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Growth Response of Norway Spruce (*Picea abies* [L.] Karst.) in Central Bohemia (Czech Republic) to Climate Change

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Abstract: Norway spruce (*Picea abies* (L.) Karst.) is a significant conifer tree species in Europe that holds significant economic and ecological value. However, it remains one of the most sensitive to climate change. This study describes the climate–growth relationship, focusing on dendroecology in hilly spruce forests (319–425 m a.s.l.) located in Bohemia, the Czech Republic, during 1950–2018. The results confirmed that the highest radial increment was obtained in locations with higher precipitation (Kostelec), while the lowest growth was observed in locations with lower precipitation (Karlstejn). Tree-ring growth shows very low increments for the years 1964 and 1976 for all plots, and the years with the least growth were confirmed by the negative pointer year analysis. This study confirmed precipitation as the main factor that affects the growth of spruce at lower altitudes. The radial growth for all study sites shows a statistically significant positive correlation with precipitation during the growing season, while no statistically significant values between radial growth and temperature were obtained. This study demonstrates that Norway spruce is affected more by precipitation than temperature, and the results indicate that this conifer is seriously affected by the lack of precipitation at lower altitudes in the Czech Republic, where the species is not native.

Keywords: climate change; Czech Republic; tree-ring width; temperature; precipitation

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1. Introduction

In Europe, the coniferous species *Picea abies* (L.) Karst.—Norway spruce—remains one of the economically and ecologically most important conifers [1] and is very sensitive to the climate [2], particularly to drought [3]. The natural distribution of Norway spruce extends from the European Alps through the Balkans and the Carpathians to northern Scandinavia and northern Russia [4]. Spruce is a continental climate conifer; its optimal conditions for growth are humid, with an annual precipitation surpassing 800 mm, and an average annual temperature not exceeding 6 °C [5]. While Norway spruce is still a major production species, it is not considered ecologically sustainable at the low and middle altitudes of the Czech forests, particularly given the current state of climate change [6].

In recent decades, Norway spruce has shown various health and growth problems [4]. Basic symptoms of Norway spruce decline are needle yellowing, defoliation, a reduction in radial growth, and death. These symptoms occur in isolated trees and in groups, affecting trees of different ages.

The Czech Republic is a Central European country with an increased disruption to Norway spruce forest management. The cause has been attributed to air pollution in the mountain areas, and, at present, to the consequences of climate change in lowland areas [7].

The reason for the decline in spruce forests located at lower and middle altitudes are high temperature, low total precipitation and its uneven distribution during the year. Spruce forests are devitalized by drought and then subsequently attacked by the spruce bark beetle [8]. The bark beetle can propagate very quickly from a septic tree to attack many more and is considered responsible for the most damage to spruce forests [9]. Besides the climatic change, the effects of acidification and nutrition depletion can play a role in the decline in Norway spruce [10].

The relationship between climate and radial increments in spruce forests has been investigated in different countries of Europe by different authors, e.g., in Northern Europe, by [11], who investigated this correlation in Sweden; in Eastern Europe, by [12], who conducted their research in four different regions in Poland; and in Central Europe, by [13] who conducted their study in a dry territory of Austria and reported that Norway spruce showed a sensitivity to drought. The topic of drought remains a frequent subject of research [5], and several dendrochronological studies have shown the actual potential to identify environmental factors that influence tree growth [14].

This study is a continuation of the previous one by [15] and it determines: (i) the radial growth dynamics of spruce in lowland study areas in Central Bohemia (Czech Republic), which are highly endangered by droughts, over a period of 68 years (1950–2018), (ii) the influence of climatic factors (temperature and precipitation) on radial increment. This period contains the principal factors influencing the growth of Norway spruce at lower altitudes during climate change. The growth response of Norway spruce show weather inconstancy in lowland forests. Tree rings could explain the effect of climate change on the increment of this conifer at lower altitudes. This study can provide useful information about trends in Norway spruce regarding the possible impact of climate change on its uncertain future.

2. Material and Methods

2.1. Study Area

The research highlighted tree forest complexes in three districts of Bohemia: Karlstejn (1), Cukrak (2), and Kostelec (3) (Figure 1). The plots have an altitude between 319 and 425 m a.s.l. (Table 1). The plots were situated in an area with a dip of 5° and a predominantly northwest exposure (Table 1). The climate of the sites is distinguished by cool and dry winters and by warm and dry summers, with a low annual thermal amplitude (Cfb) in accordance with the Köppen climate classification [16]. The maximum precipitation occurs from June to August (the minimum in the winter months) [17]. July is the month with the highest monthly temperature, while January is the month with the lowest monthly temperature. The average duration of the growing season ($T_{max} \geq 10$ °C) is 158–165 days [18].

The first study site is situated about 22 km southwest of Prague in the NNR Karlštejn and is placed in the Český Kras Protected Landscape Area (PLA) [18]. The NNR was declared in 1955 [19] on a territory of 1547 ha to protect the biodiversity of flora and fauna. Until the mid-20th century, forests in the Karlštejn area were managed as coppice-with-standards and coppice forests [20]. The most common original types of forest are part of the genus *Quercus* and *Carpinus*, but in the study area, there are also production and allochthonous species such as Norway spruce, and non-native species such as black pine and black locust [19]. Gray and red limestones are prevalent in the geological subsoil (B).

The average annual temperature is 8–9 °C, precipitation is around 560 mm [21], and the average growing season is about 165 days [18] (Figure 2). The climate varies from slightly warm to slightly dry, whereas winter can be considered mild; the maximum precipitation is in the summer (July) and the minimum in the winter months [17].

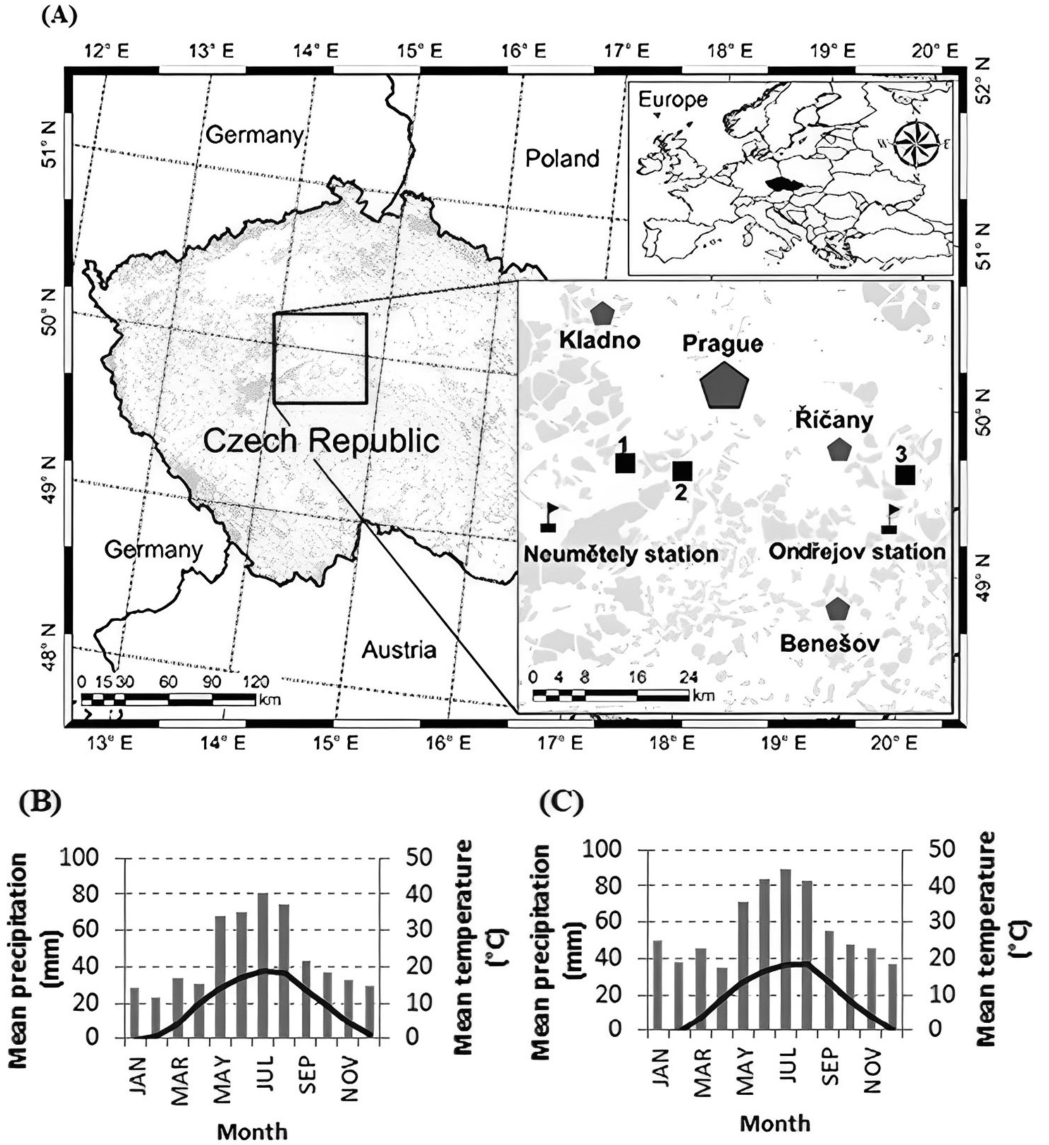

Figure 1. Localization of spruce forest plots (■) in the study area Karlstejn (1), Cukrak (2), and Kostelec (3) (**A**); meteorological stations; Climogram for research area of Karlstejn and Cukrak (**B**); Climogram for study area Kostelec (**C**)—forested areas are shadowed; the map was created in ArcGIS 10 software version 10.7 (Esri, Redlands, CA, USA); climogram black line describes temperature and grey bars describe precipitation.

The second study site, "Cukrak," is a private forest located 18 km southwest of the capital city of Prague. The research area is located at an altitude of 411 m a.s.l., occupying the area between the Vltava and Berounka rivers.

At the top of the hill, the television and radio transmitter Cukrak—with a height of 193.5 m—was built in 1961. In the vicinity, there is an extensive provenance research plot of several tree species established by the Research Institute of Forestry and Game Management. The geological parent rock is formed by Algonkian shale covered by loess of variable thickness [22]. The thermo-pluviometric data come from the same weather station of the first site, Karlstejn (Figure 1). The classification of the forest site type is *Querceto-Fagetum acidophilum* and *Querceto-Fagetum illimerosum acidophilum* [23]

The last research site, "Kostelec," is located 25–30 km southeast of Prague and it is part of a reserve created in 1955, with an area of 684 ha. A large number of ponds with tributaries are located in the studied area. The parent rock consists of granite of different textures [24].

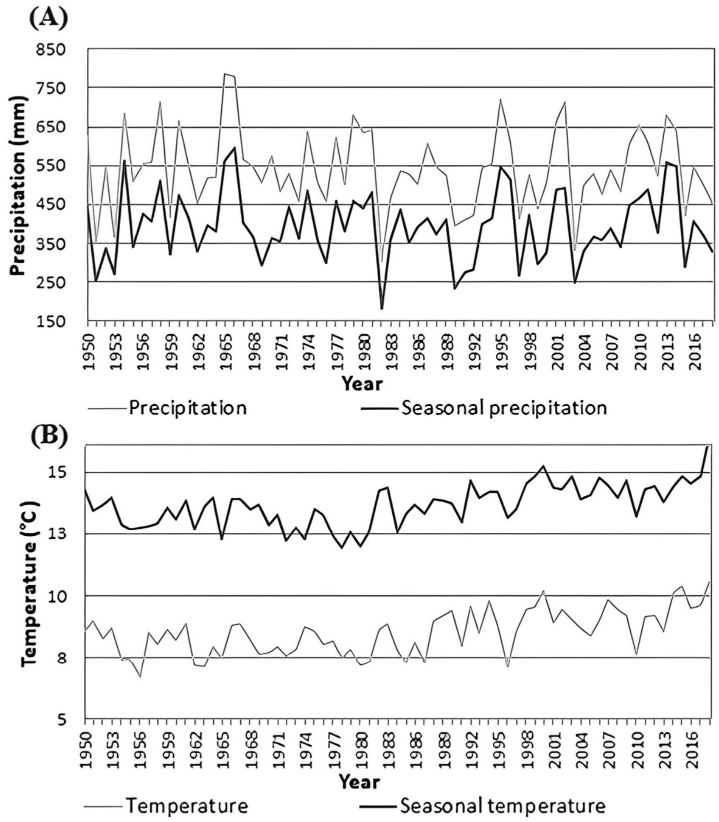

Figure 2. Dynamics of the annual and growing seasonal precipitation (**A**) and air temperature (**B**) for the Karlstejn and Cukrak locations, from the nearby meteorological stations for the period 1950–2018.

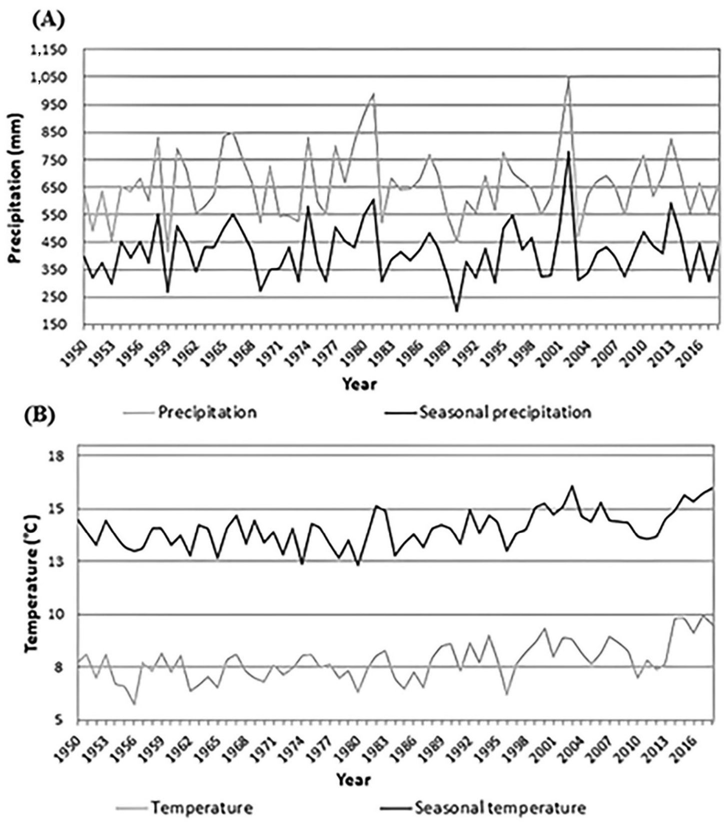

Figure 3. Dynamics of the annual and growing season precipitation (**A**) and air temperature (**B**) for the Kostelec location, from the nearby meteorological stations for 1950–2018.

The climate is moderately hot and dry, with an average annual temperature of 7.6 °C, and an average annual precipitation of around 655 mm (Ondřejov Meteorological Station) [25,26] (Figure 3).The classification of the forest site type is *Querceto-Fagetum mesotrophicum* and *Querceto-Fagetum illimerosum acidophilum* [23]; all study plots have similar altitudes, exposure and cambisol soil (Table 1).

Table 1. Overview of fundamental characteristics of the site and the tree population of the examined plots (according to the Forest Management Plan).

Plot Name	GPS (Coordinates)	Altitude (m)	Exposure	Slope (%)	Age (Years)	Height (m)	DBH (cm)	Forest (Type *)
Karlstejn 1	49°56′51.3″ N, 14°12′05.6″ E	422	N-W	5	88	25	34	3B
Cukrak 2	49°56′14.2″ N, 14°21′13.4″ E	402	N-W	5	82	25	30	3K
Kostelec 3	49°57′55.9″ N, 14°48′58.9″ E	423	N-W	5	113	31	41	3S

Notes: * Forest site type classification: 3B—*Querceto-Fagetum trophicum*, 3S—*Querceto-Fagetum mesotrophicum*, 3K—*Querceto-Fagetum acidophilum* [23], Age—age of tree layers.

2.2. Data Collection

For this study, dendrochronological samples were taken from 180 spruce trees (about 60 trees randomly selected at every site); they were collected in 2019 by standard dendrochronological methods [27]. The samples were obtained using a Presler borer. One core per dominant tree was collected 1.3 m above the ground, perpendicular to the slope, to prevent the presence of compressed wood [28]. Each core was dried and positioned into wooden slats and gradually smoothed with finer sandpaper. Using a LINTAB measuring table (Rinntech, Heidelberg, Germany) with an Olympus microscope, samples were measured from bark to the heartwood on a 0.01 mm scale. TSAP-Win software was used to process the measured tree-ring data [29], while CDendro software was used for the cross-dating procedure [30].

For the research locations of Karlstejn and Cukrak, climate data were taken from the Neumetely meteorological station (49°51′00″ N, 14°02′24″ E). The meteorological station has an altitude of 322 m a.s.l. and is situated about 16 km from the Karlstejn plot and approximately 25 km from the Cukrak plot.

For the Kostelec study area, climate data were obtained from the Ondrejov meteorological station (49°54′36″ N, 14°46′48″ E) located at an altitude of 485 m a.s.l. and about 7 km from the study area.

In Karlstejn and Cukrak, the growing season spans from April to October, while in Kostelec, it spans from May to October. The temperature variations in Kostelec are influenced by its geographical location and specific conditions of the study sites, such as the proximity to pond, which impacts the local microclimate. The Kostelec region is a forest area landscape compared to Karlstejn and Cukrak—which range from combined to agricultural landscapes. The mean annual temperature in Kostelec is lower than the average temperatures in Karlstejn and Cukrak. Moreover, Kostelec has a higher annual precipitation rate compared to Karlstejn and Cukrak. Arid winds and distinctive microclimate further contribute to the drier conditions in Karlstejn and Cukrak. Consequently, the onset of the growing season in Kostelec is delayed.

2.3. Data Analysis

Dendrochronological analyses were performed in the R-studio (R Core Team, 2018) environment using the dplR package [31]. Expressed population signal (EPS), the signal-to-noise ratio (SNR), and R-bar (inter-series correlations) were also computed. EPS values for every study site were <0.85 to preserve an effective climatic signal for the utilized chronology.

To isolate the climatic signal, each dendrochronological series was converted through the indexing procedure. In particular, the indexing was achieved through a double-detrending: tree-ring indices were calculated from a negative exponential curve (to eliminate the age trend) and then detrended a second time using a smoothing spline with 67% stiffness of the length of the line (to maintain the high- and medium-frequency variability).

The relationships between climate and growth were evaluated with the bootRes package [32], using bootstrapped confidence intervals to evaluate the significance of the correlation function coefficients. Correlation functions for $p < 0.05$ were calculated based on simultaneous iterations of temperature (T) and precipitation (P) iterations. Tree-ring width indices (RWI) and monthly climatic parameters (P and mean T) were examined for the period 1950–2018. The time window of the climate–growth correlation function was set from the precedent years (April) to the present years (October) for Cukrak and Karlstejn, and from May of the precedent year to October of the current year for Kostelec.

Finally, we have calculated negative pointer years with the WEISER program [33] to estimate the influence of extreme weather events on diameter increments. For every tree, the negative event years were considered as extreme narrow ring widths that were 75% or less compared with the average ring width values in the precedent seven years [34]. A negative pointer year occurs when an event year is specified for at least 50% of the trees in the plot.

3. Results

3.1. Dynamics of Radial Growth

Dendrochronological data reported sufficient results for processing the data of EPS ($\geq$0.98) for all study sites, and also indicate elevated R-bar values ($\geq$0.56; Table 2). The SNR showed the best dendrochronological pattern (without noise) for Karlstejn (71.85) while the worst results were found for Kostelec (49.13). The highest mean value of tree-ring width was recorded for Kostelec (1.84 mm), a site that is very rich in nutrients with the highest percentage of soil moisture compared with the limestone soils of Karlstejn (1.69 mm).

Table 2. Features of tree-ring chronologies for spruce in study sites.

Research Plot	No. Trees	Mean (mm)	Std.	R-Bar	SNR	EPS
Karlstejn	57	1.69	0.91	0.561	71.857	0.986
Cukrak	56	1.79	0.96	0.523	61.41	0.984
Kostelec	58	1.84	0.82	0.461	49.130	0.980

Notes: No. Trees—number of trees, Mean (mm)—mean tree-ring width, Std.—standard deviation, R-bar—inter-series correlation, SNR—signal-to-noise ratio, EPS—expressed population signal.

Dynamics of tree-ring width index (RWI) denoted little growth for the years 1964 and 1976 for all plots. The year 2017 indicated less growth for Karlstejn (RWI 0.370), followed by 1964 (RWI 0.434), while 1964 was the lowest growth year for Kostelec (RWI 0.635) and Cukrak (RWI 0.485) (Figure 4). The highest RWI was reached in years 2002 for Karlstejn (RWI 1.576), 2014 for Kostelec (RWI 1.474), and 2011 for Cukrak (RWI 1.599).

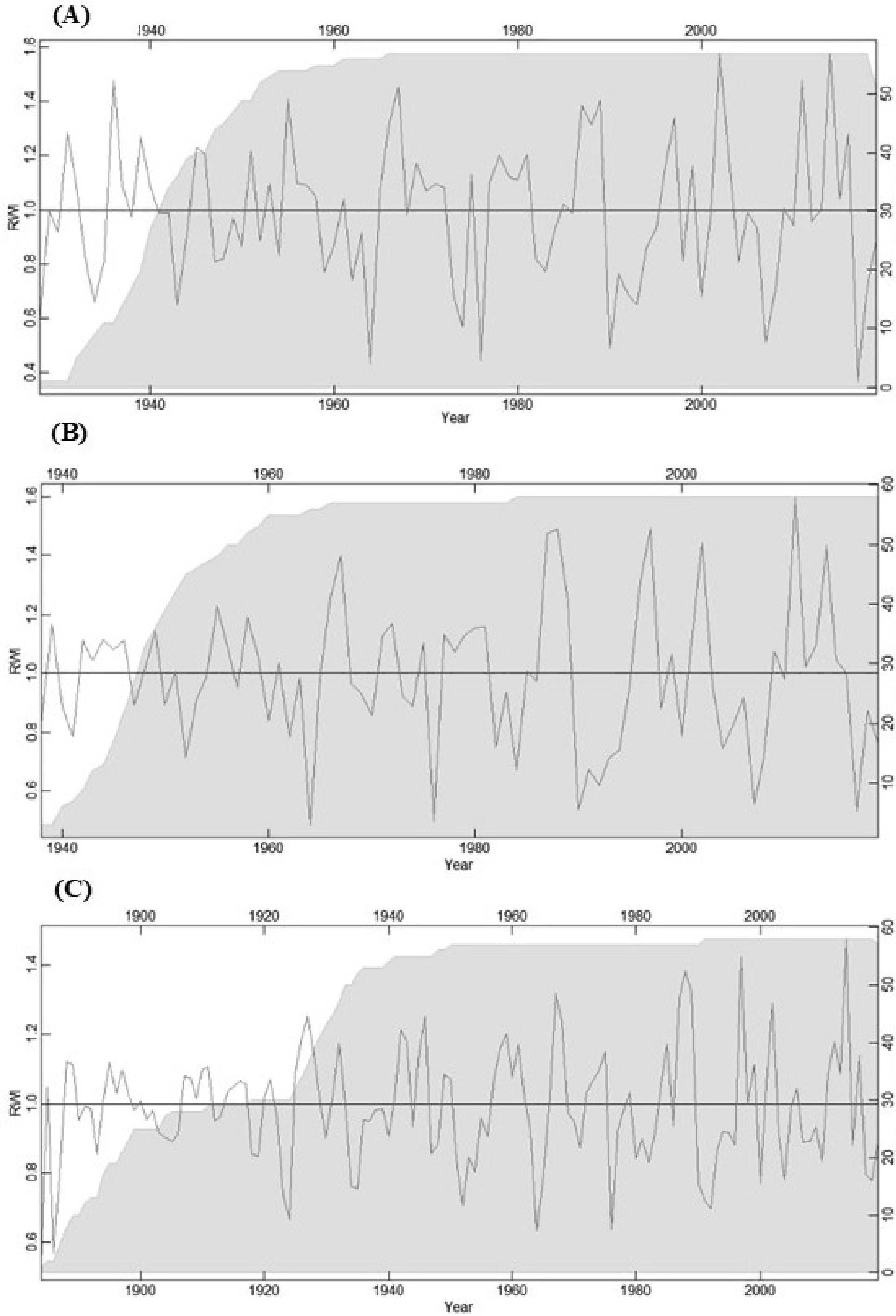

Figure 4. Characterization of RWI and sample depth for the entire chronology for the location of Karlstejn (**A**), Cukrak (**B**), and Kostelec (**C**).

3.2. *Effect of Climate on Radial Growth*

The correlation of radial increment to average monthly temperatures for the first study site, Karlstejn, shows a total of 13 months with a negative statistic value and six months with positive statistic values; however, the correlation only shows negative statistical significance for September of the precedent year and positive statistical significance ($p = 0.05$) only for September of the current year (Figure 5A). The correlation of radial increment with average monthly precipitation shows a total of 18 months with a positive statistical value and only one month with a negative statistical value, but the correlation is statistically significantly ($p = 0.05$) positively correlated only for August and December of the precedent year and for July of the current year (Figure 5B). The correlation of radial increment with average monthly precipitation and with average monthly temperature show that months of April, October, and December of the precedent year and the months of February and September of the current year are positively correlated. The correlation of the radial growth with temperatures during the growing season (April–October) shows no statistically significative values, and the correlation is statistically negative but not significant (Figure 5C), while the correlation of the radial growth with precipitation of the growing season (April–October) is positively statistically significant (Figure 5D).

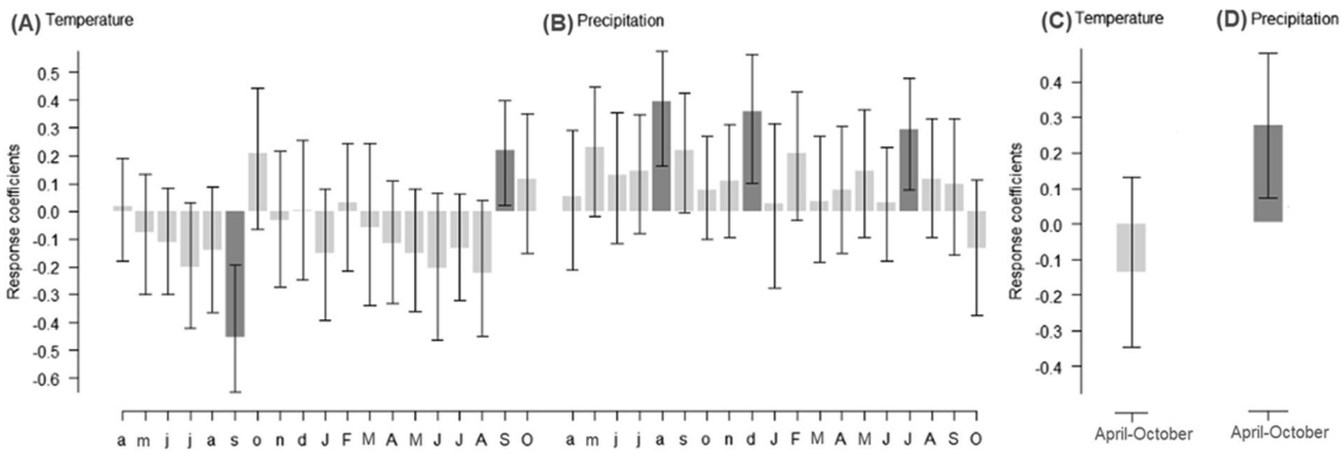

Figure 5. Response coefficients function for Karlstejn for the period 1950–2018 (from April of the precedent year to October of the current year). (**A**): average monthly temperatures (**B**): average monthly precipitation. (**C**): Summary response coefficients of monthly temperatures for the growing season (average value from current April to October). (**D**): Summary response coefficients of average monthly precipitation for the growing season (average value from current April to October). The (light/dark) gray bars describe response value with black lines that represent the 95% confidence interval. Values marked in dark gray are statistically significant ($p < 0.05$).

For the second study site, Cukrak, the radial growth correlations with average monthly temperatures show a total of 13 months with a negative statistical value and six months with positive statistic values, but the correlation is negatively statistically significant only for August and September of the precedent year and for June and July of the current year (Figure 6A). While the correlation of radial increment with average monthly precipitation shows a total of two months with negative statistical values and 17 months with positive statistical values, the correlation is statistically significantly positive only for May, July, August, September, and December of the precedent year and July of the current year (Figure 6B).

The correlation of the radial increment with temperatures of the growing season (April–October) shows no statistically significant values; the correlation is statistically negative but not significant (Figure 6C), while the correlation of the radial increment with precipitation during the growing season (April–October) is positively statistically significant (Figure 6D).

The correlation among radial increment and average monthly temperatures for the third site, Kostelec, shows a total of 11 months with a negative statistic value and seven months with positive statistic values, but the correlation is negatively statistically significantly for June, July, and September of the precedent year, while it is only statistically positively significant for October of the current year ($p = 0.05$) (Figure 7A). The correlation of radial growth with average monthly precipitation shows a total of four months with a negative statistical value and 14 months with positive statistical values, but the correlation is only positively statistically significantly correlated for May and August of the precedent year and July of the current year, while a negative statistically significant correlation is only shown for November of the precedent year (Figure 7B). The correlation of the radial growth with temperatures of the growing season (May–October) has not reported statistically significant values at present; the correlation is statistically negative but not significant (Figure 7C), while the correlation of the radial increment with precipitation of the growing season (May–October) shows a positive statistical significance (Figure 7D).

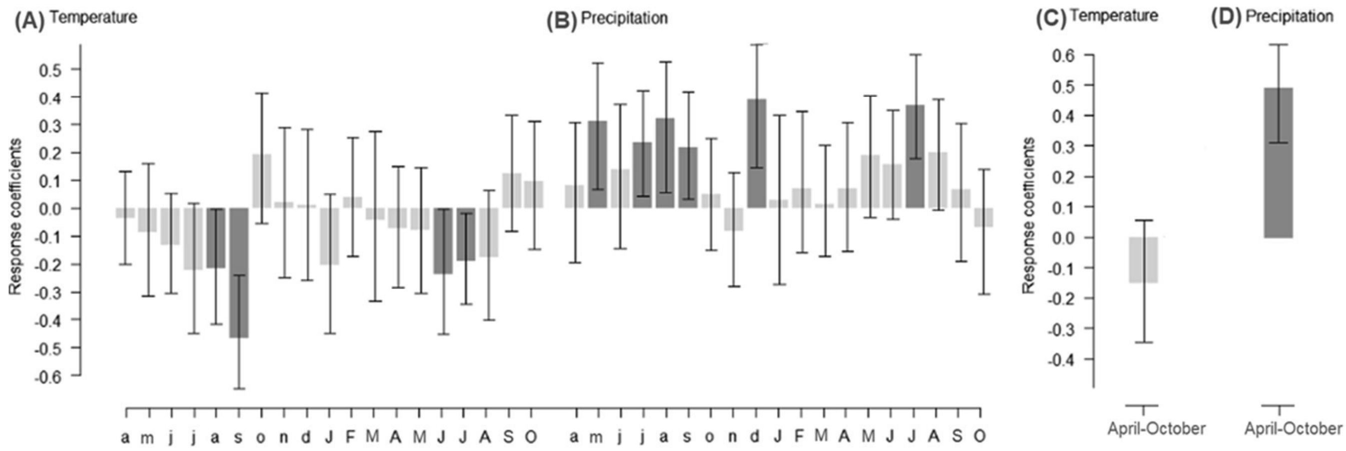

Figure 6. Response coefficients function for Cukrak for the period 1950–2018 (from April of the precedent year to October of the current year). (**A**): average monthly temperatures (**B**): average monthly precipitation. (**C**): Summary response coefficients of monthly temperatures for the growing season (average value from current April to October). (**D**): Summary response coefficients of average monthly precipitation for the growing season (average value from current April to October). The (light/dark) gray bars describe response value with black lines that represent the 95% confidence interval. Values marked in dark gray are statistically significant ($p < 0.05$).

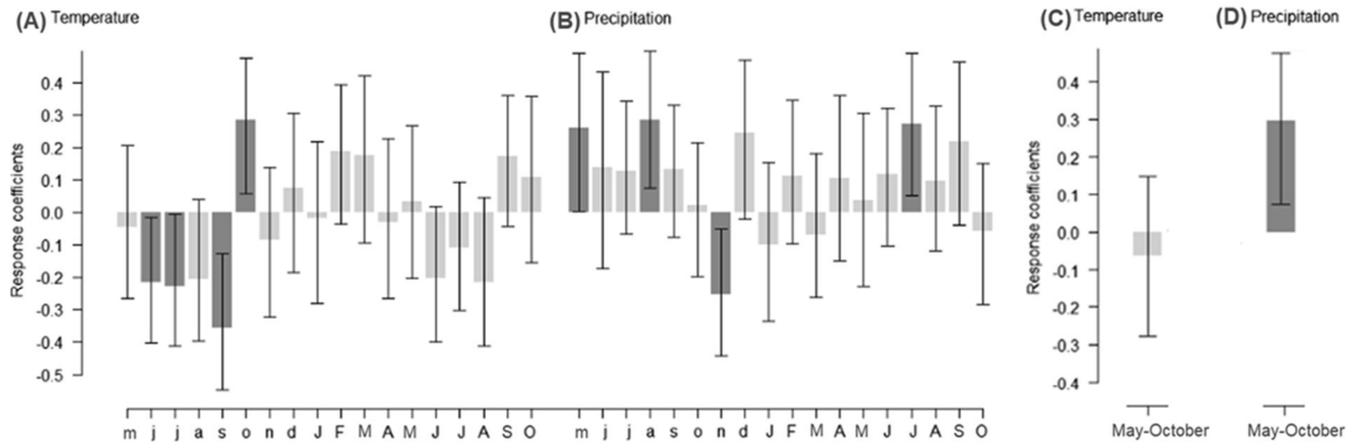

Figure 7. Response coefficients function for Kostelec for the period 1950–2018 (from May to October). (**A**): average monthly temperatures (**B**): average monthly precipitation. (**C**): Summary response coefficients of monthly temperatures for the growing season (average value from current May to October). (**D**): Summary response coefficients of average monthly precipitation for the growing season (average value from current May to October). The (light/dark) gray bars describe response value with black lines that represent the 95% confidence interval. Values marked in dark gray are statistically significant ($p < 0.05$).

Relative changes in tree ring growth of spruce are registered in Figure 8. Pointer years showed fluctuations in the radial increment of spruce.

The Karlstejn and Cukrak research sites reported the highest number of pointer years (11 pointer years). For the Karlstejn research plot, the years 1954, 1959, 1964, 1974, 1976, 1982, 1983, 1990, 2000, 2007, and 2017 are the negative pointer years; for the Cukrak research plot, the years 1952, 1960, 1964, 1976, 1982, 1984, 1990, 1998, 2000, 2007, and 2017 are the negative pointer years. Pointer years that are common for these locations were: 1964, 1976, 1982, 1990, 2000, 2007, and 2017. The research plot Kostelec had fewer pointer years (8 pointer years): 1952, 1954, 1971, 1976, 1992, 2000, 2004, and 2018.

The years 1964, 1976, and 2000 were pointer years common to all locations (Table 3). The locations with a higher number of pointer years (the Karlstejn and Cukrak research plots) are also the drier locations in comparison to the site with fewer pointer years (Kostelec).

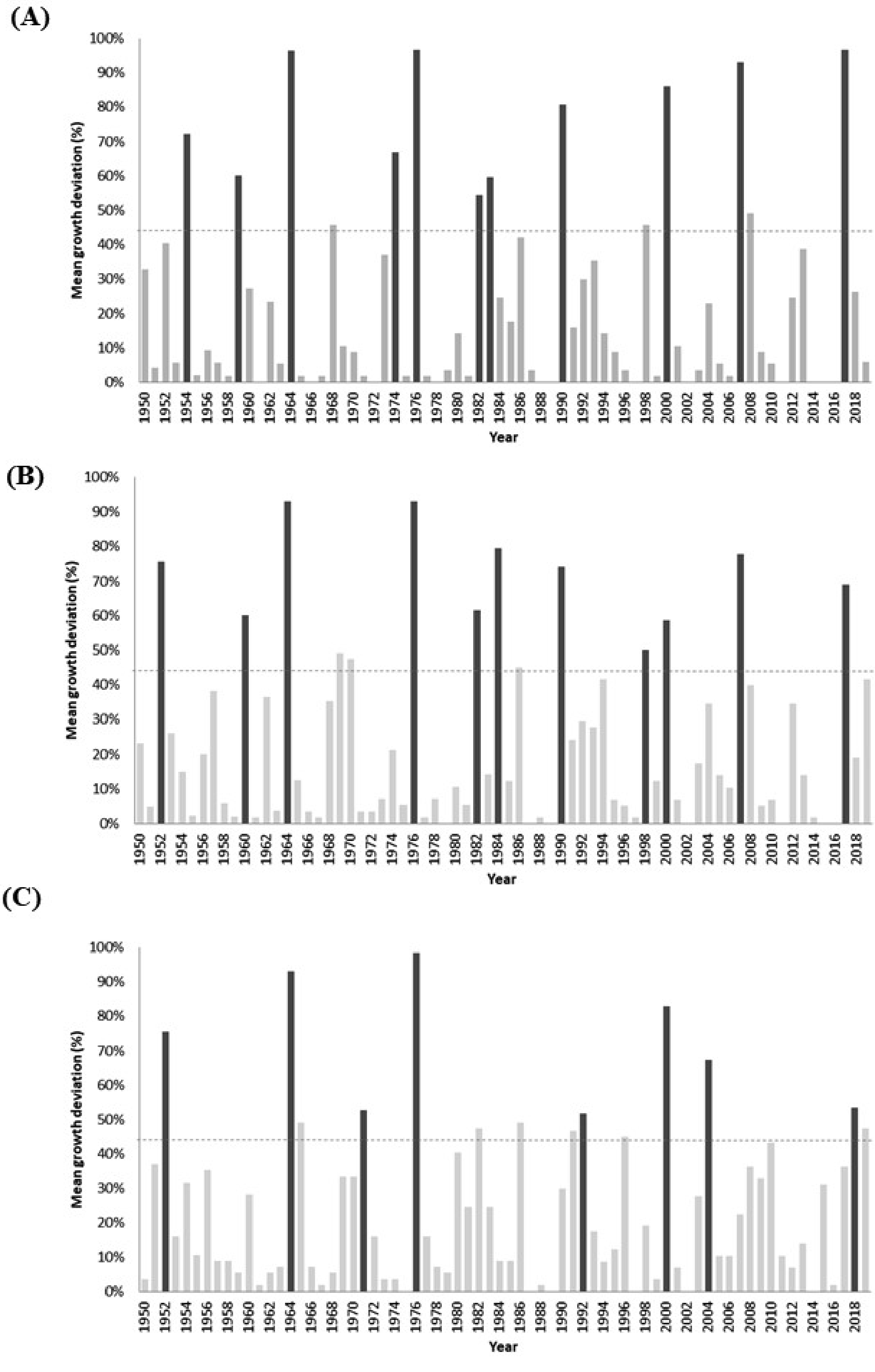

Figure 8. Pointer years of Norway spruce (1950–2018) for the Karlstejn (**A**), Cukrak (**B**), and Kostelec (**C**) study sites. Dark gray bars show statistically significant pointer years at $p < 0.05$.

Table 3. Negative pointer years common to all locations and interpretable climatic features.

Negative Pointer Year	Abnormal Climatic Characteristics
1964	Low precipitation in December 1963 and January 1964; subnormal temperature in March.
1976	Very low precipitation from February to May (especially in February); cold March for Karlstejn and Cukrak. While Kostelec saw very low precipitation in February and April; subnormal temperature in March.
2000	Very low precipitation in April; supernormal temperature in April and May for Karlstejn and Cukrak. While Kostelec saw very low precipitation in April, subnormal precipitation in June; supernormal temperature from April to June.

4. Discussion

4.1. Effect of Climate on Radial Growth

The radial increment for all sites shows a statistically significative positive correlation ($p < 0.05$) with precipitation during the growing season. The weather during the growing season significantly influences the increment of tree-ring width. The formation of narrower tree rings is caused by water stress, due to a lack of precipitation. The drought can lead to a decrease in net photosynthesis, a slower movement of nutrients and growth control, and thus cell increases and divisions [5]. However, adequate precipitation allows for plants to utilize the nutrients they need for growth during the initial tree-ring formation. In the case of spruce, precipitation during the growing season is more of a limiting factor at low and middle altitudes [35].

Precipitation during the growing season of the precedent year also influences the vitality of the roots in spruce, which has shallow roots and is therefore very susceptible to drier condition [36], as well as the production capacity in the subsequent year [35]. A positive correlation between precipitation and increments of tree-ring width was discovered for May–September in another location near Drahanská vrchovina (Drahany Highlands) [37]. In Europe, many similar studies have shown comparable results concerning the positive influence of rainfall on the radial increment of Norway spruce during the summer period or in only one of the summer months, e.g., in the Rhone valley (Valais, Switzerland), Reference [38] found the highest correlation with June precipitation for chronology sites in a colinear belt. In the Sławno forest district in Western Pomerania, the diametric increment of Norway spruce was found to be influenced by summer rainfall. Reference [12] discovered that the increment of the spruce is positively correlated with precipitation from May to July in northern Polish sites, whereas [5] discovered that diametric increments only show positive statistically significant values with (average monthly) precipitation from May to August of the current year in the southeastern part of the Českomoravská vrchovina (Bohemian–Moravian Highlands, Czech Republic).

In all sites, temperatures for September had a negative relation with radial growth. Similar results were observed in the central part of the Českomoravská vrchovina [35], in Archangelsk [39], in the Romanian Carpathians [40], and in Norway [41]. During the growing season, high temperatures cause moisture stress with a consequent reduction in the tree rings [39,42–44]. This not only appeared in the year in which the moisture stress occurred, but also in the subsequent year [5]. An increase in the monthly average temperature of more than 3 °C is also considered to be risky [45,46]. Higher temperatures increase evapotranspiration, and plants react to this problem with stomatal closure and the reduction in net photosynthesis. All these strategies are implemented to minimize water losses [47].

4.2. Dynamics of Radial Growth and Pointer Years

In all examined forest stands, radial increment descriptions showed that 1964 was the year with the least growth. Interestingly, this result can be explained by the precipitation data from 1963; for Karlstejn and Cukrak, the total precipitation was 518 mm, while that for Kostelec totaled 581 mm (these values are not sufficient for spruce growth since the total annual precipitation must exceed 800 mm for spruce) [5]. For the Karlstejn site, 1964 was the year with lowest growth, next to 2017; this result can be explained by the results reported by [48], which document that, since mid-July 2017, many countries in Europe have been affected by prolonged drought.

Additionally, 1976 was a year of exceptional dryness and low growth. This result was confirmed by [38] at colinear sites in the Rhone valley in Switzerland, and by [49] in the lowest elevations of the French Alps (Tarentaise and the Maurienne). In French study sites, 1976 was especially dry from March to June, with prolonged water stress damage. This was also reported by [50] from the low-elevation zone of the Šumava Mountains (Czech Republic). It is presumably connected with insufficient rainfall during the growing season (primarily in May and June).

Our study indicates that the growth of spruce is mainly related to precipitation. This result was also found by other authors, e.g., by [12] in the Polish lowlands, and by [51] in the German lowlands. Furthermore, a phenomenon linked to drought affecting spruce forests is the development of the bark beetle (*Ips typographus* L.) epidemic, which recently caused spikes in Central European spruce mortality [52], particularly, in the Czech Republic, which became Europe's epicenter for the spruce bark beetle epidemic [53]. This insect is considered the most destructive pest for spruce, which can lead to extensive forest mortality since its rapid spread is exacerbated by the drought phenomena [54] caused by low precipitation and high temperatures [55].

The growth of spruce on research plots ranged from 1.69 to 1.84 mm, with the highest radial increments were found at the plot with the best soil water supply (Kostelec), and the lowest at the site with limestone soil (Karlstejn), which confirms that spruce prefers predominately cool and humid climatic conditions [56,57]. Drought leads to the destruction of forests in the region [58]. This phenomenon, in combination with other factors such as climate change and the consequent damage by bark beetles, has caused the greatest damage to Czech Republic's forest sector, leading to the loss of about 1.12 billion EUR in forests [9].

5. Conclusions

Dryness can be considered a new phenomenon in Central European forests, and it is considered the main cause of development of mass epidemics of bark beetle and the decay of Norway spruce forests, especially at lower altitudes. This was confirmed by the research results, focusing on the relationship between climate and spruce increments in Central Bohemia at an altitude between 319 and 425 m a.s.l. The results confirm that, at low altitudes, precipitation is the primary factor that affects spruce growth. The radial increment in spruce for all sites shows a statistically significant positive correlation with precipitation during the growing season, while temperature negatively effects growth in the studied forests. Furthermore, tree-ring chronology indicates a small increase for the years 1964 and 1976 for all plots, and the years with small increases were also confirmed by the negative pointer years' analysis. This study could improve the forest research on Norway spruce at low altitudes in the Czech Republic during climate change. Similar studies are essential to understand the natural processes that affect Central European forests at present, especially Norway spruce.

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