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Simulated bark stripping reduces stem growth in young Norway spruce: Evidence from continuous dendrometer monitoring

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Abstract: Norway spruce [*Picea abies* (L.) Karst.] is Europe's most important commercial tree species, whose stability, vitality, and production potential can be significantly compromised by cervids. Their populations in Europe have been growing over time. This study aimed to analyse the effect of simulated circumferential trunk damage – mimicking bark stripping by ungulates – on the diameter growth of young spruce trees through continuous measurements with point dendrometers at 15-minute intervals. Dendrometers were installed at two permanent research plots (PRPs) in the Lužické hory (Lusatian Mountains) and at another two PRPs in the Krušné hory (Ore Mountains) on spruce stands aged 16–21 years. At each PRP, 15 co-dominant trees were monitored; five served as undamaged control trees, while ten were experimentally damaged by removing bark over an area ranging from 5–90% of the trunk circumference. The most intense diameter growth occurred during an approximately 14-day period at the turn of May and June. The growth activity ceased on all PRPs during the second to third week of September. Even during the first growing season after the experimental damage, significantly lower diameter growth was observed in the evaluated trees when compared with undamaged control trees ($P < 0.05$). On PRP 2, undamaged trees achieved up to 87.8% higher growth than the damaged ones. Overall, the diameter growth of damaged trees was 37.9–43.2% lower than that of undamaged control ones, depending on the damage category, although no significant differences were found among the damage categories of 5–30%, 40–60%, and 70–90%, respectively. The results show that simulated bark damage can considerably reduce the diameter growth of young spruce trees as early as the first growing season, underscoring the importance of effective stand protection from harm caused by ungulates.

Keywords: climate change; game damage; Krušné hory; Lužické hory; *Picea abies* (L.) Karst.; red deer

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Global climate change has already led to widespread forest dieback throughout Europe and to the creation of large barren areas that are difficult to reforest. Paradoxically, forest ecosystems play a crucial role in mitigating the effects of climate change (Fetting 2020). As climate change progresses, trees' sensitivity to environmental factors – and to consequent pest outbreaks – is changing and, generally, increasing (Camarero et al. 2021; Vacek et al. 2023), which complicates the understanding and prediction of forest ecosystems' responses to altered environmental conditions (Luo et al. 2015). Furthermore, the sensitivity of radial increment to climatic factors can vary noticeably following periods of extreme drought or large-scale disturbances (Leifsson et al. 2023). In the short term, these changes may compromise forest resilience and heighten their vulnerability; over time, they can fundamentally alter species composition, jeopardise their stability, and undermine long-term forest management sustainability (Hanewinkel et al. 2013; De Marco et al. 2022; Vacek et al. 2023).

Among the most vulnerable tree species in Europe is the Norway spruce [*Picea abies* (L.) Karst.; Popa et al. 2024], which is also a key conifer from an economic and ecological standpoint (Zhou et al. 2020). At the same time, it is highly susceptible to climate extremes (Rybníček et al. 2010), particularly to prolonged drought (Zang et al. 2014; Vacek et al. 2023). Norway spruce's natural range extends from the European Alps through the Balkans and the Carpathians to northern Scandinavia and northern Russia (Sidor et al. 2015). Norway spruce is a conifer of continental climates; its optimal growing conditions are moist habitats with annual precipitation over 800 mm and an average annual temperature not exceeding 6 °C (Rybníček et al. 2012). Although Norway spruce remains an important commercial tree species, it is not considered ecologically sustainable at low and mid-altitudes, especially under conditions of climate change (Černý 2023; Remeš et al. 2020; Vacek et al. 2023). Over recent decades, Norway spruce has faced various health and growth problems (Sidor et al. 2015). The primary symptoms of Norway spruce decline are the yellowing and shedding of needles, reduced diameter growth, and subsequent die-off (Sidor et al. 2015; Putalová et al. 2019; Vacek et al. 2015, 2019, 2020a). The decline of spruce forests at lower and mid-altitudes is caused by high temperatures, low precipitation

totals, and their uneven distribution throughout the year (Schuldt et al. 2020; Patacca et al. 2022; Vacek et al. 2023; Grünig et al. 2026). Drought weakens spruce stands and increases their susceptibility to secondary pest attacks, primarily the bark beetle (Dudík et al. 2021; Hlásny et al. 2021; Potterf et al. 2025). Alongside wind disturbances, the bark beetle causes the most damage in spruce forests (Toth et al. 2020; Hlásny et al. 2021). In addition to climate change, the effects of acidification and nutrient depletion in forest soils may also play a role in the decline of Norway spruce (Borůvka et al. 2005). The relationship between climate, various disturbance types, and diameter growth in spruce forests has been studied in several European countries (e.g. Pichler, Oberhuber 2007; Cukor et al. 2019a, b; Vacek et al. 2020a; Rocha et al. 2021; D'Andrea et al. 2023; Potterf et al. 2026) because understanding these relationships is essential for assessing growth changes under prevalent environmental conditions and predicting their future development (Tumajer et al. 2017).

The impacts of global warming have so far been documented by numerous dendrochronological studies, which pointed to increased mortality (Cailleret et al. 2019), changes in carbon and water dynamics (Babst et al. 2019; Buras et al. 2023), and changes in long-term climate variability, identified through tree-ring analyses (Esper et al. 2016; Rocha et al. 2021). Tree rings represent a valuable indicator of long-term growth variability and its response to climatic conditions, showing climate variability across the growing season (Babst et al. 2018). Tree-ring analyses can significantly help to assess various types of harm to forest trees. However, interpreting the climatic signal captured in tree rings is complicated by the concurrent interaction of several factors. Diameter growth is simultaneously impacted by biotic and abiotic factors, such as air pollution (Vacek, Lepš 1987, 1996; Opała-Owczarek et al. 2019), pests and pathogens (Vacek et al. 2015; Šimůnek et al. 2025), silvicultural practices (Černý 2023; Štefančík et al. 2018), and climatic influences (Šimůnek et al. 2019). Among these factors, damage caused by wildlife ranks among the most prominent (Konôpka et al. 2020). Within the group of large herbivores that have a dramatic impact on forest ecosystems, cervids play a key role (Dobrowolska et al. 2020). The family *Cervidae* adapted well to changes in land use and has successfully colonised the modern agricul-

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tural landscape (Brazaitis et al. 2014), which has been considerably transformed by human activity in recent decades (Assandri et al. 2019). Cloven-hoofed game thus responds to these new conditions through the flexibility of its social behaviour. An increase in the populations of large ungulates has been documented in recent years in several European countries (Baltzinger et al. 2016; Fattebert et al. 2017). In Europe, the abundance and range of some native cervid species, including the red deer (*Cervus elaphus* L.), are expanding alongside introduced species (Borkowski et al. 2019).

As the deer population grows, so does the risk of damage to spruce stands caused by browsing and bark stripping (Cukor et al. 2019a, b, 2022; Vacek et al. 2020b). At the same time, bark removal – whether through winter browsing or summer stripping – constitutes a serious type of degradation to forest stands (Nagaike 2020), the severity of which is influenced by deer population density and other factors, such as the age of the forest stands or the social status of the trees (Vospersnik 2006). We find this kind of bark destruction most frequently in young forest stands under 40 years of age (Čermák et al. 2011). However, in recent years, browsing and stripping harm has progressively shifted to thinner diameter classes; as a result, trees as young as 10 years old with a breast height diameter of 1–2 cm are now commonly affected (Cukor et al. 2024). This type of impairment reduces the economic value of the timber (Welch, Scott 2017), as well as the volume of timber production and the trees' resilience to other disturbances (Cukor et al. 2019a, b).

Bark damage can indirectly cause a higher incidence of trunk infection by fungal pathogens (Vospersnik 2006; Vacek et al. 2020b). Wounds caused by bark damage also serve as entry points for fungal pathogens, particularly the bleeding conifer crust (*Stereum sanguinolentum* Alb. & Schw.: Fr.). Infection risk rises substantially even with wounds as small as 50–100 cm². This vulnerability peaks during winter, particularly when ambient air temperatures fluctuate from –8.5 °C to +5.0 °C (Vospersnik 2006; Assefa, Abate 2018). In the Czech Republic, approximately 45% of trees weakened by browsing and bark stripping are infected by bleeding conifer crust. Rot infection and reduced diameter growth in spruce are related to the extent of the trauma, with the rate of rot spread reaching up to 70 cm per year (Čermák et al. 2011; Cukor et al. 2024). This leads to a disruption of the

mechanical stability of stands, a reduction in timber production and quality, and consequently, severe economic losses (Rönnberg et al. 2013; Vacek et al. 2020b). For example, in the Krušné hory Mts, spruce trees heavily browsed and stripped by red deer had a 50% lower stem volume, while in the Pilsen region, damage caused by sika deer resulted in a total production drop of up to 71% compared to healthy stands (Cukor et al. 2019b; Vacek et al. 2020b).

The long-term effects of bark damage on the productivity and health of spruce stands have been well-documented, yet our understanding of how this impairment affects the dynamics of diameter growth during the growing season remains limited. Continuous dendrometric measurements, however, can capture the temporal dynamics of trees' growth responses at very high temporal resolution. In this study, we monitored the diameter growth of young spruce exposed to simulated bark damage of varying intensities using automatic point dendrometers. This study's aim was to evaluate (i) the dynamics of Norway spruce diameter growth at individual sites and, in particular, (ii) the effect of simulated circumferential damage to the trunks of young spruce stands – mimicking bark stripping by ungulates – on diameter growth, using continuous measurements with point dendrometers in the Lužické hory and Krušné hory Mts.

MATERIAL AND METHODS

Study sites. The study was conducted at four permanent research plots (PRPs) in two forest districts of Lesy ČR (Forests of the Czech Republic, state enterprise), Rumburk and Klášterec nad Ohří. Two of the PRPs were located in the Lužické hory Mts (Rumburk Forest District) and two in the Krušné hory Mts (Klášterec nad Ohří Forest District). The study plots covered an elevation gradient ranging from 450 m a.s.l. to 891 m a.s.l. In the Rumburk Forest District, the average air temperature ranges from 5 °C to 8 °C, with an annual precipitation total of 700–900 mm, whereas in the Klášterec nad Ohří Forest District, the average air temperature ranges from 2.7 °C to 8.0 °C, with an annual precipitation total of 450–1 000 mm. According to the Köppen–Geiger climate classification, Rumburk is located in the Cfb climate region, characterised by a temperate oceanic climate with mild summers and no distinct dry season, whereas Klášterec nad Ohří belongs to the Dfb region, repre-

senting a humid continental climate with warm summers, cold winters, and no pronounced dry season (Peel et al. 2007).

Two PRPs were established in each forest district within fenced spruce monocultures aged 16–21 years. The PRPs in the Lužické hory Mts were located at 450 m a.s.l. and 533 m a.s.l., while those in the Krušné hory Mts were situated at 877 m a.s.l. and 891 m a.s.l., respectively. Detailed site and stand parameters for each PRP are listed in Table 1.

Data collection and analysis. In April 2024, TOMST point dendrometers (TOMST, Czech Republic) were installed at all four PRPs to con-

tinuously monitor the growth response of Norway spruce to simulated browsing and bark stripping wounds by ungulates. All PRPs were fenced off to eliminate the risk of further damage to the monitored trees by red deer and the resulting impact on the experiment. Two spruce stands in the Lužické hory Mts and two in the Krušné hory Mts were selected for the placement of the dendrometers. To minimise the effect of varying social status on the growth response of individual trees, we selected 15 co-dominant trees for each PRP. The placement of the instrument on the tree trunk is shown in Figure 1.

Table 1. Basic stand and site parameters of spruce stands on permanent research plots (PRPs) in the Krušné hory and Lužické hory Mts

PRP	Forest district	DBH (cm)	Height (m)	GFST	Altitude (m a.s.l.)	Slope (°)	Exposure	Soil type	GPS
1	Rumburk	14.3	10.9	5V	450	4	E	Haplic Gleysol	50°50'23"N, 14°28'50"E
2	Rumburk	12.8	9.5	5V	533	9	W	Gleyic Cambisol	50°50'06"N, 14°30'04"E
3	Kláštorec nad Ohří	11.0	7.8	6K	891	3	N	Haplic Podzol	50°30'10"N, 13°09'50"E
4	Kláštorec nad Ohří	11.2	9.2	6K	877	7	S	Haplic Podzol	50°29'22"N, 13°12'30"E

DBH – diameter at breast height (cm); GFST – group of forest site type: 5V – *Abieto-Fagetum fraxinosum humidum*, 6K – *Piceeto-Fagetum acidophilum* (Viewegh et al. 2003)



Figure 1. Example of a spot dendrometer installation on PRP 2 in the Rumburk Forest District

PRP – permanent research plot

Photo: Jan Cukor

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Of these 15 trees, five were left undamaged and served as the control group. The remaining ten trees were experimentally damaged by removing bark from a predetermined percentage of the trunk circumference and then fitted with dendrometers. A ten-degree scale of damage was set for each PRP, corresponding to the removal of bark from 5, 10, 20, 30, 40, 50, 60, 70, 80, and 90% of the trunk circumference, with each damage degree represented by one tree. The experiment thus encompassed a gradient ranging from mild to severe bark damage.

The dendrometers were installed at a height of 1.3 m above the ground on the north side of the trunk. Changes in trunk radius were recorded at 15-minute intervals with a resolution of 0.27 μm and a measuring range of 8 890 μm . The manufacturer-specified deviation from linearity is less than 5%. Following installation, the dendrometers remained in the stands for the entire monitoring period, automatically and simultaneously recording air temperature. Measurements were taken autonomously. The data were continuously stored in the device's internal memory, downloaded approximately every six months, and backed up on an ongoing basis.

The measured time series were processed using the Lolly software (Version 2026.1, 2026). The raw data on changes in stem radius were then checked, and records containing artefacts – such as abrupt changes caused by handling or adjusting the dendrometer – were corrected or removed. The data were then aggregated into daily averages using the PLOTer package in R (Matula et al. 2023). The results were visualised in MS Excel (Version 2608, 2026).

For statistical analysis, the damaged trees were grouped into three categories based on the extent of bark removal: low damage (5–30% of the trunk's circumference; $n = 4$ per PRP), moderate damage (40–60%; $n = 3$ per PRP), and severe damage (70–90%; $n = 3$ per PRP). Together with the undamaged control variant ($n = 5$ per PRP), four variants were thus evaluated.

Before performing a statistical analysis on the differences between the variants, the normality of the data distribution and the homogeneity of variances were verified. When the assumptions of parametric tests were met, the differences between the variants were evaluated using analysis of variance (ANOVA); otherwise, the Kruskal–Wallis test was used. Statistical analyses were performed using Statistica (Version 14.1.0.8, 2023).

RESULTS

The extent of the simulated bark damage at the start of the experiment in April 2024 and the subsequent condition of the wounds after 19 months are documented in Figures 2 and 3. In the tree with 20% circumferential damage, the wound completely pitched out and a protective callus barrier formed, while in the tree with 40% damage, the wound remained open (Figure 3).

The onset of notable diameter increment differed between the two study areas. In the Lužické hory Mts, it was recorded around the fourth week of April, while it was around the second week of May in the Krušné hory Mts (Figure 4). The most intense diameter growth occurred at all of the sites approximately two weeks at the turn of May and June. The growth gradually slowed down and ceased at all PRPs during the second to third week of September.

Figure 4 also shows that as early as the first year following the experimental circumferential damage to the bark, a significant ($P < 0.05$) difference was observed in diameter growth between the variants. On all four sites, the significantly ($P < 0.05$) highest diameter growth was achieved in undamaged (healthy) trees; in one case, also for the category involving 5–30% circumferential damage (PRP 3). On the other hand, at three sites, no significant difference was found among the three damage categories, with the exception of PRP 3. Overall, the lowest increment occurred at two sites with 70–90% circumferential trunk damage, and in one case, in the variants with 40–60% and 5–30% circumferential trunk damage, respectively. The greatest difference between undamaged trees and trees with varying degrees of damage was observed on PRP 2, where healthy trees achieved up to 87.8% higher diameter increment compared to trees affected by simulated bark stripping.

Figure 5 presents the differences in diameter increment of Norway spruce summed up for all four PRPs. After six months, the highest diameter growth was statistically significantly higher in healthy individuals – undamaged control trees ($P < 0.05$). These were followed by trees with damage degrees of 5–30%, 40–60%, and 70–90%, respectively, with no statistically significant differences found among the individual damage degrees ($P > 0.05$). Compared to healthy control trees, damaged trees exhibited, depending on the degree of damage, an average of 37.9–43.2% lower diameter increment after the first growing season.



Figure 2. Different degrees of simulated bark damage: (A) 5% and (B) 90% of the trunk circumference in April 2024 – initial stage

Photo: Jan Cukor



Figure 3. Different degrees of simulated bark damage: (A) 20% and (B) 40% of the trunk circumference in October 2025 – 19 months after the experiment began

Photo: Václav Trojan

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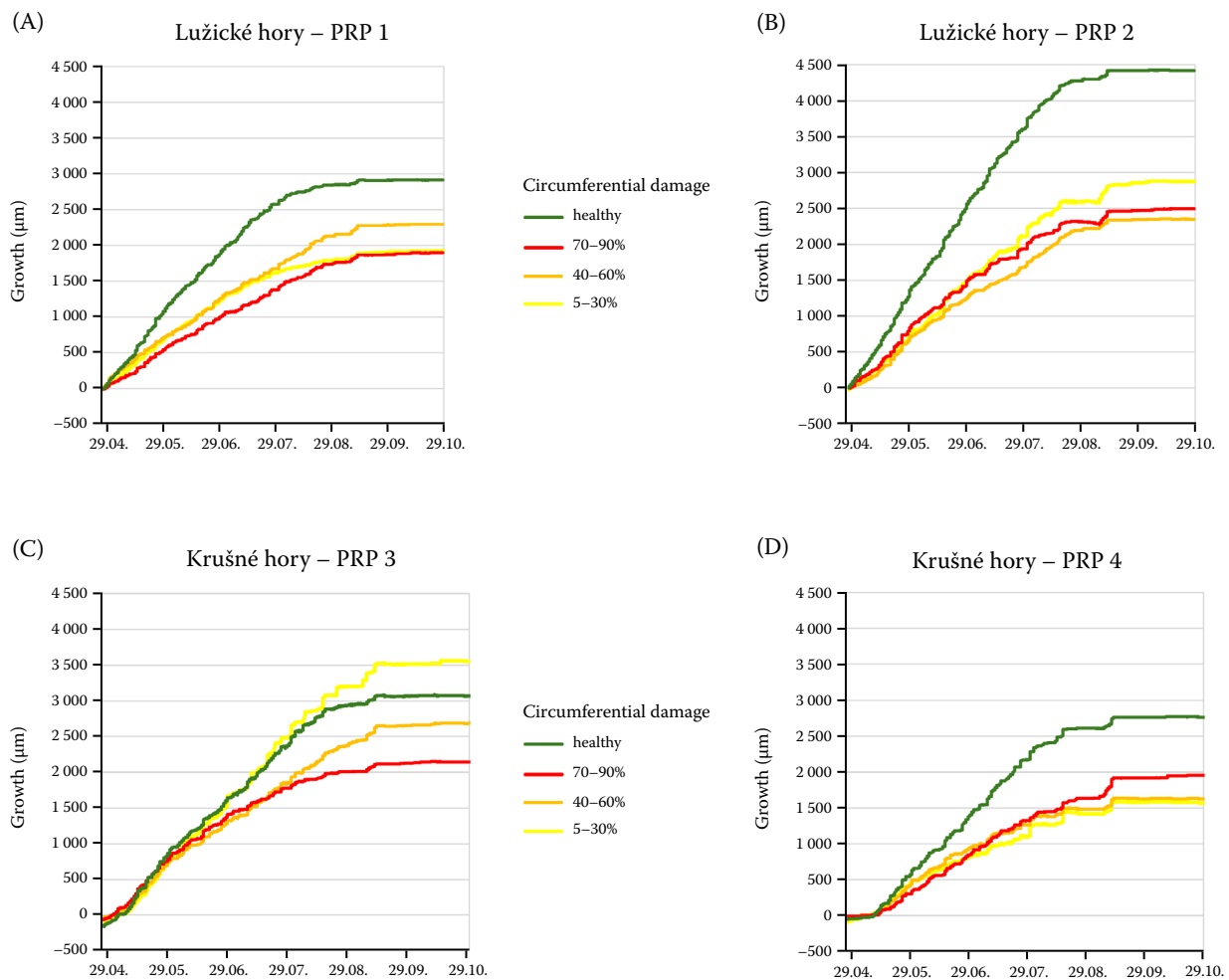


Figure 4. Diameter growth dynamics of Norway spruce in 2024 across four long-term observation sites in the Lužické hory and Krušné hory Mts, under the four scenarios of bark damage

PRP – permanent research plot

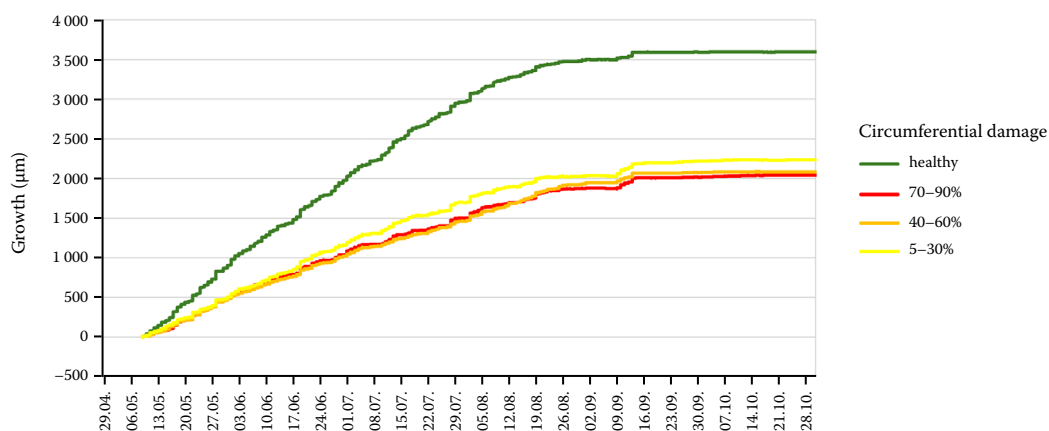


Figure 5. Norway spruce diameter increments in 2024, summarised for all four PRP sites in the Krušné hory and Lužické hory Mts, under the four scenarios of bark damage, with the beginning corresponding to the onset of the growing season

PRP – permanent research plot

DISCUSSION

Tree diameter growth is notably linked to the provision of a range of ecosystem services, such as timber production and associated carbon sequestration, microclimate regulation, and climate change mitigation (Felipe-Lucia 2018; Vacek et al. 2022). Understanding the growth dynamics of trees is therefore essential in the context of climate change and various types of disturbances that lead to a global redistribution of growth patterns (Tumajer et al. 2025). In mountainous regions, trees exhibit reduced temperature sensitivity during wood formation (D'Arrigo et al. 2008). Contrastingly, the combined effects of climate stress and other disturbances, including wildlife damage, can lead to reduced growth and increased tree mortality (Allen et al. 2010; Vacek et al. 2020b). To better predict future forest growth, it is imperative to deepen our understanding of growth responses to advancing climate change and various types of disturbances, including damage caused by ungulates (Camarero et al. 2021; Vacek et al. 2023; Klesse et al. 2024). Recently, diverse species-specific growth trends have been observed in temperate-zone biomes, ranging from accelerated growth to sharp declines (Pretzsch et al. 2014; Kašpar et al. 2024). However, our study demonstrated that simulated bark damage on Norway spruce in the Krušné hory and Lužické hory Mts substantially impeded diameter increment compared to undamaged control trees. Damage to bark and the associated disruption of the phloem and cambium can severely limit the transport of assimilates and the formation of new wood. This results in reduced diameter increment (Bouriaud et al. 2015; Schmied et al. 2023). It is noteworthy that the effect of changes in spring temperature on growth phenology in temperate zones – and how this translates into tree ring growth – is not linear due to the interplay of numerous factors (temperature, moisture, nutrients, disturbances) that lead to the spring reactivation of the cambium (Delpierre et al. 2019). Moreover, site- and species-specific growth phenology interacts with meteorological extremes and disturbance types, whose impact on tree growth and vigour hinges on their timing within the growing season (Scharnweber et al. 2020). Emphatically, Norway spruce is the most important commercial tree species in the Czech Republic, yet it is highly susceptible to bark damage caused by browsing

and bark stripping (Verheyden et al. 2006; Krisans et al. 2020). Bark damage to Norway spruce depends on many components, including the population density of red deer and other ungulate species that cause this type of impairment (Cukor et al. 2024). However, the age structure of forest stands, the surrounding landscape features, and silvicultural management practices also play supporting roles (Konôpka et al. 2022; Brabec et al. 2024). Gradually, browsing and bark stripping damage shifts to younger stands with an average age of around ten years (Cukor et al. 2024), which corresponds to the lower limit of stand susceptibility to the negative effects of cervids (Gill 1992; Cukor et al. 2019a).

In our study, the highest spruce increment recorded by dendrometers was accomplished over two weeks at the turn of May and June, varying by the PRP location in the Krušné hory and Lužické hory Mts. Diameter increment then ceased at all PRPs during the second to third week of September. Controlled circumferential bark damage caused significant ($P < 0.05$) differences in diameter growth among the evaluated variants during the very first growing season. On all four PRP sites, the significantly ($P < 0.05$) highest diameter growth was achieved by undamaged (healthy) trees. These were followed by trees with damage degrees of 5–30%, 40–60%, and 70–90%, respectively. Compared to healthy ones, damaged trees exhibited, on average, 37.9–43.2% lower diameter increment at the measurement point after the first growing season, depending on the degree of damage. Therefore, this study confirmed notable differences in diameter increment between undamaged and damaged trees. However, no statistically significant differences were found overall between the individual categories of impairment severity. Bark removal thus had a substantial negative impact on diameter increment as early as the first growing season after the damage occurred. Furthermore, previous studies have shown that damaged spruce trees may be more sensitive to precipitation deficits and prolonged drought than healthy ones (Mäkinen et al. 2001; Cukor et al. 2019a). Conversely, the effect of precipitation was low in healthy trees, resp. increased temperature had a stronger effect on healthy trees due to sufficient water supply (Vacek et al. 2020b). Regarding xylem formation and an increase in spruce trunk radius, Mäkinen et al. (2003) report that the fastest daily diameter growth was recorded in June and

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July, with a slowdown in August. Similar growth trends, assessed using dendrometers, are reported by Matula et al. (2023) and Vacek et al. (2025). Vacek et al. (2020b) also report that the average stem volume was 71% lower in severely damaged Norway spruce trees in Klášterec nad Ohří and 50% lower in Stříbro compared to healthy trees. Analogous results were observed in older Norway spruce stands, where the stand volume of severely damaged trees was nearly half that of healthy trees (Cukor et al. 2019a).

However, bark removal affects more than just tree growth. It also diminishes wood quality, as the resulting wounds can become entry points for fungal pathogens that may invade the wood and cause trunk deformities (Čermák, Strejček 2007; Čermák et al. 2004b). For example, the bleeding conifer crust can colonise weakened trunks as early as the first year after bark removal. A wound as small as 50 cm² can allow pathogens to enter (Vasiliauskas, Stenlid 1998; Lygis et al. 2004). Damage to such young spruce trees dramatically increases the risk of rot, which can hinder their further development (Cukor et al. 2024). The spread of rot within the trunk accelerates as the stand ages (Bendz-Hellgren, Stenlid 1995; Vacek et al. 2020b), resulting in considerable economic losses. Specifically, rot associated with infection by the bleeding conifer crust leads to EUR 2 500 losses per hectare of forest stand (Čermák et al. 2004a), while total losses caused by bark stripping averaged EUR 10 200 per hectare in the Czech Republic (Simon, Kolář 2001). For these reasons, more focus should be placed on protecting stands from ungulate-induced damage.

CONCLUSION

Using continuous measurements with automatic point dendrometers, we quantified the effects of simulated ungulate bark injury on the diameter growth of young Norway spruce trees. The results showed a substantial response in diameter growth to the experimental bark damage. Significantly lower diameter increments at the measurement point in damaged trees, compared to undamaged control trees, were observed during the very first growing season after the experimental bark removal. Depending on the damage category, average growth values were 37.9–43.2% lower. The largest numerical reduction in growth was recorded in trees with

70–90% impairment; however, no significant differences were found in the aggregate between the individual degree of damage categories. On all monitored sites (PRPs), the primary growth activity of spruce was concentrated in an approximately two-week period at the turn of May and June, with growth activity ceasing on all PRPs in the second to third week of September.

The results also show that even minor bark damage can lead to reduced diameter increment during the first growing season after the injury occurred. In the context of ongoing climate change and high browsing pressure from ungulates, damage to bark critically affects the productive capacity and further development of young spruce stands. Therefore, protecting young coniferous stands from bark stripping and browsing is essential for maintaining their economic value, ecological functions, and provision of ecosystem services. The results of this study improve our understanding of how Norway spruce responds to biotic disturbances caused by ungulate bark damage. This information can be used to manage and protect spruce stands more effectively under changing climatic conditions.

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