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Pilot study on the effect of slope aspect on growth dynamics and drought response of Norway spruce (*Picea abies* [L.] H. Karst.) in low-elevation temperate forests

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Abstract

In general, slope aspect modifies the phenology and growth dynamics of trees in temperate forests of Central Europe. This study investigates radial growth dynamics and phenology of Norway spruce (*Picea abies* [L.] H. Karst.) in two forest stands with contrasting slope aspect (north vs. south) located in low-elevation temperate zones. Using automatic dendrometers, stem diameter variations and growth phenology were monitored throughout the 2025 growing season, complemented by continuous measurements of volumetric soil moisture. Pilot results indicate that trees on north aspect slope initiated growth earlier, maintained a longer growing season, and achieved greater radial increments compared to those on south aspect slope. The factor of this differential growth response was probably higher soil water availability on northern aspects, which buffered the effects of summer drought. The findings highlight the importance of microclimatic conditions (temperature, available soil moisture, and soil properties) shaped by topography in regulating the phenology and growth dynamics of Norway spruce. They further suggest that north-facing slopes may hypothetically serve as microclimatic refugia for the Norway spruce cultivation at lower elevations under climate-change conditions. However, the local and pilot nature of this study limits the extent to which broader generalizations can be made.

Key words: radial growth; drought response; topographic aspect; Norway spruce

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1. Introduction

Climate change significantly affects the length of the growing season in European forest ecosystems, as well as in individual tree species (Menzel et al. 2006). Due to rising temperatures, the onset of the growing season is shifting to earlier spring days and extends into late autumn (Menzel & Fabian 1999), thereby prolonging the growing period and potentially increasing forest productivity and seasonal carbon uptake by trees (Pretzsch et al. 2014; Zani et al. 2020). However, this temperature increase is accompanied by a growing water deficit during the growing season, driven by enhanced evapotranspiration and increasing frequency and intensity of drought events (IPCC 2014; Rožnovský et al. 2020). Reduced water availability limits tree growth (Bose et al. 2021; Montibeller et al. 2022; Kasper et al. 2023), which contradicts the potential productivity gains associated with a longer growing season (Buermann et al. 2018). For instance, Matula et al. (2023) demonstrated such productivity decline due to drought induced by elevated temperatures in eight European tree species. In light of these findings, forest managers must carefully consider species composition during forest regeneration, taking into account local microclimatic site variations.

Topography can substantially modify macroclimatic characteristics (Daly 2006). One approach to identifying microclimatic "refugia" as defined by Stark & Fridley (2022) for cold-adapted species is to exploit slope aspect, which can mitigate the impacts of global climate change through its microclimatic differences (Stark & Fridley 2022) (Slavich et al. 2014; Barnard et al. 2017), thereby influencing the distribution ranges of individual tree species (Kusbach et al. 2023). Norway spruce (*Picea abies* [L.] H. Karst.), as a species of montane origin, is relatively demanding in terms of water availability (Úradníček et al.

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2010). However, not only in the Czech Republic, this tree species has spread to lower altitudes for reasons of better production. Nowadays, Norway spruce has suffered significantly from recurring droughts in the Czech Republic, which have emerged as a primary ecological factor driving large-scale decline of managed Norway spruce stands (Čermák et al. 2019). Therefore, further cultivation of Norway spruce at lower altitudes is risky, mainly due to lower moisture availability during the growing season (Popa et al. 2024). Precipitation is the main limiting factor for the growth of Norway spruce at elevations of 319–425 m a.s.l. in the Czech Republic (D'Andrea et al. 2022). From a scientific perspective, it is widely accepted that Norway spruce at elevations around 350 m a.s.l. has not long term future in Central Europe (Čermák et al. 2021; Kermavnar et al. 2023) and forest management should therefore aim to replace it with tree species that are more tolerant to drought and heat. Although Norway spruce is not suitable for widespread cultivation at lower altitudes, its targeted preservation on limited areas can be beneficial from ecological, landscape, and forestry perspectives. It is important that Norway spruce is grown under these conditions consciously and with a clear purpose, and that it does not become the dominant tree species in areas with elevated risks of drought, wind damage, or bark beetle infestation. In such cases, it is appropriate to focus attention on sites with favourable microclimatic regimes that have not yet been sufficiently explored (De Frenne et al. 2021).

The aim of this study is therefore to determine whether selected microclimatic environmental factors specifically soil moisture can explain radial stem diameter changes in Norway spruce indicative of drought stress, comparing extremely contrasting south- and north slope aspects within the low-elevation Norway spruce forest stands.

2. Material and methods

2.1. Study site

The study was conducted in two forest stands with different aspect located in the temperate zone of Central Europe. The dominant tree species is Norway spruce. The stands were chosen to ensure similar elevation, comparable site conditions, and proximity of stands (aerial distance between stands was 1.7 km). The research area is situated within the cadastral territory of the municipality of Dobruška in the Hradec Králové Region, Czech Republic (Fig. 1, Table 1). These are mixed forests at low elevations, featuring small-scale stands of Norway spruce monocultures. The forest structure description of the studied stands is provided in Table 1.

For the climatic characterization of the study area in 2025, data from the meteorological station (manufacturer: Libor Deneš) operated by the Forestry and Game Management Research Institute (VÚLHM) in Opočno were used. The station is situated approximately 3 km from the studied forest stands and operates in accordance with the standards of the Czech Hydrometeorological Institute.

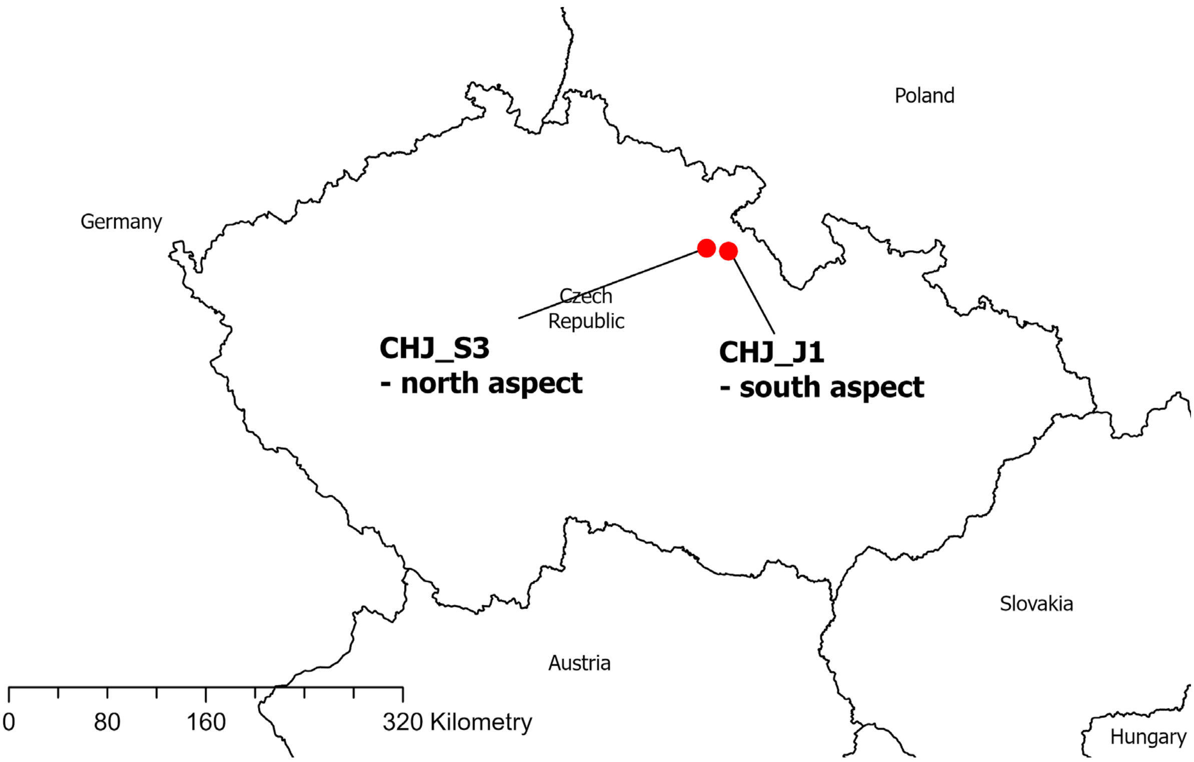

Fig. 1. Localization of the study forest stands.

Table 1. Characteristics of study Norway spruce forest stands. FSTC – forest site type complex according to Viewegh et al. (2003). DBH – diameter at breast height, H – height, BA – basal area, CPP – crown projection area.

Attributes	South aspect	North aspect
Species	Norway spruce	Norway spruce
Latitude (°N)	50°16'16.437"N	50°15'59.623"N,
Longitude (°E)	16°9'32.926"E	16°10'48.583"E
Altitude (m a.s.l.)	335	340
Slope inclination (°)	17	22
FSTC	*Querceto-Fagetum eutrophicum*	*Querceto-Fagetum illimerosum trophicum*
Age	43	46
∅ DBH (mm)	167	158
∅ H (m)	15.9	16.3
BA (m^2)	55.8	58.9
CPP (m^2)	12,728.6	20,886.4
Number of stems	144	121
Number of species	5	6

The investigated stands are characterized by different soil-typological units, which differ not only in their water-holding capacity but also in their respective soil hydrolimits. The south-facing site is characterized by the soil taxonomic unit dystric, luvic Cambisol with the humus form humimor. The north-facing site is characterized by the soil taxonomic unit pelic, leached, melanistic, mesobasic, eutrophic Cambisol with the humus form moder. The most relevant hydro-physical soil parameters of the study forest stand are provided in Table 2.

2.2. Data collection

Measurement of stands structure was conducted using the Field Map technology (IFER Ltd.), a hardware and software platform designed for efficient, computer aided field data acquisition and processing. Stand structural attributes including tree position, tree species, diameter at breast height, total tree height, and crown projection area were recorded within a circular plot of 500 m^2.

To monitor tree growth, growth dynamics, and phenology, a total of ten automatic point dendrometers (TOMST, Prague, Czech Republic) were installed in 2024. In each stand, five healthy dominant trees with crowns in the main canopy layer were selected. Dendrometers were mounted on the north aspect side of each tree at a height of 1.3 m above ground level, with bark carefully removed at the measurement point. The tree groups in both stands were growing on a slope, where the occurrence of asymmetric stem growth was therefore likely. Because slope-induced stem eccentricity is primarily determined by the inclination of the terrain, standardizing the orientation of the point dendrometer on the stem relative to the slope minimized this effect. From the time of installation (July 2024), the dendrometers recorded stem radius changes automatically at an hourly recording and resolution of 1 µm, storing the data in internal dataloggers. Devices were regularly checked for malfunctions, and data were retrieved after the end of the growing season (August 2025). For this study, data from the 2025 growing season were used. Raw stem radius data (RadStem) downloaded from the dendrometers were inspected and corrected for erroneous measurements (e.g., abrupt shifts due to maintenance or adjustments). The data were then aggregated into daily averages using the PLOTeR package (version 1.0.4) in the R statistical software (R Core Team 2022). This package was used to derive the variables listed below.

To quantify differences in growth phenology and radial growth between the studied stands, the following variables were calculated: start of growing season (GS_start), end of growing season (GS_end), length of the growing season (GS_length), cumulative daily growth (GRO), total annual stem increment (GROts), daily growth rate model (GRm), and maximal daily growth rate model (maxGRm). All parameters were calculated for individual trees equipped with dendrometers, and subsequent analyses were based on the mean values of these parameters computed for each of the studied stands. The above variables were derived from the data using the PLOTeR package, except for the TWD parameter, which was calculated using the zero-growth concept (Zweifel et al. 2016). The TWD indicates stem shrinkage and reflects the amount of water deficit in the tree, serving as a proxy for drought stress. TWD is computed as the difference between the current stem radius and the previous maximum radius (Zweifel 2016). The reason for using the PLOTeR package was that the zero-growth (ZG) concept does not account for volume changes in bark tissues associated with cell collapse; stem shrinkage is therefore attributed solely to reversible changes in the turgor pressure of living cells. When applied strictly, ZG may lead to a delayed detection of the onset of the growing season (i.e. activation of the secondary cambium) in some species or individuals compared to the actual phenological timing. To reduce this potential bias, the PLOTeR package identifies the start and end of the growing season as the first and last day when stem growth exceeds a user-defined minimum growth rate (typically 1–2 µm day^{-1}). Because dendrometer records contain pronounced short-term fluctuations, daily growth rates are smoothed using a 14-day simple moving average with a 1-day step, a commonly applied approach that effectively preserves overall growth dynamics while suppressing noise. The window length was selected based on sensitivity testing and literature evidence e.g., Etzold et al. (2022). Periods potentially affected by freeze-induced shrinkage are excluded, and the detection is constrained to the interval between 5% and 95% of total cumulative growth. Optionally, a GAM model can be applied for additional smoothing. Final estimates of the growing season onset and cessation are verified visually using growth rate and cumulative growth plots. The detection of growing season phases was already used in study Matula et al. (2023). RadStem and GRO were also derived based on the method

Table 2. The hydro-physical soil parameters of study Norway spruce forest stands. CSH – classification of soil horizons.

Atribut	South aspect				North aspect			
CSH	Ah	Bvt	Bv/Cr	Cr	Am	Bvp	Bvp/Ck	Ck
Wilting point (%)	7.9	7.1	skeletal material	skeletal material	16.5	17.4	25.8	skeletal material
Water retention capacity (%)	19.3	18.8	skeletal material	skeletal material	36.7	34.5	40.6	skeletal material
Bulk density (g/cm)	1.1	1.2	skeletal material	skeletal material	1.1	1.2	1.3	skeletal material
Available water (mm per 20 cm of soil depth)	22.8	23.2	skeletal material	skeletal material	40.4	34.1	29.6	skeletal material

14-day simple moving average with a 1-day step. The GRm data were smoothed using a generalized additive model (GAM) with cubic regression splines (s(bs='cs')) and a basis dimension (k) set to 25. This setting was chosen so that the GAM could sufficiently smooth the noise in the daily GRm data while still capturing the main seasonal and short-term changes in growth dynamics; cubic regression splines provide a smooth curve without unrealistic oscillations, and the basis dimension (k = 25) represents a compromise between model flexibility and the risk of overfitting. The maxGRm was determined by identifying peak GRm values for each dendrometer and calculating the average maxGRm per stand.

Soil volumetric water content (VWC) as well air and soil temperature (Fig. 3) was measured using automatic MeteoUNI (AMET) meteorological stations equipped with three VIRRIB (FIEDLER) sensors. The sensor is used to measure soil VWC at any depth and was placed in duplicate in each of the two stands. Meteorological stations were placed interior of both studied forest stands. Given that stand density was comparable at both sites, the meteorological stations were positioned to maintain an average distance from surrounding tree stems, always placed centrally relative to neighbouring individuals. The architecture and spatial distribution of the Norway spruce rhizosphere inherently conditioned this methodological approach, particularly with respect to rooting depth, which is strongly influenced by the species' fine-root system (1–2 mm). Measurements were taken at 15-minute intervals and regularly transmitted to a web server. Soil moisture was monitored at depths of 10, 20, and 50 cm. Sensors were installed horizontally at the corresponding soil depths and placed within the fine soil fraction layer (< 2 mm) to ensure optimal contact with the soil matrix. As a complement to each stand, soil samples were taken from both stands to determine the hydro-physical parameters of the soils. As a complement to each stand, soil samples were taken from both stands to determine the hydro-physical parameters of the soils. The soil analyses and hydrolimits were determined in the laboratory using a standard methodology (Kutílek 1978; Kutílek & Nielsen 1994; Carter & Gregorich 2008; Vavříček & Kučera 2024).

2.3. Data analysis

To statistically evaluate tree growth and phenology data in relation to slope aspect (i.e., tree groupings), normality of the data was assessed using the Shapiro-Wilk test separately for each group of trees equipped with dendrometers. If both groups exhibited normal distribution and homogeneity of variance was confirmed via Levene's test, a two-sample t-test was applied. In cases where normality was violated in at least one group or variances were significantly different, the non-parametric Wilcoxon test was used. Furthermore, correlation analyses were conducted between the length of the growing season, total annual stem increment, and maximum daily growth rate using either Pearson's or Spearman's correlation test, depending on the distribution of the data. To support the assumption that soil moisture represents the important factor of radial growth, we additionally fitted a simple linear model relating GRm to VWC. For each stand, GRm were regressed against corresponding VWC values from three soil depths. The results were supplemented with graphical outputs in the form of boxplots and scatter plots, which enabled visual comparison between slope aspects, as well as tabular outputs of statistical analyses. All statistical analyses were performed using the R software environment (R Core Team 2022).

3. Results

3.1. Evaluation of meteorological and soil measurement results

The average annual temperature in 2025 was 9.8 °C. The warmest month was July (average temperature 19.2 °C), while the coldest was February, with an average temperature of –0.2 °C. The total annual precipitation in 2025 was 569 mm. The long term mean air temperature and precipitation (period 2001–2024) are 9.8 °C and 569 mm, respectively (long-term mean are practically identical to the values from 2025). The development of monthly summaries of precipitation and temperature is shown in Figure 2.

The seasonal dynamics of air and soil temperature differed slightly between the two Norway spruce stands with contrasting stand aspect (Fig. 3). The north-facing stand exhibited a slightly higher mean annual air temperature (9.2 °C) compared to the south-facing stand (8.8 °C), although short-term fluctuations were largely synchronous in both sites. Soil temperature showed a smoother temporal course with lower short-term variability than air temperature. In contrast to air temperature, the south-

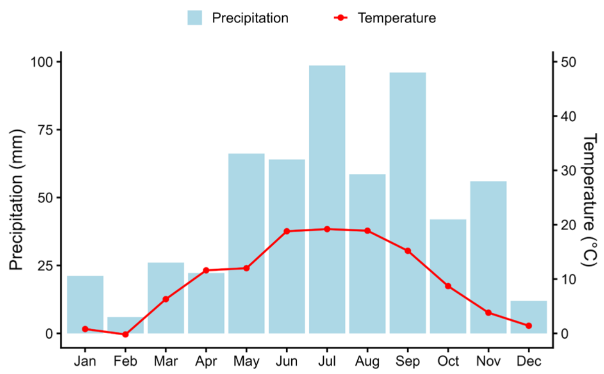

Fig. 2. Trends in average monthly precipitation and temperature for the year 2025.

facing stand had a higher mean annual soil temperature (10.9 °C) than the north-facing stand (10.4 °C). The seasonal increase in soil temperature lagged slightly behind the rise in air temperature in spring, and similarly, soil cooling in autumn was more gradual. Overall, both stands displayed comparable temporal patterns, with modest but consistent differences in mean values associated with stand aspect.

The seasonal course of VWC content differed markedly between the north- and south-facing Norway spruce stands and among soil depths (Fig. 4). In the north-facing stand, VWC was generally higher and more stable throughout the year, particularly at 50 cm depth. At the beginning of the year, VWC ranged approximately

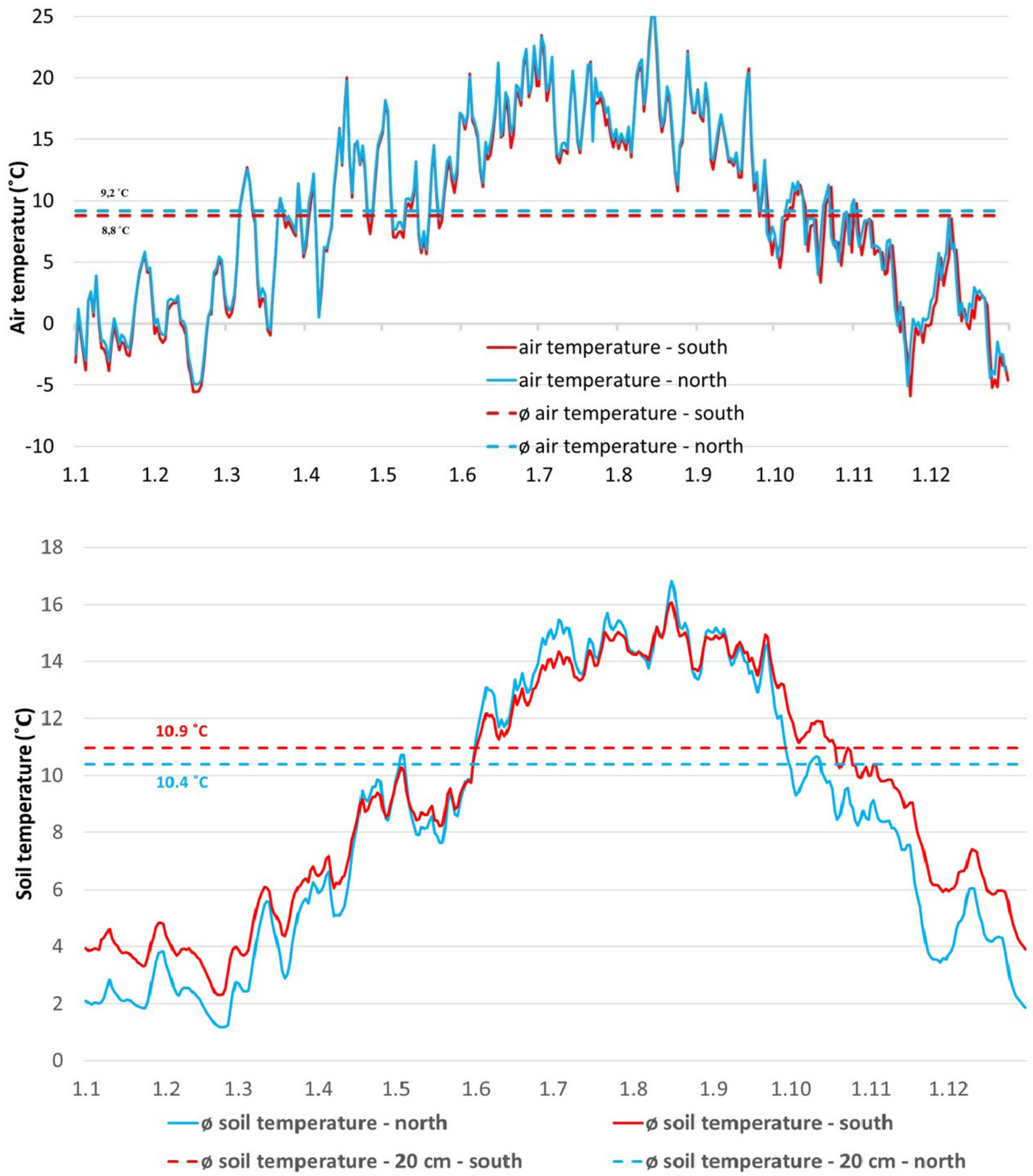

Fig. 3. Comparison of daily mean air and soil temperatures in forest stands with different slope aspects.

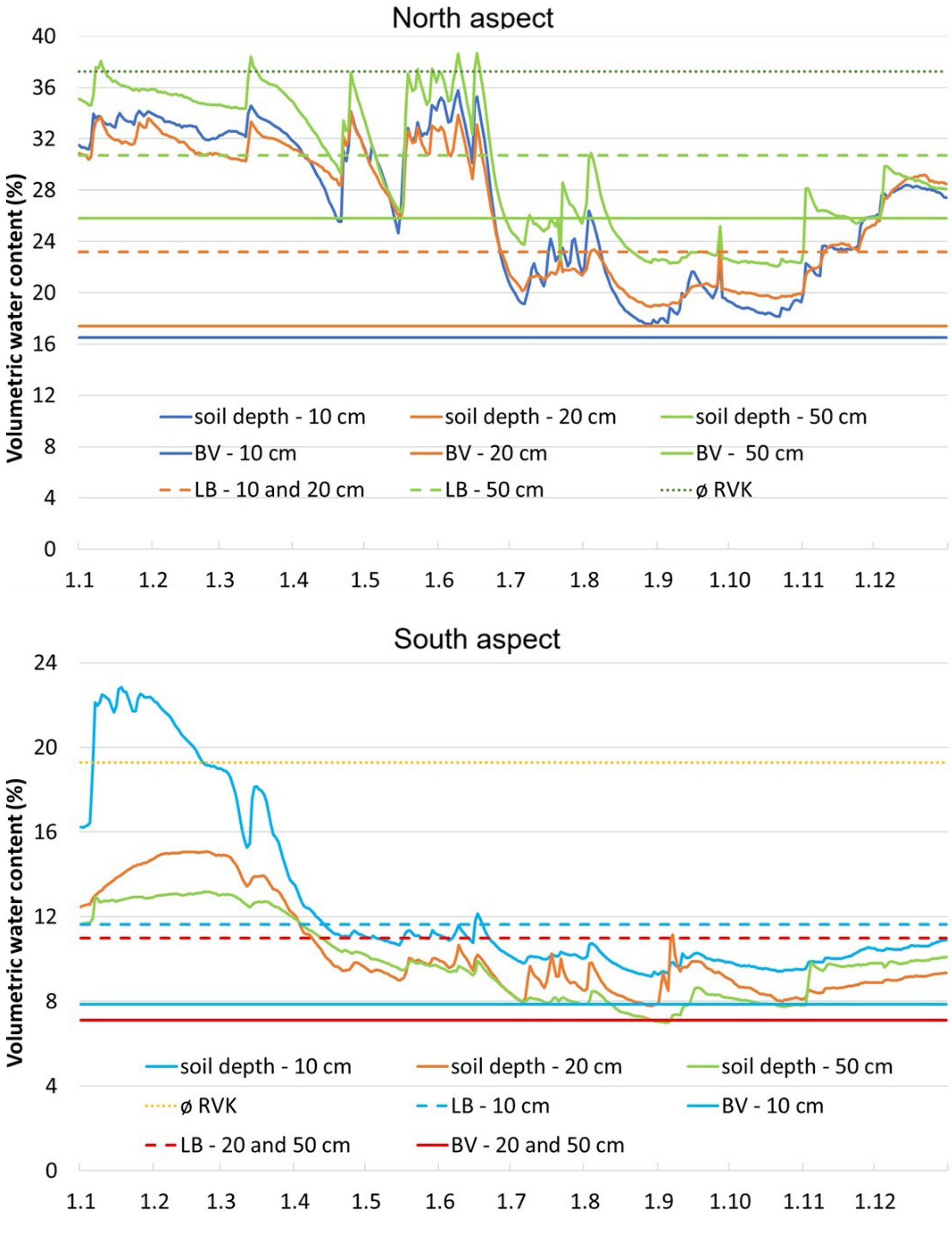

Fig. 4. Soil volumetric water content (VWC) in Norway spruce stands with different slope aspect. BV – wilting point, LB – lentocapillary point indicating the onset of drought, soil water retention capacity.

between 31–34% at 10 and 20 cm and reached up to 36–38% at 50 cm. A pronounced decline occurred in late spring and early summer (around June–July), when moisture at 10 and 20 cm decreased to about 19–22%, while the 50 cm layer dropped more moderately to approximately 24–27%. During late summer and early autumn, VWC approached or temporarily fell near the lower boundary values lentocapillary point (LB). Recovery of VWC was observed in autumn (October–December), with all depths showing a gradual increase toward winter values.

In contrast, the south-facing stand exhibited substantially lower VWC and greater susceptibility to drying. A rapid and pronounced decline occurred from spring to early summer. At 20 and 50 cm depth, VWC frequently approached the lower boundary LB. Compared to the north-facing stand, the deeper soil layers in the south-facing stand did not provide a substantial moisture buffer, and differences among depths were smaller. A partial recovery of VWC occurred in autumn; however, values remained considerably lower than those recorded in the north-facing stand.

3.2. Evaluation of growth phenology

A statistically significant difference in the onset of growth was observed when comparing the growth phenology of Norway spruce between the studied site (Table 3). Trees in the north aspect stand initiated growth 8 days earlier than those in the south aspect stand, although growth cessation occurred on nearly the same day in August (Table 4). The length of the growing season at north aspect site lasted 88 days, whereas at the south aspect site it was 10 days shorter. Norway spruce trees at the northern site ceased growth in early August, coinciding with the onset of a drought period at the turn of June and July and with severe drought conditions in August (Fig. 4).

3.3. Norway spruce growth and derived parameters

A statistically significant difference in the mean total annual stem increment (GROts) was confirmed between the studied sites (Table 3, Fig. 5). Trees in the south aspect stand exhibited an average stem diameter increment of approximately 900 μm during the growing season, whereas trees in the north aspect stand achieved an increment of approximately 1,700 μm – nearly double (Fig. 5). Cumulative daily growth (GRO) was consistently higher in the north aspect stand from the beginning of the growing season compared to the south aspect stand (Fig. 6). Analysis of the daily growth rate model (GRm) revealed that Norway spruce trees on the north aspect slope maintained higher growth rates throughout the entire growing season (Fig. 6). Peaks in GRm occurred in June for both slope aspects, although with differing amplitudes. Maximum daily growth rate (maxGRm) was significantly higher ($P \leq 0.001$; Table 3, Fig. 5) in the north aspect stand (12.09 ± 1.53 μm day^{-1}) compared to the south aspect stand (6.92 ± 1.55 μm day^{-1}). On average, maxGRm occurred 25 days earlier in the

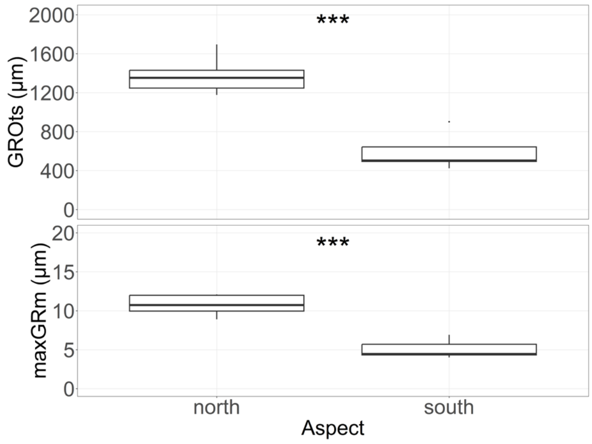

Fig. 5. Average annual stem increment (GROts) and maximum daily growth rate (maxGRm) on north- and south-facing slopes. *** – statistically significant difference between groups, p < 0.001.

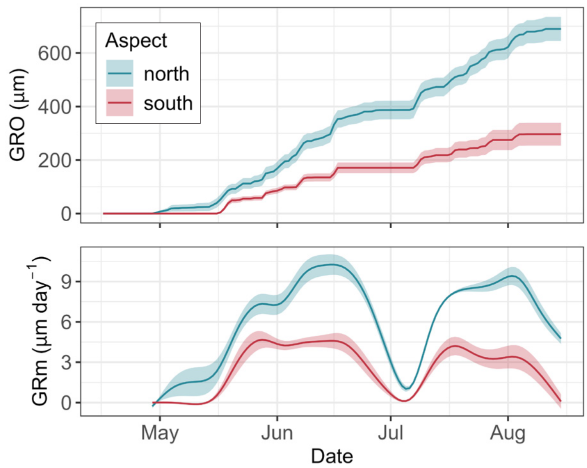

Fig. 6. Cumulative daily growth (GRO) and model of daily growth rate (GRm) of Norway spruce under different slope aspect. The lighter zones of lines represent the 95% confidence intervals.

Table 3. Results of statistical analyses. 95% CI – confidence interval of the difference. Statistically significant differences are highlighted in bold.

Test	Test statistic	Degrees of freedom / n	p-value	95% CI	Variable description
t-test	t = 6.3654	df = 7.974	**0.0002**	[501.9, 1072.7]	north vs south GROts
t-test	t = 6.9598	df = 7.521	**0.0001**	[3.771, 7.521]	north vs south maxGRm
Wilcoxon test	W = 25	n = 10	**0.0110**	—	north vs south GS_length
Wilcoxon test	W = 0	n = 10	**0.0100**	—	north vs south GS_start_doy
Wilcoxon test	W = 19	n = 10	0.1210	—	north vs southGS_end_doy
Pearson correlation	t = 0.827	df = 3	0.4680	[–0.728, 0.951]	GS_length vs GROts – north
Pearson correlation	t = 2.968	df = 3	0.4750	[–0.731, 0.951]	GS_length vsGROts – south
Spearman correlation	S = 21.05	n = 5	0.933	—	GS_length vs maxGRm - north
Spearman correlation	S = 10.76	n = 5	0.433	—	GS_length vs maxGRm - south

Table 4. Growth phenology data of Norway spruce in sites with different slope aspect. GS_start – start of the growing season, GS_end – end of the growing season, GS_length – length of the growing season. Doy – day of the year.

Aspect	GS_start (doy)	GS_end (doy)	GS_length (days)
south	137	215	78
north	129	216	88

south aspect stand than in the north aspect one. Neither maxGRm nor GROts showed significant correlations with the length of the growing season for either slope aspect (Table 3, Fig. 7).

The course of volumetric water content (VWC) was, on average, 14 percentage points higher in the north aspect stand (Fig. 4) in soil depth 10 cm. Despite this, both stands experienced a decline in VWC. The dry period occurred at the turn of June and July in north aspect and at the turn of April and May in south aspect. A more pronounced drop in VWC was observed in August, even in the north aspect stand, where the soil had been relatively well-supplied with water since January. The decrease in VWC during the drought period led to tree stress, as illustrated in Fig. 8. The linear model assessing the effect of VWC on GRm revealed a statistically strong positive relationship between soil moisture and growth at the 10 and 50-cm measurement depth in both stands (Table 5). This relationship was not statistically significant in the soil depths 20 cm in south aspect.

The calculated parameter TWD (tree water deficit), which indicates stem shrinkage and reflects the amount of water deficit in the tree, showed a marked decline during late June and early July, particularly in the south aspect stand (Fig. 8). This may indicate severe drought stress in trees and corresponds with the drop in VWC close to the wilting point observed in both stands. In Norway spruce trees at the south aspect site, growth did not fully recover following this drought episode.

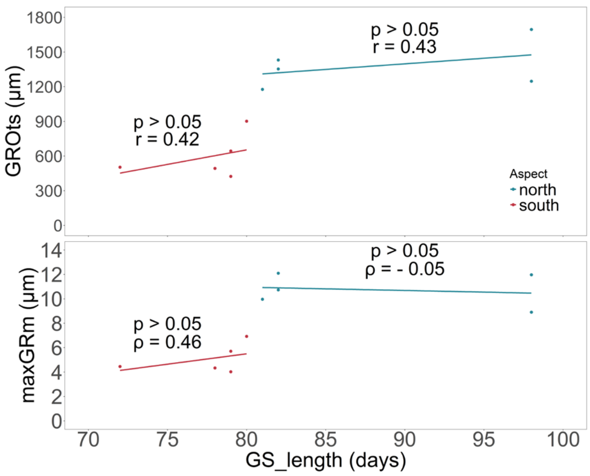

Fig. 7. Relationship between total annual stem increment (GROts) and maximum daily growth rate (maxGRm) with the length of the growing season (GS_length) and slope aspect. No statistically significant correlations were found. r – value of Pearson's correlation coefficient, ρ – value of Spearman's correlation coefficient.

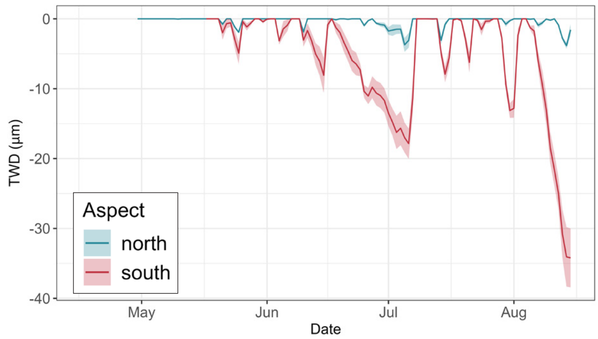

Fig. 8. Development of the tree water stress indicator (TWD) of Norway spruce depending on slope aspect. The lighter zones of lines represent the 95% confidence intervals.

4. Discussion

In general, the long term cultivation of Norway spruce at low elevations lacks viability under current climate change conditions, as widespread stand decline has been observed (Čermák et al. 2021; Kermavnar et al. 2023). Soil moisture dynamics are logically dependent on the temporal distribution of precipitation; however, precipitation totals in recent years have shown pronounced variability. Moreover, Norway spruce stands have been secondarily affected by outbreaks of the Norway spruce bark beetle as a consequence of episodic drought events. In the context of climate change and an increasing risk of extreme droughts during the 21st century, this finding has important implications for forest management activities since the risk of drought induced tree mortality appears to be affected by soil conditions (Rehschuh et al. 2017).

It was found that trees in the north aspect stand initiated growth 8 days earlier than those in the south aspect stand, although growth cessation occurred on nearly the same day in August. The north aspect site exhibited

Table 5. Effects of soil volumetric water content (VWC) predictors on daily growth rate model (GRO rate) – linear regression model. 10 cm – soil volumetric water content at a depth of 10 cm, 20 cm – soil volumetric water content at a depth of 20 cm, 50 cm – soil volumetric water content at a depth of 50 cm. Bold p-values indicate a statistically significant test result.

Predictor	Aspect	Estimate	Std. Error	t-value	p-value
Intercept	north	4.757	1.051	4.527	**≤ 0.005**
10 cm	north	0.426	0.142	2.984	**≤ 0.005**
20 cm	north	–1.176	0.148	–7.933	**≤ 0.005**
50 cm	north	0.711	0.096	7.344	**≤ 0.005**
Intercept	south	–11.276	3.156	–3.572	**≤ 0.005**
10 cm	south	–2.919	0.704	4.145	**≤ 0.005**
20 cm	south	–0.071	0.380	–0.188	≥ 0.050
50 cm	south	–1.585	0.386	–4.107	**≤ 0.005**

significantly higher volumetric soil moisture, providing trees with greater water availability at the onset of growth. The higher spring soil moisture in the forest stand with a north-facing aspect may be attributed to the longer persistence of the snowpack. Soil temperature at a depth of 20 cm which is used for the indicative assessment of the forest vegetation zone during the period from March to November (Plíva 1971), corresponded with the typological classification of the forest site unit and matched the designation of the 3rd forest vegetation zone. Soil temperature differed significantly between the north and south facing sites. During the March–November period, the difference was approximately 0.6 °C, and over the entire year it reached about 1 °C. These differences are substantial and confirm the strong influence of slope aspect on the soil temperature regime beneath a Norway spruce canopy, with more ecologically favourable conditions for Norway spruce occurring on the north-facing slope. Air temperature was higher at the northern site, which also contributed to the phenological differences observed between the two locations. These differences were driven primarily by annual minimum air temperatures on the south-facing slope (5.0 °C – mean of monthly minimum air temperatures (mean Tmin), slope inclination 17 °), which were considerably lower than those at the north-facing slope (5.9 °C – mean Tmin, slope inclination 22 °), particularly during winter. Conversely, annual mean maximum air temperature was consistently higher on the south-facing stand (13.0 °C mean of monthly maximum air temperatures – mean Tmax) compared with the north-facing stand (12.4 °C – mean Tmax), particularly during the summer months. The specific microclimate of both sites is strongly shaped by the dominant tree species, Norway spruce, whose characteristic stand structure and humus forms in monocultures modify both soil and stand microclimatic conditions.

The above findings – soil moisture patterns, soil temperature regimes, and both mean monthly maximum and minimum air temperatures (annual) are fully consistent with the observed phenological phases of the respective sites. Matula et al. (2023) reported a 10–15 day longer growing season for Norway spruce at a thermally similar but precipitation-divergent site, with an earlier onset of growth. Barnard et al. (2017) observed that coniferous species in the mountainous regions of Colorado had up to 21 days longer growing seasons on south aspect slopes. While this pattern generally applies to montane environments, our study suggests that in lower elevations, certain species may benefit from north aspects under specific conditions. This can be supported by the hypothesis of the formation of microclimatic refugia (Stark & Fridley 2022) favourable for cold-adapted tree species such as Norway spruce. More favourable conditions (especially smaller fluctuations in climatic characteristics) of northern aspect for the growth of trees at lower altitudes have also been confirmed by beech forests in southern Europe (Rita et al. 2021). These findings highlight the complex interactions between topography and environmental conditions in shaping tree growth and phenology (Bruening et al. 2017; Tran et al. 2017). The identical timing of growth cessation does not agree with previous studies indicating that the end of the growing season is primarily governed by temperature or photoperiod (Kramer et al. 2000; Rossi et al. 2007). Since plants perceive photoperiod through direct, diffuse, and reflected light (Holmes & Smith 1977), it is unlikely that slope aspect plays a significant role in determining the end of the growing season. Soil temperature, which was similar in August, could also be a controlling variable determining the cessation of tree growth. The growing season was 10 days longer in the north aspect stand, which may be attributed, among other factors, to higher soil moisture – on average 14 percentage points greater than in the south aspect stand.

Previous studies have identified the timing of spring growth initiation as a key determinant of annual radial growth (Rossi et al. 2013; Oberhuber et al. 2014) and have shown that this timing can shift in response to mean annual temperature (Sullivan et al. 2015). This is consistent with our results. Therefore, the earlier onset of growth in the north aspect stand, coupled with higher volumetric soil moisture (VWC), likely contributed to the greater cumulative growth (GRO) observed. This is further supported by Barnard et al. (2017), who reported a positive correlation between growing season length and basal area increment. Climate and tree competition are critical factors affecting tree growth (Fan & Gheyret 2025). Competition with neighbouring trees represents an important biotic factor modulating radial growth, with its impact often depending on a combination of species-specific traits and site conditions. Analyses of extensive datasets indicate that competition can substantially restrict growth, particularly in light demanding species, for which the importance of competitive interactions remains high even at low stand densities. At the same time, the relative influence of competition varies with resource availability (Kunstler et al. 2011). The influence of competition for Norway spruce, as a semi to shade-tolerant species, may not represent a major growth-limiting factor, although it can play a role, particularly on nutrient-rich sites.

Growth rate peaks (GRm) occurred during the same period in both slope aspects, however with different amplitudes. This suggests that GRm is more strongly influenced by the amount of available soil moisture and, in this context, by the soil's hydrophysical properties than by slope aspect. This hypothesis is supported by findings from Adams et al. (2014), who demonstrated a significant relationship between interannual precipitation variability and tree-ring growth, indicating that water availability can regulate radial growth rates. Some studies have identified peak radial growth in early July, with cessation in August (Seo et al. 2011; Cuny et al. 2012; Oberhuber et al. 2014). However, our findings differ, as

GRm peaked in mid-June, indicating an earlier growth culmination. The maxGRm occurred approximately 25 days earlier in the stand on the south-facing slope compared with the north-facing stand. This finding is surprising, particularly given the assumed advantage of northern aspect. Air temperature and soil-moisture development likely play a key role. South-facing slopes experience more rapid warming of both the air and the upper soil horizons in spring. However, due to higher evapotranspiration, the soil profile also dries out much more quickly on southern aspects. Norway spruce, whose root system is concentrated predominantly in the upper horizons, is therefore exposed to rapidly emerging water stress. This results in an early limitation of physiological processes related to radial growth most notably reduced xylem conductivity, decreased turgor, and constrained formation of new cell layers in the secondary xylem. As a consequence, the growth curve peaks early and subsequently declines sharply. Early season growth peaks have also been reported in previous studies from temperate regions of Europe (Etzold et al. 2022) and North America (Dow et al. 2022). Fig. 6 also illustrates a marked decline in GRm and near cessation of GRO during July, coinciding with a drought period characterized by an absence of precipitation, clearly visible in Fig. 4. During this dry spell, soil moisture in both stands dropped close to the critical wilting point. Following rainfall in the second half of July, growth rates and daily cumulative increments nearly returned to previous levels, but only in the north aspect stand.

Elevated water deficit reduces tree growth by inhibiting cambial proliferation and subsequent wood cell formation (Balducci et al. 2013; Körner 2015). Soil water deficit is often accompanied by heatwaves, which further exacerbate growth limitations and drought stress in trees (Teskey et al. 2015). Trees in the north aspect stand experienced less drought stress, likely due to higher VWC at the onset of the dry period, which prevented the decline in soil moisture from becoming a limiting factor for growth. Aspect is determined by a set of parameters that define it as a fundamental environmental factor shaping stand-level micro- and mesorelief conditions, and it cannot be generalized into a single conclusion indicating an unequivocal drought risk. The annual dynamics of VWC at both stands (aspects) follow a similar pattern. Even though the sorption–hydric capacity is lower at the south-facing site, its relation to the respective hydrolimits exhibits the same developmental trajectory as that of the north-facing site. Soil type plays a significant role in determining the amount of water available to trees (Mathys et al. 2014). The investigated stands are characterized by different soil typological units, which differ not only in their water holding capacity but also in their respective hydrolimits. These hydrolimits are essential for determining the hydric conditions of the soil profile with respect to water availability for trees. Moisture deficit in trees occurs when volumetric soil water content falls below the lentocapillary point, at which capillary pore continuity is disrupted, although part of the root system may remain hydrologically supplied. A critical risk arises particularly when soil moisture declines below the permanent wilting point, which represents a pronounced drought stress threshold (Rehschuh et al. 2017). At neither site was this limit reached during the 2025 growing season. Soil evaporation is strongly reduced by the canopy cover of the Norway spruce stand, as well as by the specific humus forms that develop under Norway spruce monocultures.

Norway spruce has a high shading capacity, substantially suppressing site level evaporation. Consequently, solar infrared radiation does not reach the soil surface directly, which significantly reduces soil evaporation and simultaneously moderates soil temperature. Besides the effect of aspect, this variable may also have contributed to the lower VWC dynamics in the stand on the south facing slope, where the crown projection area is smaller. For Norway spruce and its primary rhizosphere, the upper layer of the organo mineral and partly the mineral soil horizon is crucial from both nutritional and hydric perspectives. As indicated by the VWC graph, soil moisture dynamics at both sites were largely similar, and at no depth did soil water content fall below the permanent wilting point. During part of the growing season, soil moisture fell below the lentocapillary threshold but remained above the wilting point, defined by a matric potential of 2 MPa. When volumetric soil water content declines below the lentocapillary hydrolimit, root growth is stimulated toward hydrologically saturated pores. Daily stem increment dynamics were supported by the higher soil moisture levels, which on the north facing site remained within an optimal moisture range until late June.

5. Conclusions

The results of this pilot study indicate that slope aspect representing the complex of ecological factors probably influences the growth phenology and radial increment of Norway spruce in low-elevation temperate forest conditions. Trees on north aspect slopes exhibited earlier growth onset, a longer growing season, and higher daily and cumulative stem increments. Differences in growth dynamics were associated with higher volumetric soil moisture on northern slopes, which enabled trees to maintain growth even during periods of climatic stress. These findings support the hypothesis that north aspect slopes may serve as suitable microclimatic refugia for the cultivation of Norway spruce in regions increasingly threatened by drought. However, it is important to emphasize that growing Norway spruce at lower altitudes does not have a long-term perspective, also in the context of our findings, which indicate that soil moisture availability, together with the important related influence of soil type, appears to be a limiting factor for tree growth. Given the pilot character of this study and methodological limitations, further research across multiple sites and extended timeframes is recommended to gain deeper insights into the interactions between topography, soil, microclimate, and the physiological responses of forest tree species.

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