliminated.

According to Schwarz et al. (2020), the majority of studies used raw annual tree-ring widths to calculate resilience indices and only one study found an influence of raw data that disappeared after detrending.

Results

Climate-growth relationship

The correlation coefficient between the indexed tree-ring chronology and the average annual temperatures for the period 1930-2012 is 0.39, while the correlation with the annual precipitation for the same period is -0.34 (Fig. 5, Fig. 6). The correlation with summer temperatures (July-August) is negative (correlation coefficient is -0.29), which indicates negative impact of hot and usually dry summers. There is an accumulation of negative impact from high temperatures, with the temperature in September of the current year having the greatest influence (Fig. 6A). The constant high amount of precipitation has a positive effect on radial growth, although it is not as strongly expressed (Fig. 6B).

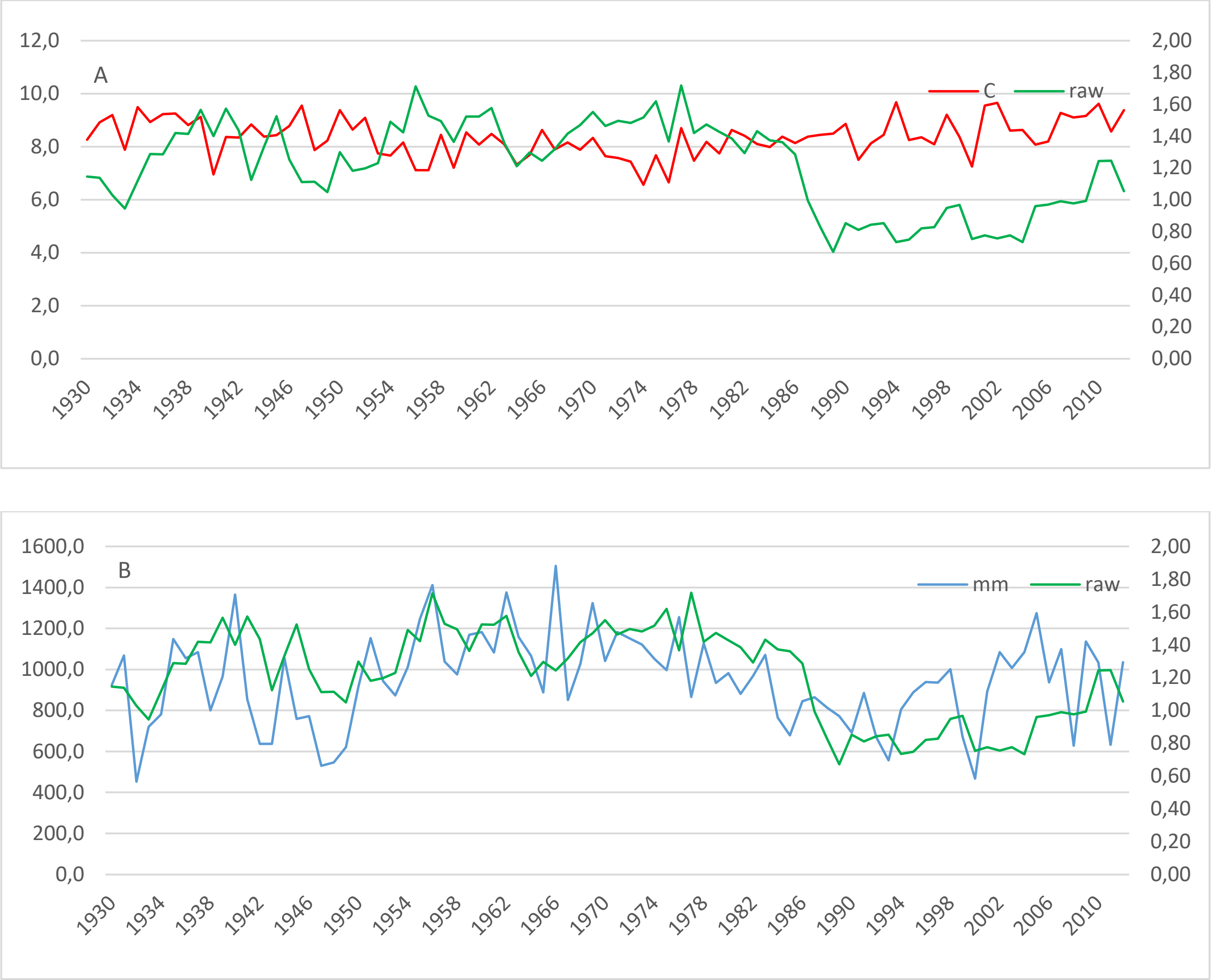

Fig. 5. Tree ring width (raw) chronology and annual temperature (A) and precipitation (B).

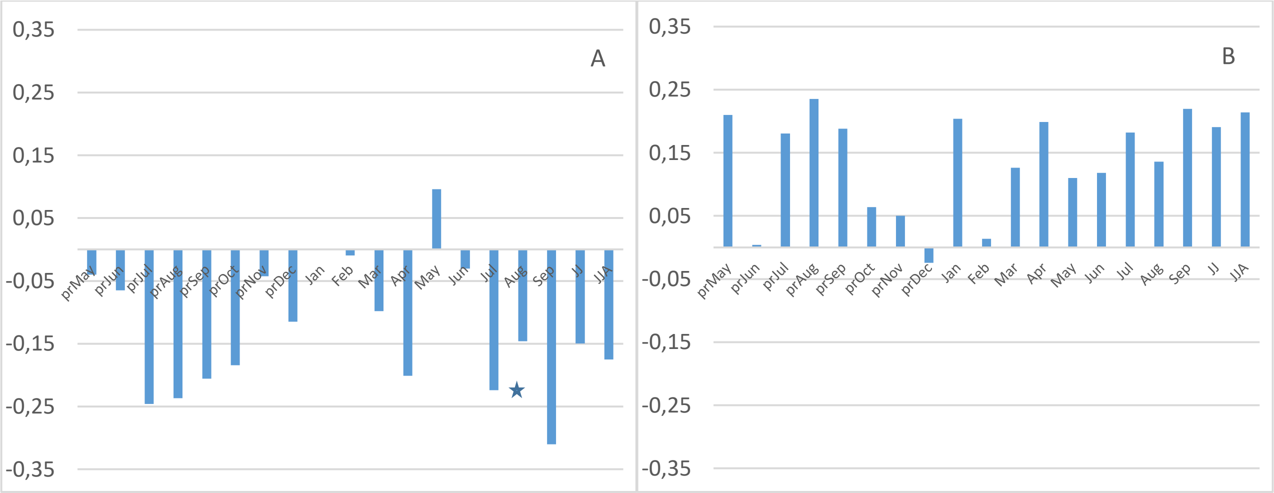

Fig. 6. Correlations between the standardized tree-ring width chronology and average monthly temperatures (A) and monthly precipitation sums (B). Statistically significant values are marked with an asterisk (significance level: $p < 0.05$).

Response to hot summers without evidence of typical drought

The average resistance and resilience values for the studied years are close to 1 (2003 is slightly below 1) which indicate small growth reduction in 2003 and 2007 and the years after in relation to the reference 10 previous years (Fig. 7). The average values of total growth reduction fluctuate around 0, with some individuals exceeding 1.

Low fluctuations in growth dynamics also determine a short recovery period for reaching the initial radial growth levels before the event (Fig. 8). The average values of the recovery index are above 1 for the studied years.

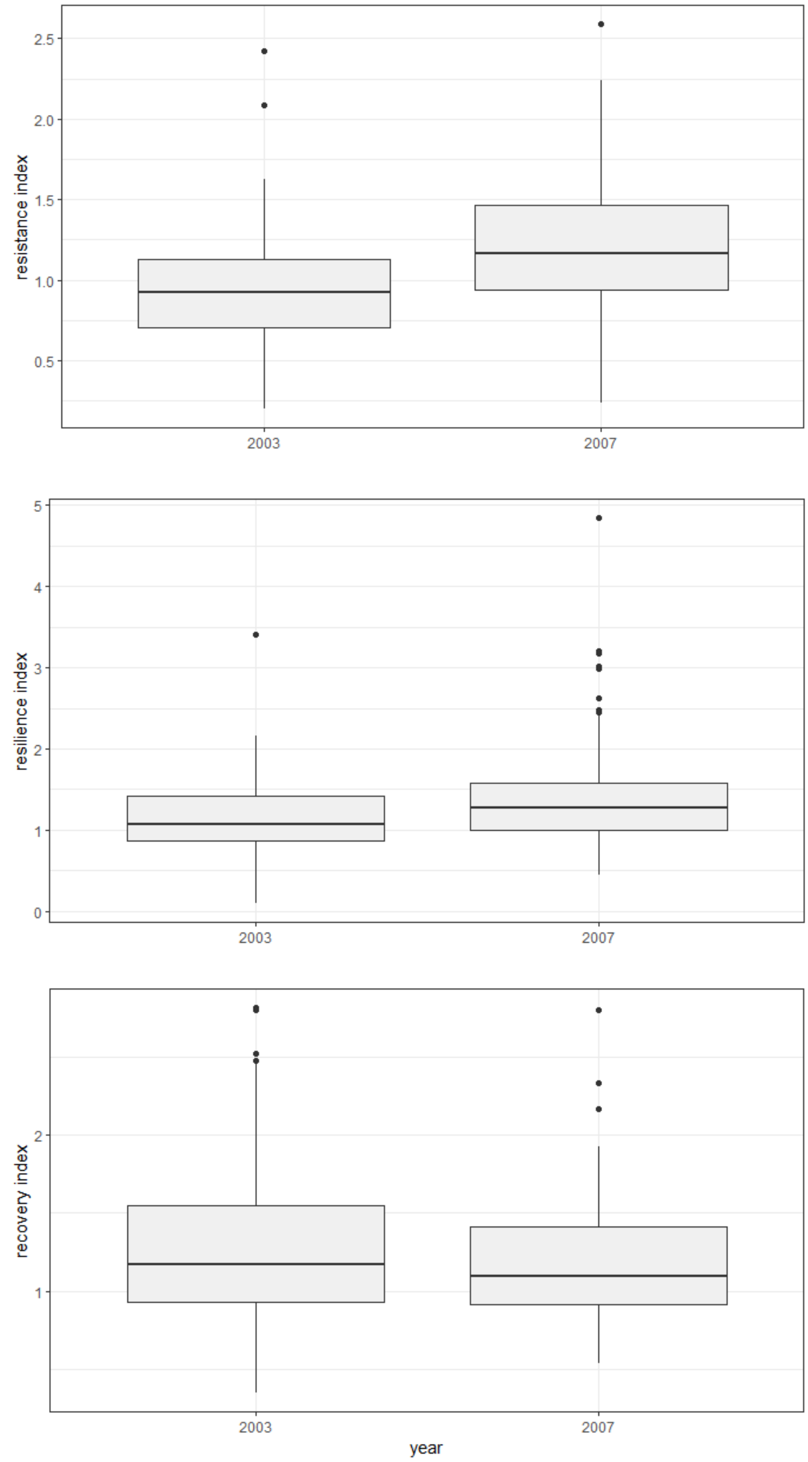

Fig. 7. Indices of *resistance*, *resilience* and *recovery* in hot summers without evidence of typical drought for Norway spruce from Beglika region.

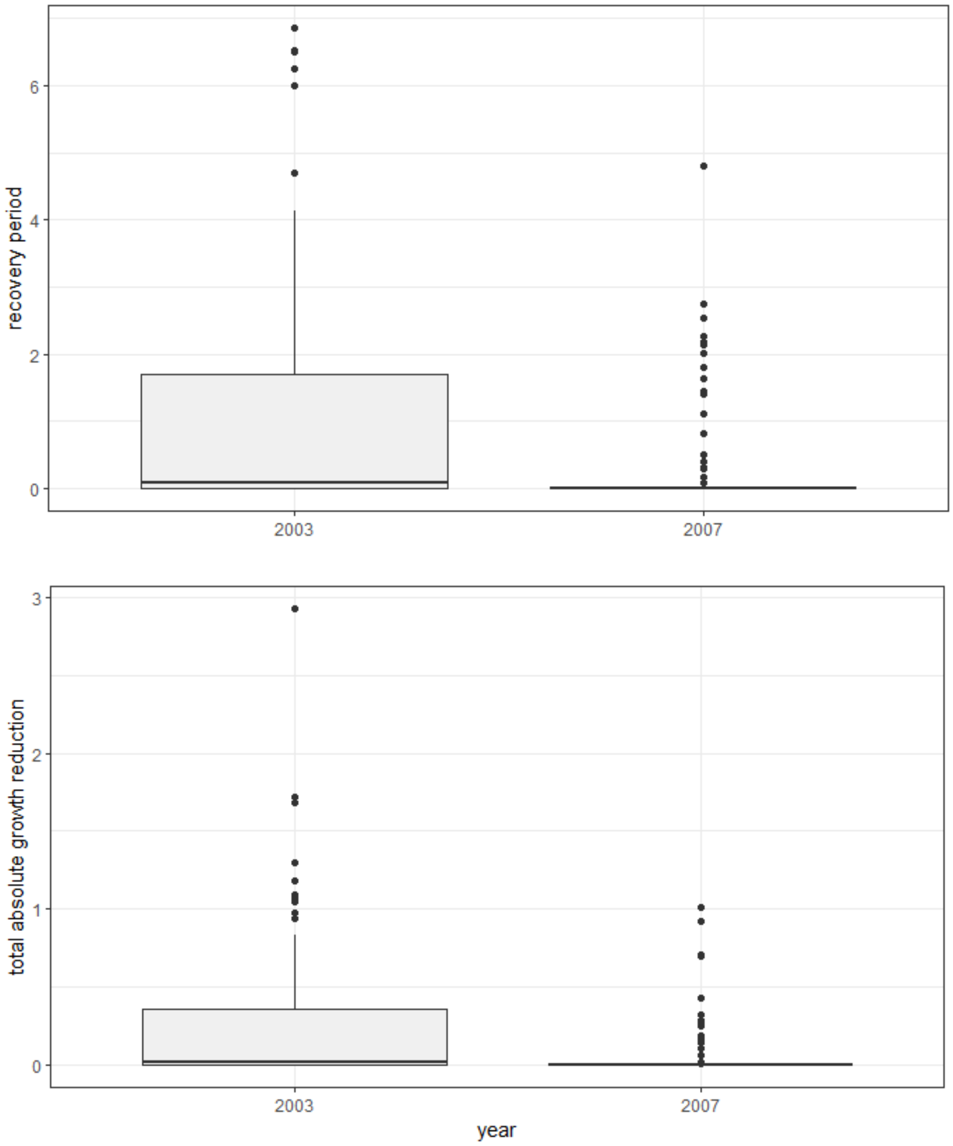

Fig. 8. Indices for *recovery period* and *total growth reduction* in hot summers without evidence of typical drought for Norway spruce.

Response to dry and hot summers

In the studied years with hot and dry summers, the average values for both resistance and resilience fall below 1 with lower values for 1946 and 2000 (Fig. 9). However, there are exceptions: 1993 stands out for resistance, while 2000 shows a higher recovery index (above 1). Indices of total growth reduction in hot and dry summers are low, with large individual differ-rences. Therefore, average recovery periods are low, although, individual recoveries in some specimens can be as long as 3-4 years (Fig. 10).

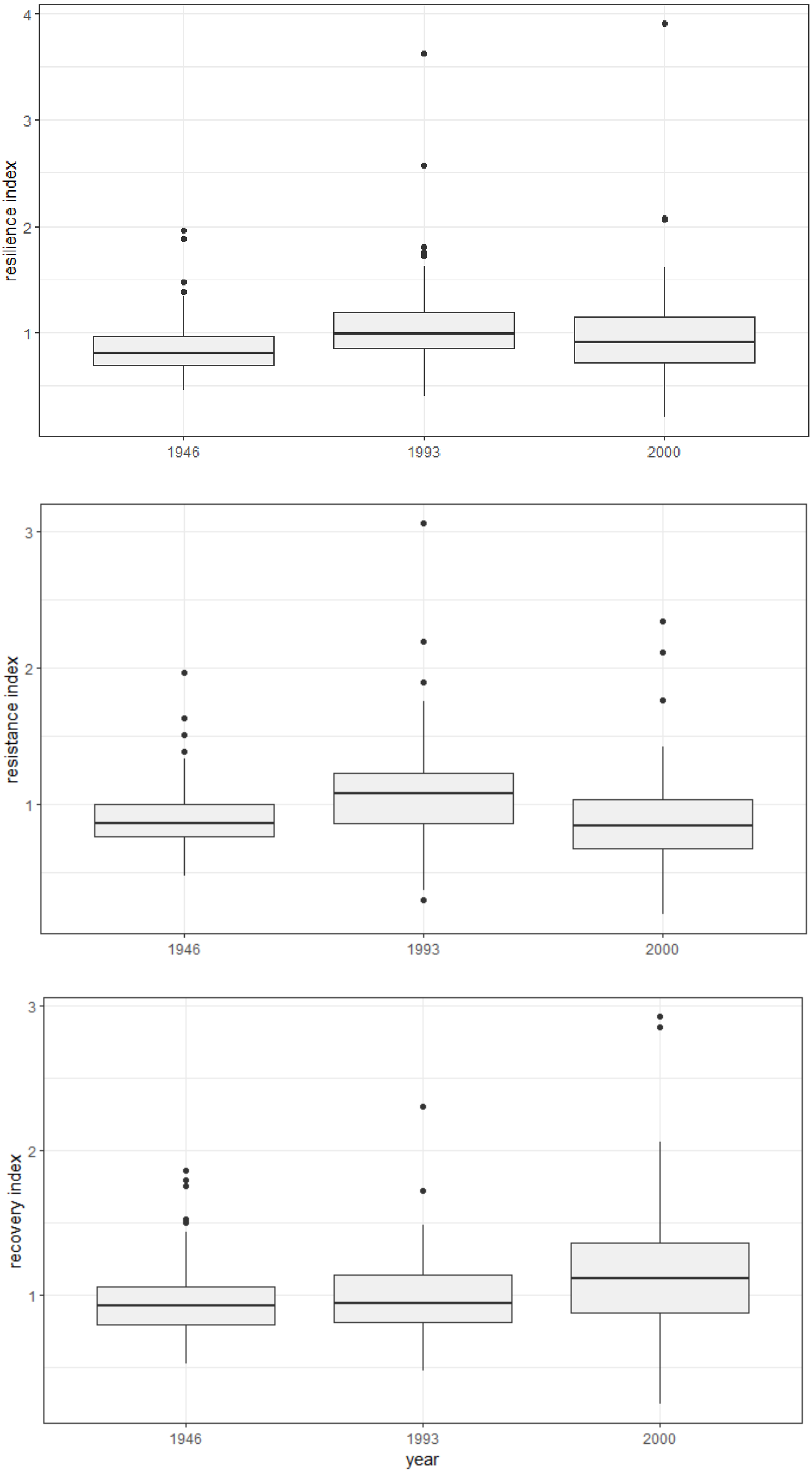

Fig. 9. Indices of *resistance*, *resilience* and *recovery* in hot and dry summers for Norway spruce.

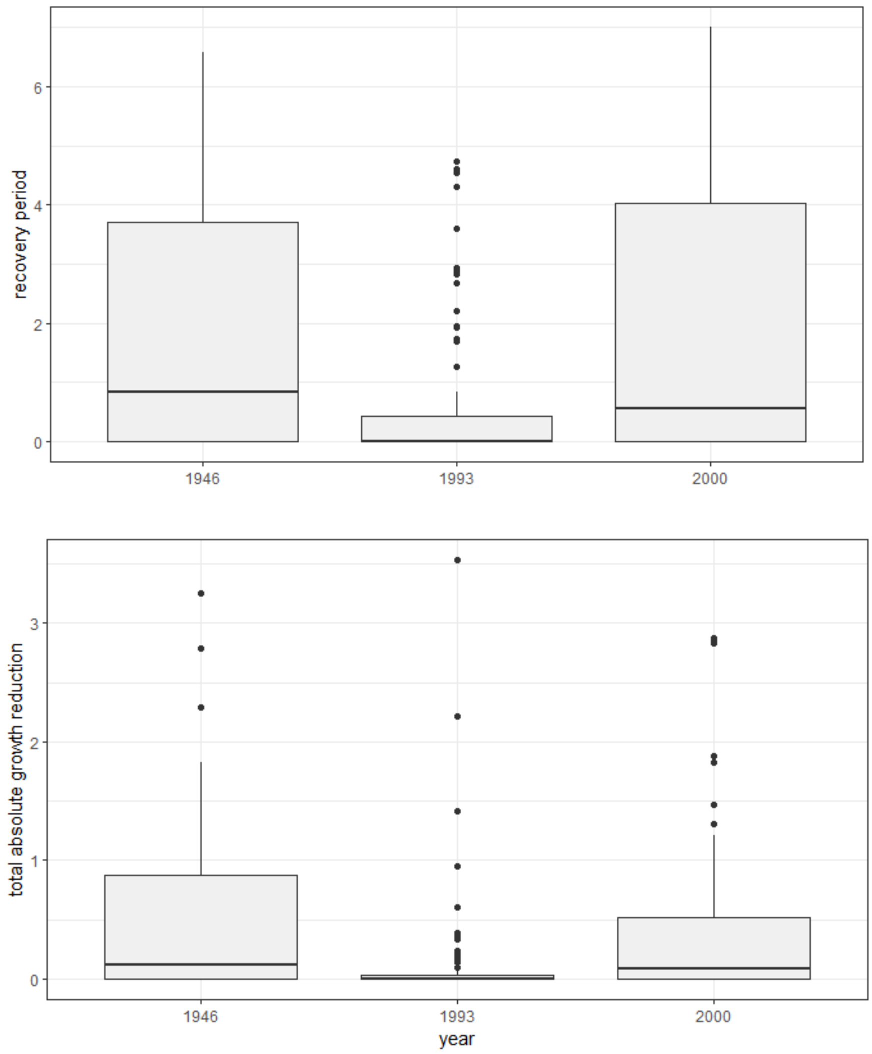

Fig. 10. Indices of *recovery period* and *total growth reduction* in hot and dry summers for Norway spruce.

Discussion

Response to hot summers without evidence of typical drought

The resilience of Norway spruce to climate changes cannot be presented with one value only. Usually this is done by a set of indices whose values must be considered altogether. Often the indices of resistance and resilience are very closely related, and for their interpretation the total growth reduction must also be considered.

In our study site in hot summers without typical drought, Norway spruce coped with high temperatures without showing a significant reduction in radial growth. It is of interest that in 2003, the response of Norway spruce was slightly stronger compared to 2007. The previous year, 2002, was characterized by an increased amount of precipitation compared to prior years, while temperatures were not characterized by elevated values. The following year, 2004, had more precipitation and was cooler than 2003 (Fig. 5). These conditions enabled a rapid recovery, resulting in short recovery period of up to 1-2 years (Fig. 8). The negative impact of the temperatures is cumulative, meaning that the total impact of the temperatures over the summer months is greater than the impact of any one month, as the temperature in May has a positive effect (Fig. 6). The production of new tracheid cells in Norway spruce starts in May and stops in late August, early September for high mountains (Rossi et al., 2006). Abnormally high temperatures in September can further enhance the effect of accumulated drought during the summer months.

Response to dry and hot summers

Similar to other regions, southeastern Europe is also expected to experience more frequent, intense, and prolonged periods of abnormal temperatures and drought spells in future, especially in the second half of the century (Chervenkov and Malcheva, 2023). For this reason, the interest in the potential response of Norway spruce to hot and dry years is high. As expected, dry years have a greater influence on growth (Fig. 10). It has been suggested that in such years the resistance index may be of the greatest importance, as species with high resistance (i.e. lower growth decrease during years with unfavorable conditions) have less need for recovery compared to species with lower resistance (Hoffmann et al., 2018). More acute was the response of trees during and after the droughts in 1946 and 2000. These years were characterized by severe droughts in July-August. At that period usually the moisture reserves in soils have diminished and if there is no precipitation the trees experience severe lack of moisture which directly affects cambial activity and the production of new tracheids. Despite the higher values of resistance, resilience and recovery in 1993, the year is characterized by low levels of radial growth reduction and a very short recovery period. Specific to this year was a more severe drought in early summer, but increase in precipitation and hence no drought in July. The temperature was unusually high, but was not among the most extreme values. Gazol et al. (2017) found high levels of resistance under wet conditions, even in Mediterranean climates. In opposite shallow, stony and poor soils can enhance the effect of drought (Heydari et al., 2023), while rich soils limit it. This can be a reason for less severe reaction in the studied forest, which grows on relatively rich and deep soils.

A decrease in radial growth is observed after the 1980s (Fig. 5), when hot and dry summers become more frequent. The fact that the trees are over 100 years old should not be neglected, and the effect of age also has an impact on the recovery potential of individuals. Ecophysiological studies have shown that functional processes are strongly coupled to tree growth undergo changes with increasing tree age. This suggests that growth-related environmental signals are likely to be age-dependent (Carrer and Urbinati, 2004). Growth during drought may be sustained by previously stored carbohydrates (Galiano et al. 2011). In problematic previous periods, where there is more loss of non-structural (not used for compounds) carbon, slower recovery can be expected (Schwarz et al., 2020). Therefore, high resistance can lead to slow recovery and vice versa, while resistance has equal values (indices). Nevertheless, high reserve consumption (low resistance) can lead to fast recovery if it does not depend only on remaining reserves but can be supported by other factors (e.g. preserved photosynthetic apparatus or intact canopy - Galiano et al., 2011). Norway spruce produces a large amount of carbohydrates, thus having high values of resistance and resilience indices, showing some buffer capacity to respond to atypical events (Beck and Müller, 2007). This high carbohydrate productivity is the result of intensive water usage (Anev, 2016), and as a result, its growth response in atypical years will be influenced less by its age than by specific site conditions (Boden et al., 2014).

Resistance is only one aspect of tree growth, and intra-annual plasticity must also be considered when analyzing drought impacts on forests (Zlobin, 2022). Forest structure is also an important factor influencing growth dynamics. Aleksandrov (2022) points out that spruce forests in the Beglika Biosphere Reserve are characterized by a complex heterogeneous, multi-aged structure. The relatively open canopy of multi-aged forests allows individual trees to be characterized by a well-developed canopy. The different ages and sizes of the trees, respectively, form a complex stepped-like canopy, which allows them to use light more efficiently and increases their photosynthetic activity. In combination with deep and relatively nutrient-rich soils, this can be taken as another reason for the better resistance and resilience indices. Increasing anthropogenic pressure on forests may affect their resistance to drought. In managed forests, forest structure is shaped by the type of silvicultural systems applied. The maintenance of a complex multi-aged structure of spruce forests can be considered as one of the tools for adaptation to expected climate changes.

Conclusions

Our findings indicate that Norway spruce in Beglika Reserve, Western Rhodope Mountains, exhibits a surprising degree of tolerance to drier and warmer summers. Notably, we haven't observed any long-term decline in growth. It is important to remember that the response of Norway spruce to climate change will vary geographically. Local microclimates will play a crucial role in determining the impact. Our data support two key points: 1) Climate change is a factor influencing Norway spruce growth; 2) Higher summer temperatures have cumulative negative effect, with September temperatures exerting the strongest influence. Higher precipitation, in contrast, has consistently positive impact regardless of the month, while droughts cause growth decline. This suggests that future changes in the range or health of Norway spruce are more likely to occur in locations that are atypical for the species or at the fringes of its natural distribution.

Acknowledgments

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