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Bark stripping, the crucial factor affecting stem rot development and timber production of Norway spruce forests in Central Europe

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ABSTRACT

Bark stripping damage and the resultant stem rot to Norway spruce (*Picea abies* [L]. Karst), one of the most important tree species, poses a serious problem for forest management in Europe. Our research objective was to determine the effect of bark stripping, the subsequent rot decay and the impact of climatic factors in young (42–49 years) spruce stands. Moreover, we compared the differences between damage caused by red deer (*Cervus elaphus* L.) and sika deer (*Cervus nippon* Temminck). In all the cases studied, game damage was lower in forest stands when caused by sika deer (SD − 77.3%) compared to red deer (RD − 88.8%); 27.8% (SD) – 32.0% (RD) of stem circumference was damaged in average. Damaged trees showed higher growth variability and were more sensitive to a lack of precipitation and droughts, while air temperature had a higher effect on the growth of healthy trees. The initial game damage was observed in the 11 (SD) – 14 (RD) year of the mean tree age. The stem volume was lower by 25% (SD) – 28% (RD) in lightly damaged trees, and 50% (SD) – 71% (RD) in heavily damaged trees compared to healthy trees. The vertical stem decay reached a maximum of up to 4.5 m (SD) – 6.0 m (RD) (mean 1.9–3.1 m) with the mean speed of vertical spreading of 5.7 cm yr^{-1} (SD) – 9.6 (RD) cm yr^{-1}. The mean decayed wood accounted for 30% (SD) – 39% (RD) of the stem volume. The peripheral stem damage by bark stripping and the age of the first occurrence were significant factors in predicting damaged crosscut area and vertical rot spreading in the stem. During this time of climate change, the stability of damaged spruce stands has been significantly disturbed by deer game.

1. Introduction

Health status, stability and the production of forest ecosystems are affected by numerous biotic and abiotic factors, such as air pollution load (Králíček et al., 2017; Vacek et al., 2017a; Opała-Owczarek et al., 2019), pest and pathogens (Brang et al., 2002; Vacek et al., 2015b), fertilization (Cukor et al., 2017; Vacek et al., 2019), silviculture practices (Bílek et al., 2016; Bolte et al., 2009; Štefančík et al., 2018, Gallo et al., 2020) and climatic factors (Lorz et al., 2010; Suvanto et al., 2016; Putalová et al., 2019; Šimůnek et al., 2019). The damage caused by wildlife is one of the most significant of these factors (Vlad and Sidor, 2013; Ambrož et al., 2015; Slanař et al., 2017; Konôpka et al., 2019). The large herbivores which negatively affect woodland ecosystems are the deer species (Gill and Beardall, 2001; Dobrowolska et al., 2020). *Cervidae* adapted well to the land use changes and have successfully colonized the current agricultural landscape (Brazaitis et al., 2014), which was significantly changed by human activities in recent decades (Levers et al., 2016; Agnoletti et al., 2019; Assandri et al., 2019). Animals respond through the flexibility of their social behavior to new conditions (Jaedrzejewski et al., 2006; Barja and Rosellini, 2008). The increase of wildlife populations of large ungulates has been documented across many countries in Europe in previous years (Côté et al., 2004; Hagen et al., 2014; Thulin et al., 2015; Baltzinger et al., 2016; Fattebert et al., 2017).

In Europe, the native deer species, including red deer (*Cervus elaphus* L.), are expanding, along with the introduced ones (Carden et al., 2011; Borkowski et al., 2019). For instance, sika deer (*Cervus nippon* Temminck) is one of the successfully introduced species of the *Cervidae* family with a current rapid population growth (Pitra and Lutz, 2005; Pérez-Espona et al., 2009; Carden et al., 2011; Barančeková et al., 2012). Due to the increasing influence of deer on tree species richness in forest ecosystems caused by their feeding behavior, wild ungulates are defined as keystone species (Côté et al., 2004; Takarabe and Iijima, 2019). The well-described effects of game damage are leader browsing on young trees (forest regeneration), shrubs and herbs, which alters the

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vegetation structure and composition and may retard woodland successional development (Gill and Beardall, 2001; Rossell et al., 2007; Bílek et al., 2018). However, the damage range depends on browsing pressure (Gill, 1992; Stokely and Betts, 2020). Fraying is another type of damage resulting from the removal of stem bark by antlers (Gill, 1992; Motta, 1996), but this game damage is not often compared to the others (Caudullo et al., 2003).

Bark stripping is the last serious type of damage caused to forest stands (Akashi and Nakashizuka, 1999; Nagaike, 2019). We distinguish between winter bark stripping (gnawing off with the aid of the lower incisors) or spring/summer bark stripping (tearing off the strips of bark in the longitudinal direction) (Gill, 1992). The inflicted damage can vary from minor scarring to significant deformation of the trunk, and potentially, the death of the tree (White, 2019). The intensity of bark stripping is again influenced by population density of *Cervidae* and other factors like the age of the forest stands or social position of the tree (Welch et al., 1988; Vospernik, 2006). Bark stripping mostly occurs in young forest stands under 40 years of age (Welch et al., 1988; Gill, 1992; Čermák et al., 2011). This type of damage affects not only the wood quality – from the point of economic evaluation (Welch and Scott, 2017), but also the wood production and lower resistance to natural disturbances (Cukor et al., 2019b, 2019a; Schwarz et al., 2007).[1]

The secondary impact of bark stripping is the higher occurrence of stem rot infection (Vasiliauskas, 2001; Vospernik, 2006). Heart rot fungi typically enter trees through wounds, mostly caused by mammals (Garbelotto and Gonthier, 2013; Warren et al., 2013; Assefa and Abate, 2018). The rot infection seems to be related to the range of bark-stripped area. In the case of one of the most widespread tree species in Europe – Norway spruce (*Picea abies* [L.] Karst.), the bark-stripped tree could be attacked most often by the fungal pathogen *Stereum sanguinolentum* (Alb. & Schwein.) Fr. immediately in the first year after the bark has been damaged (El Atta and Hayes, 1987; Čermák and Strejček, 2007). Only 50 cm^2 of stripped area on the stem is sufficient for penetration of *S. sanguinolentum* (Vasiliauskas et al., 1996). Another significant decay fungus causing extensive rot of trunks includes *Heterobasidion annosum* (Fr.) Bref., but this fungal pathogen attacks spruce mostly near the tree base (Piri, 1996; Arhipova et al., 2011). The resistance of individual tree species to the stem rot development varies considerably, Norway spruce is considered as one of the most sensitive species (Gill, 1992; Vospernik, 2006). The importance of rot infection could contribute to financial losses that were quantified, for example, in Scandinavia. The rot damage losses caused by *Heterobasidion* spp. were estimated to be approximately € 0.5–1 billion per year (Rönnberg et al., 2013).

Current studies have dealt with the effects of bark stripping on growth of Norway spruce (Kiffner et al., 2008; Månsson and Jarnemo, 2013) but we lack comprehensive research which focuses on losses of timber production, the effects of climatic factors and the spread of rot in the trunk, related to the level of damage caused by sika deer and red deer. The objectives of this research were to: (1) determine the effects of bark stripping on the timber production and structure of the Norway spruce forest stands, (2) compare the differences between bark stripping damage caused by native red deer and introduced sika deer, (3) evaluate stem rot development in relation to different bark stripping parameters, and (4) determine the effects of climate factors (precipitation, temperature) on the radial growth according to the magnitude of the deer damage.

2. Material and methods

2.1. Study area

The research was conducted on twelve monoculture Norway spruce forest stands in two locations (2 areas × 6 stands). The effect of sika deer was studied in the Forest management unit (FMU) Stříbro in the western part of the Západočeská pahorkatina (West Bohemian Upland), and the effect of red deer in the FMU Klášterec na Ohří, in the central part of Krušné hory (the Ore Mts.) area which are both in the Czech Republic (Fig. 1). The studied spruce stands were of similar age (42–47 years in FMU Stříbro, 43–49 years in FMU Klášterec nad Ohří) according to the forest management plans. The site quality index and the soil type (Cambisol) were identical between all stands in both locations. The prevailing bedrock was mostly composed of slate and phyllite. The spruce stands were artificially established and protected by deer fences for 9–15 years after plantation (depending on location). The altitude of the study location ranged from 471 to 551 m a.s.l. in FMU Stříbro and 539–636 m a.s.l. in FMU Klášterec na Ohří.

In both cases, the forest owner is Forests of the Czech Republic, state enterprise, so identical silvicultural and management practices were performed. Soft thinning from below (harvested suppressed trees) according to Kraft (1884) classification is applied with a focus on the gradual removal of dead, dying and heavily damaged trees. Thinning is performed once in about every 12–17 years with a stocking reduction by a maximum of 20%. The studied stands were measured before the thinning intervention at both sites. In the first FMU Stříbro (hunting district Rochlov, 1861 ha), 7.5 sika deer individuals were hunted annually per 100 ha in 2013–2018 on the average. In FMU Stříbro, the red deer are not present and therefore are also not hunted. In the second location, FMU Klášterec na Ohří (hunting district Perštejn, 2023 ha), 2.2 red deer individuals were hunted per 100 ha in 2013–2018 on the average. In FMU Klášterec nad Ohří, the sika deer are not present and therefore are also not hunted.

The climatic conditions on both sites are comparable. The mean annual temperature in the study area was approximately 7.5–7.8 °C with the minimum temperature recorded in January (−1.8 to −2.2 °C), and the maximum recorded in July (17.0–17.8 °C; Fig. 1). The mean annual precipitation ranged from 500 to 540 mm yr^{-1}, with the lowest precipitation recorded in February (21–25 mm) and the highest in June (66–67 mm). The duration of snow coverage was approximately 54 days, with the average maximum snow depth recorded at 25 cm. The growing season ($T_{max} > 10$ °C) lasted approximately 150 days, with a mean precipitation of 350 mm and a mean temperature of 13.7 °C. The number of tropical days ($T_{max} < 30$ °C) was 5, the number of ice days ($T_{max} < 0$ °C) was 32, and the number of arctic days ($T_{max} < -10$ °C) was also 5. The annual sunshine is 1634 h, on the average. The study area qualified as a humid continental climate zone, characterized by warm to hot, humid summers and cold to severely cold winters (Dfb) as stated by the Köppen climate classification (Köppen, 1931). According to the detailed Quitt climate classification (Quitt, 1971), the area can be classified in the cold climatic region (subregion CH 6). In terms of phytocoenology, all permanent research plots (PRPs) belong to *Querceto-Fagetum acidophilum* (Acidic Oak-Beech site) and *Fagetum acidophilum* (Acidic Beech site) and to the alliance *Luzulo-Fagion sylvaticae* Lohmeyer et Tüxen in Tüxen 1954.

2.2. Data collection

In 2019, Field-Map technology (IFER – Monitoring and Mapping Solutions, Jílové u Prahy, Czech Republic) was used to establish 47 radial plots (23 plots in FMU Stříbro, 24 plots in FMU Klášterec) with the size of 100 m^2 (r = 5.64 m). The position of the trees was measured by Field-Map technology, diameter at breast height (DBH cm ≥ 4 cm; accuracy 1 mm) measured by Mantax Blue metal caliper (Haglöf, Långsele, Västernorrland, Sweden), and tree height (accuracy 0.1 m) measured by Laser Vertex hypsometer (Haglöf, Långsele, Västernorrland, Sweden). Game damage was evaluated and classified using the methodology of the Institute of Forest Ecosystem Research, Ltd. (IFER, Jílové u Prahy, Czech Republic) and Forest Management Institute (ÚHÚL, Brandýs nad Labem, Czech Republic) applying

[1] Could you please sort the references according to year of publication? The correct version should be Schwarz et al., 2007; Cukor et al., 2019a, 2019b.

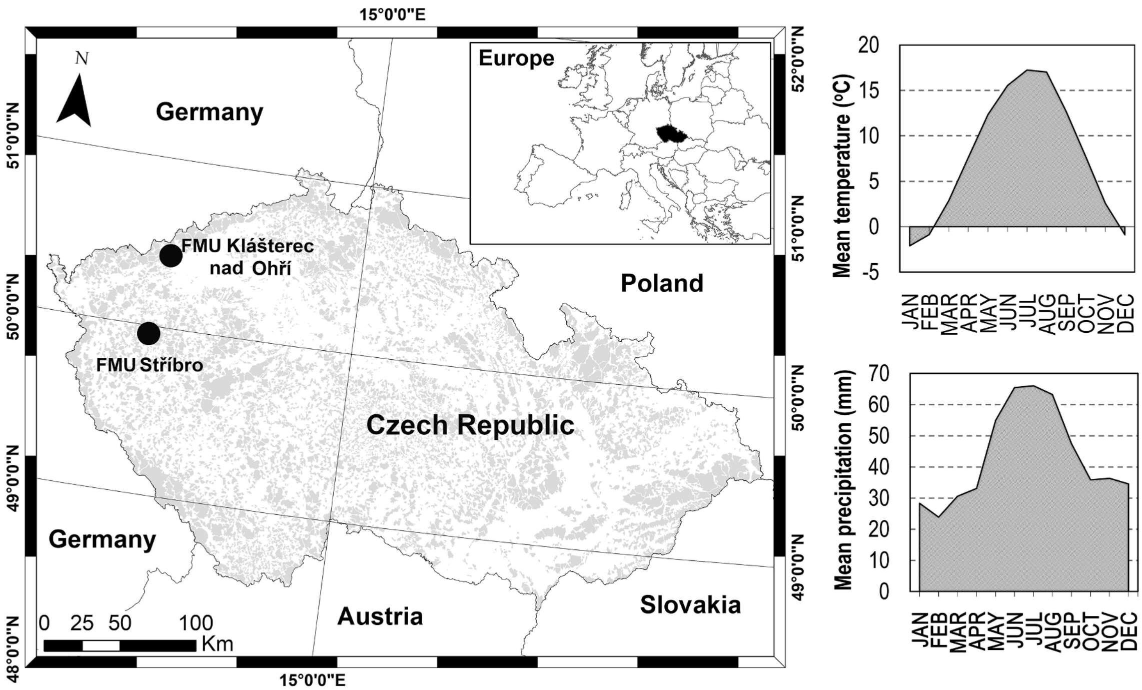

Fig. 1. The localization of permanent research plots (PRPs) established within Norway spruce stands in the Forest management unit Stříbro in the Západočeská pahorkatina (West Bohemian Upland) (sika deer) and the Forest management unit Klášterec nad Ohří in the Krušné hory (the Ore Mts.) (red deer) and monthly climatic characteristics (the mean temperature and sum of precipitation between 1961 and 2018); the grey layer in the map symbolizes the forest cover in the Czech Republic.

national inventory measurements. Bark stripping was measured along the girth of the tree stem utilizing a tape (to the nearest 1 mm) at DBH and was subsequently divided into three categories: healthy trees (damaged circumference ≤ 1/8 of the stem girth), minor game-induced damage (damaged circumference > 1/8 and ≤ 1/3 of the stem girth), and extensive game-induced damage (damaged circumference > 1/3 of the stem girth) (Cukor et al., 2019b; Kosmala and Suchocka, 2008[2]). Furthermore, the length and mean height (the widest damaged place on stem) of the bark stripping was documented. Winter or spring/summer bark stripping were not differentiated due to the prolonged elapse of time after the game-induced damage to tree.

In November of 2019, increment core samples of 23–24 spruce trees from each tree-damage variant (3 samples on one plot) in both Forest management units (totally 141 core samples) were taken at DBH using a Pressler auger (Haglöf, Långsele, Västernorrland, Sweden). Predominant and dominant trees according to Kraft (1884) classification were randomly chosen by the RNG function (Excel, Microsoft). Core samples were taken perpendicularly to the tree stem axis. Tree-ring widths were measured to the nearest 0.01 mm with an Olympus stereo microscope (Olympus, Tokyo, Japan) on a LINTAB measurement table (RINNTECH, Heidelberg, Germany) and recorded by the TSAPWIN software (RESISTOGRAPH, Heidelberg, Germany). Throughout the dendrochronological analysis, the occurrence of bark stripping damage (year) and stem rot (the percentage of diameter affected by rot) were visually recorded by significant color changes (fungi, black coloring in the stripping damage, etc.), separations of ring widths, occurrences of defects (resin, rind galls, etc.), and changes in the mechanical structure of each sample (Cukor et al., 2019b).

Forty trees with different levels of game damage in each Forest management unit were harvested by chainsaw Husqvarna 550 XP (Husqvarna, Stockholm, Sweden) to determine the size and spread of stem rot. The stem was first cut at the widest point of the bark stripping damage. Subsequently, the stem was cut in 20 cm segments from both directions to the end of the rot area. The rot surface was marked on each tree cross-section, documented and photographed perpendicularly to the cut together with the ruler (for scale) with a Canon camera (Canon, Óta, Japan) equipped with lens with focal length of 50 mm to ensure minimal distortion of the image. The photos of the rot area were measured in the image processing program ImageJ (Schindelin et al., 2015). Ultimately, the main fungal species that caused wood decay (*Stereum sanguinolentum* [Alb. & Schwein.] Fr. or *Heterobasidion annosum* [Fr.] Bref.) were determined optically in the zoomed photos according to the main features (color, shape of rot, gray zones, procedure, decomposition).

2.3. Data analysis

Based upon the measured dendrometric data, the tree volume of spruce was computed for the tree layer (Petráš and Pajtík, 1991). Basic production parameters (DBH, tree height, stem volume) were computed separately for selected types of damage on both sites, and were statistically compared separately for each location. The Kruskal-Wallis test was used with subsequent multiple comparisons (Siegel and Castellan Jr., 1988) as assumptions of ANOVA (normality, tested by the Shapiro-Wilk test) but were not met in all cases. Height curves were constructed using the Näslund height-diameter function (Näslund, 1937). R-squared values were computed as the residual sum of squares/total sum of squares ratio. The standard deviation (σ) was used to express the statistical variability of the data.

For the basic description of bark stripping damage, the height of damage on the stem, and the length of bark-stripped area on the stem were analyzed. The differences between selected locations in these parameters were tested by the Wilcoxon rank-sum test, as the assumption of data normality was not met in both cases. Also, the ratio of rot-affected timber to the log timber total was assessed (total log timber was computed for the stem part of which the thinner-end diameter was greater than 7 cm). The differences in rot-affected timber ratio between

[2] Could you please sort the references according to year of publishing? The references should be cited as followings: Kosmala and Suchocka (2008), Cukor et al. (2019b).

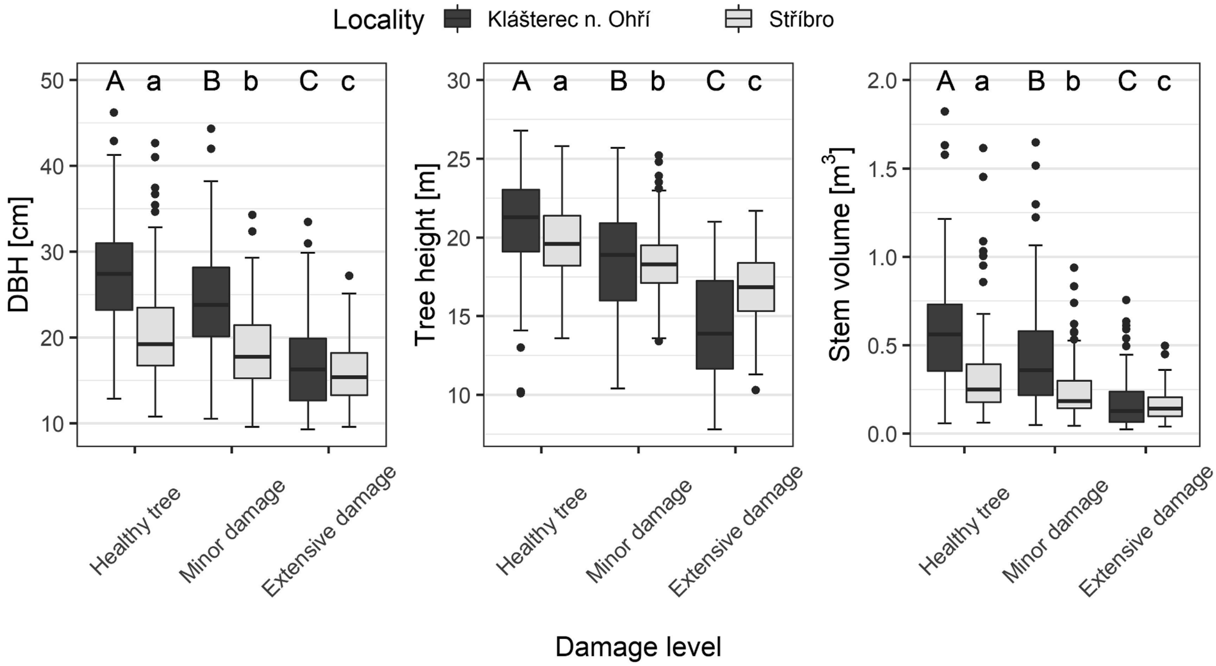

Fig. 2. The results of testing for differences in basic production parameters between selected damage levels. Two Kruskal-Wallis tests with subsequent multiple comparisons were performed (for each location separately). The indices of statistically significant differences (letters above boxes) are depicted separately for each location (capitals for Klášterec nad Ohří – red deer, small caps for Stříbro – sika deer).

selected locations were analyzed by the Wilcoxon rank-sum test (as normality of data was violated).

The relationship between current visible bark-stripping and rot-damaged crosscut area at the place of stripping on the stem was analyzed by linear regression. Quadratic regression was further used for modelling of the rot damage along the stem relative to the damage at the place of defacement – those two models together could be used for predicting of the extent of rot inside the stem. R-squared values – as in previous cases – were computed as the ratio of the residual sum of squares/total sum of squares. We used a linear model to assess the relation of the age and the bark stripping damage extent at its first occurrence.

Finally, the imaging of the extent of rot to the stem put into scale was made. All computations were performed in R software (R Core Team, 2018). Plots were made in R software via "ggplot2" package (Wickham, 2016). Surface plots were made in software Gnuplot 5.2 (Williams et al., 2019). The significance level of alpha = 0.05 was set for all statistical tests.

Tree-ring increment series were individually cross-dated (removal of errors connected with the occurrence of missing tree rings) using t-tests, and subsequently, were visually checked according to the Yamaguchi method (Yamaguchi, 1991). Particular curves from the PRPs were detrended in a standard way and mean tree-ring series were created from collected data in the R software (R Core Team, 2018). Annual tree-ring width was standardized by the tree age and represented by the tree ring width index. Package dplR (Bunn, 2008) was used to create smoothing spline for a different time window using a built-in method to detrend, filter, and visualize the tree-ring series data (Bunn, 2010). The detrended ring-width data were used to compute the expressed population signal (EPS). The EPS indicates the reliability of a chronology as a fraction of the joint variance to the theoretical infinite tree population (Fritts, 1976). The signal to noise ratio (SNR) that evaluates the signal strength of chronology, and R-bar interseries correlations (Fritts, 1976) were also computed. The raw dendrochronological data was used to calculate mean sensitivity (MS).

The standard age detrended chronology was interleaved and plotted with a 16-year spline for removing short-term fluctuations. The analysis of negative pointer years was conducted according to Schweingruber et al. (1990). For each tree, the pointer year was identified as an extremely narrow tree ring that did not reach 40% of the average increment from the previous four years. A negative year was defined as the occurrence of a strong increment reduction in at least 20% of the trees on their respective plot. For modelling the diameter increments in relation to climate characteristics (monthly precipitation and temperature), the DENDROCLIM2002 software (Biondi and Waikul, 2004) was used for statistical relationships between climate and tree radial growth using correlation and response functions. The software used bootstrapped confidence intervals to estimate the significance of both correlation and response function coefficients. In this case, we used correlation and response functions for monthly precipitation and temperature from May of the previous year to September of the current year, in the range with our climatic data. Climatic data (1961–2018) were obtained from the meteorological station in Kralovice (468 m a.s.l.; WGS84 49°58′51″N, 13°29′06″E) approximately 30 km away for FMU Stříbro, and about 25 km away from the meteorological station in Olšová Vrata (606 m a.s.l.; WGS84 50°12′6″N, 12°54′52″E) in the case of FMU Klášterec n. Ohří. These meteorological stations are operated by the Czech Hydrometeorological Institute (ČHMÚ), and the provider of historical data is the National Center for Environmental Information (NCDC).

3. Results

3.1. Stand production and structure

The differences in the basic production parameters (DBH, tree height, stem volume) between selected damage levels for each location were tested via the Kruskal-Wallis test with subsequent multiple comparisons. The Kruskal-Wallis test revealed significant differences in all cases (Fig. 2). The p-values showed in all cases a very high significance ($p < 0.001$). Also, significant differences were found between all damage levels from all parameters in both locations. In the case of all damage types, DBH was higher in Klášterec, on average, compared to Stříbro. On average, trees with minor damage showed ca. 12% smaller

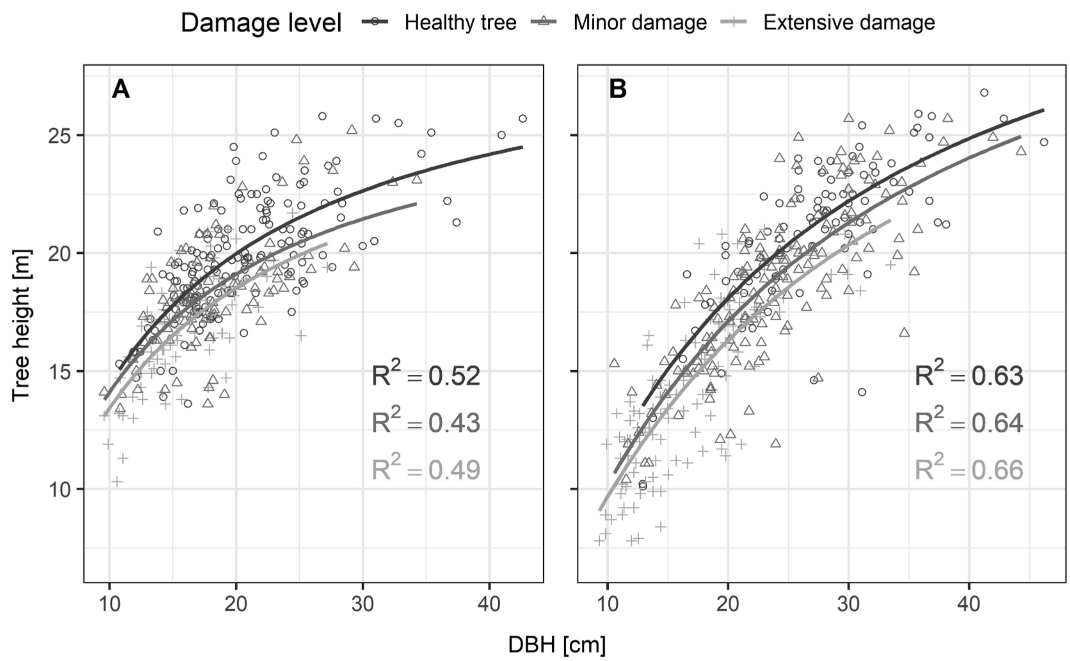

Fig. 3. Näslund height-diameter functions for all selected types of damage at both study locations; plot A – Stříbro (sika deer), plot B – Klášterec nad Ohří (red deer).

DBH than healthy trees in the Klášterec location (10% in Stříbro). In the case of trees with extensive damage, the mean DBH was lower by 38% compared to healthy trees in Klášterec (22% in Stříbro). Tree height and stem volume showed a similar pattern, as the highest trees were the healthy ones, followed by trees with minor damage, of which the height was on average 11% lower in the case of Klášterec and 8% lower in the case of the Stříbro location. The lowest tree height was observed in trees with extensive damage, where the mean height was 32% lower compared to healthy trees in Klášterec, and by 16% in the Stříbro location. The tree stem volume was also the highest in the case of healthy trees, on average. Trees with minor damage showed a lower stem volume by 28% in the Klášterec location (25% in Stříbro). In the case of trees with extensive damage, the mean tree stem volume was 71% lower compared to healthy trees in Klášterec and 50% lower in Stříbro.

The tree height-diameter function (fitted by Näslund H-D function) showed the highest values in the case of healthy trees from both locations, followed by trees with minor damage and trees with extensive damage. The graphic depiction of functions together with relevant R-squared values are shown in Fig. 3. At both locations, healthy trees showed highest Height-Diameter ratio, followed by trees with minor damage and trees with extensive damage. The fitted parameters for Näslund H-D function were the following: the Stříbro location – Healthy trees ($a = 0.186$, $b = 0.896$), Minor damage ($a = 0.195$, $b = 0.851$), Extensive damage ($a = -0.195$, $b = -0.925$); the Klášterec n. Ohří location – Healthy trees ($a = 0.168$, $b = 1.522$), Minor damage ($a = 0.168$, $b = 1.673$), Extensive damage ($a = 0.171$, $b = 1.745$).

3.2. Bark stripping and stem rot

Damage caused by bark stripping was found in 77.3% trees in the Stříbro location (sika deer) and 88.8% trees in the Klášterec location (red deer). In damaged trees, the mean circumferential damage by bark stripping was 27.8% of stem in Stříbro and 32.0% in Klášterec. Out of 679 trees examined for estimation of production parameters (at both locations together), 250 (37%) were classified as healthy trees (the bark-stripping damage did not reach 1/8 of stem circumference). Minor damage was observed on 240 trees (35%) and extensive damage (the bark-stripping damage reached over 1/3 of stem circumference) was observed in the rest (189 trees; 28%; Fig. 4).

On average, trees were damaged to the height of 87.9 (σ 18.0) cm above ground in Stříbro and 128.2 (σ 27.7) cm in Klášterec. The Wilcoxon rank sum-test showed highly significant differences ($W = 8786$, $p < 0.001$). The length of the damage (along the stem) was 39.0 cm (σ 24.5) cm in Stříbro and 73.7 (σ 38.5) cm in Klášterec – the Wilcoxon rank-sum test revealed significant differences between these locations ($W = 19297$, $p < 0.001$).

The relationship between the current visible tree the grit damage and the rot-damaged crosscut area at the spot of the highest damage on the stem was evaluated. Linear regression showed that damaged girth is a significant factor in predicting damaged crosscut area at both locations ($p < 0.001$ in both cases). The R-squared values were 0.61 in the case of Klášterec, and 0.46 in the case of Stříbro. Regression function together with its graphic depiction and other data are depicted in Fig. 5.

Further modeling describes the distribution of stem rot along the trunk segments. The rot-damaged crosscut area at the damaged place on the stem was taken as a reference (100%). The relationship between the relative damaged area to the distance from the damaged place on the stem was assessed by regression via quadratic function. The R-squared reached value 0.52 in Stříbro and 0.30 in Klášterec. The depictions of regression functions together with their equations are shown in Fig. 6.

In the Stříbro location, the stem rot reached maximally up to 4.52 (mean 1.92) m of height (inside the stem), in the Klášterec location up to 6.04 (mean 3.07) m. First damage was observed at 11 years of age on average in Stříbro, 14 years of age in Klášterec, respectively. That means, the average speed of rot spreading upwards through the stem was observed to be 5.65 cm yr^{-1} in Stříbro and 9.59 cm yr^{-1} in Klášterec. The dependence of the tree age and damaged girth at the first occurrence of bark-stripping on the length of the stem rot on the higher part of the stem is explained in detail by a linear model (Table 1, Fig. 7). In relation to fungal pathogen species, 91.9% samples were classified as rot caused by *Stereum sanguinolentum* and 8.1% by *Heterobasidion annosum*.

The timber volume degradation due to stem rot relative to overall volume of negotiable timber (log with the thinner-end diameter > 7 cm) showed marginally insignificant differences between both locations. The mean degraded timber volume was 29.6% in Stříbro and 39.3% in Klášterec – the Wilcoxon rank-sum test: $W = 282$, $p = 0.09$.

Fig. 4. Heavily bark-stripped Norway spruce stem with subsequent rot infection by *Stereum sanguinolentum* measured in software Gnuplot 5.2 (left) and vertical rot development in the stem (right).

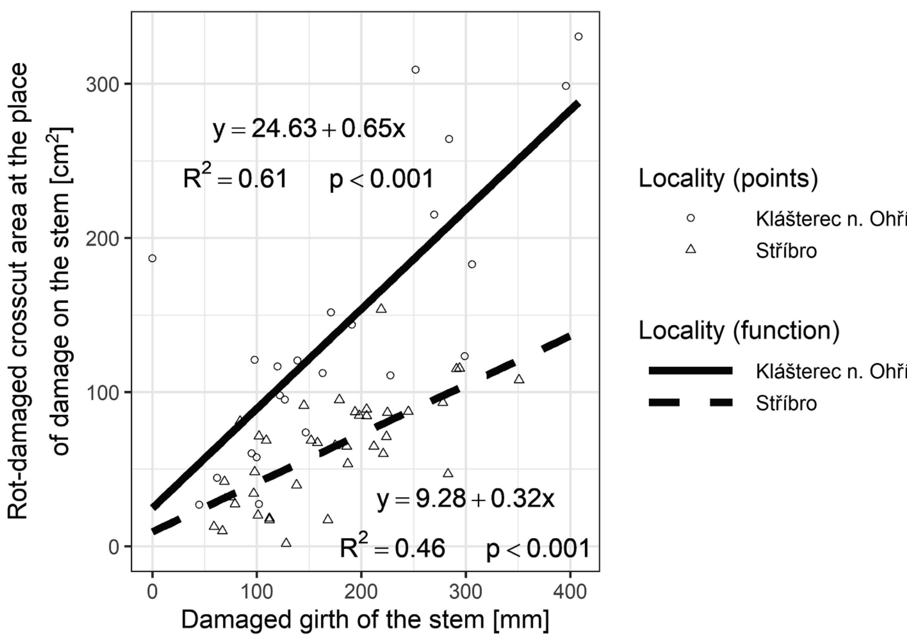

Fig. 5. The relationship between the current visible tree girth damage (in millimeters) and the rot-damaged crosscut area at the spot of the highest damage on the stem. Displayed p-values are for null hypothesis that × parameter in regression function is equal to zero.

3.3. Dynamics of radial growth and effect of climate

The highest mean value of tree-ring width was found in healthy trees in Stříbro (sika deer), while the lowest mean was found in trees with the extensive damage in Klášterec (red deer; Table 2). In both locations, the highest mean radial growth was observed in healthy trees, while the increment decreased with the increasing size of damage. Standard deviation of radial growth was the highest in the trees with extensive damage. The mean sensitivity was the lowest in healthy trees. The SNR shows the best dendrochronological pattern (without any noise) in healthy trees in Stříbro and the poorest in trees with extensive damage in Klášterec. This indicated that these variants with a higher SNR are more homogeneous than variants with a low SNR. Reliability of a chronology was significant (EPS > 0.850) in all variants except trees with extensive damage in Klášterec (0.845).

The dynamics of radial growth in Norway spruce showed the general trend of healthy trees' growth which was higher compared to the damaged variants (Fig. 8). Healthy trees and trees with minor damage showed higher similarity compared to differences in trees with minor and extensive damage, especially in the Klášterec location. The years of an extremely low radial growth are apparent. The low diameter increments in the Stříbro location that occurred in 2003 and 2015 qualified them as significant negative pointer years. Year 2003 was the driest year recorded since 1961 (the beginning of meteorological measurements) through 2019 (304 mm, long-term mean 488 mm), especially with respect to the growing season (196 mm, long-term mean 325 mm). In 2015, lower diameter increments were caused by extremely high temperatures (annual temperature 9.9 °C, long-term mean 7.9 °C), with low amounts of precipitation in summer months (monthly precipitation 40 mm, long-term mean 62 mm). Moreover, significant negative pointer year 1998 was observed for trees with extensive damage. The first half of 1998 had the warmest recorded temperatures (8.2 °C, long-term mean 6.1 °C).

Similarly, a significant negative pointer year 2003 was observed for radial growth of spruce in FMU Klášterec for years 2013 and 2018 (Fig. 8). Year 2003 was also in this FMU characterized by extreme droughts with the lowest amount of precipitation in March ever recorded from 1961 to 2019 (7 mm, long-term mean 34 mm). Also, year 2018 was characterized by extremely low precipitation amounts in the growing season, especially with the historically minimum in August

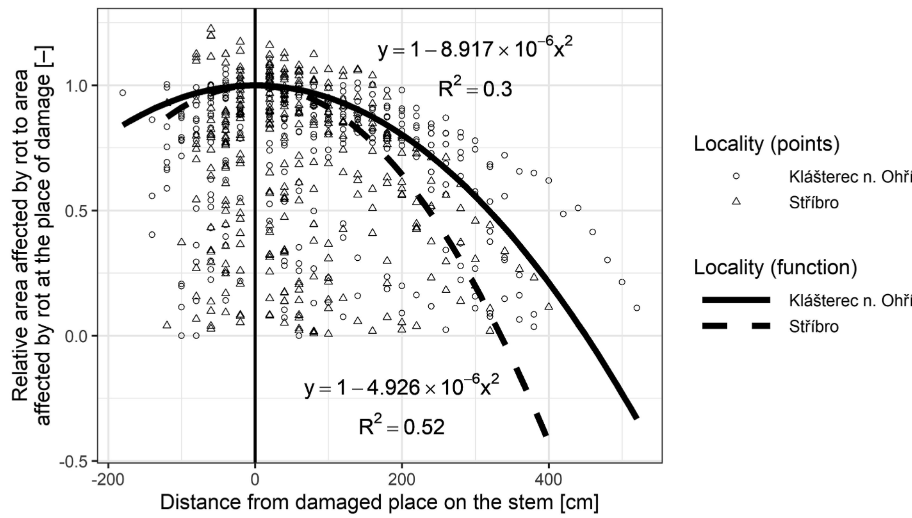

Fig. 6. Distribution of stem rot along the trunk segments. Quadratic regression was used to fit the regression curves. The vertical line depicts the value at the spot of damage (equal to 1; 100%), to which all the other values are related.

Table 1
The results of the general linear model for estimation of stem-rot damage extent based on the first damage parameters.

Dependent value: The length of the stem-rot damage from the bark-stripped place on the stem [cm]					
Locality: Stříbro	$R^2 = 0.55$		*Locality: Klášterec n. Ohří*	$R^2 = 0.35$	
Parameter	Coefficient	p-value	Parameter	Coefficient	p-value
[Intercept]	−62.75	0.07	[Intercept]	−25.07	0.74
Age at the first damage occurrence	4.18	0.02	Age at the first damage occurrence	2.03	0.62
Damaged girth by the first damage occurrence (%)	4.43	< 0.001	Damaged girth by the first damage occurrence (%)	4.57	0.007

(10 mm, long-term mean 63 mm), and also by the highest temperature in April (11.0 °C, long-term mean 7.1 °C) and May (14.5 °C, long-term mean 11.7 °C). The year 2013 was characterized by late frosts; the lowest temperature in March was observed (-2.3 °C, long-term mean 2.5 °C). Also, there was extremely overcast weather in the first half of 2013 (monthly 78 h of sunshine, long-term mean 142 h). Moreover, a significant lower increment was analyzed for year 1996 in the variant with extensive damage. In 1996, the highest number of days with snow cover occurred (115 days, long-term mean 62 days) and of ice days (81 days, long-term mean 39 days) since 1961.

Comparing growth variability (standard deviation) of particular variants in Stříbro, the highest variability of the ring width index was observed in trees with extensive damage, while relatively balanced growth was documented in healthy trees. A similar situation was observed also in Klášterec.

Regarding the effects of precipitation in 1995–2019, significant ($p < 0.05$) positive correlations were observed in 3 (Stříbro) or 4 (Klášterec) months in the case of trees with extensive damage compared to healthy trees (2 and 1 significant correlation; Fig. 9). Trees with extensive damage showed the highest sensitivity to a lack of precipitation. Temperature correlations show opposite trends. The lowest effect of temperature was observed in the case of trees with extensive damage, but the differences among variants were lower compared to precipitation. Generally, temperature had a higher effect on radial growth in the study area compared to the precipitation. The highest effect of precipitation and temperature on radial growth was observed in January–March and then in August of the current year, the most

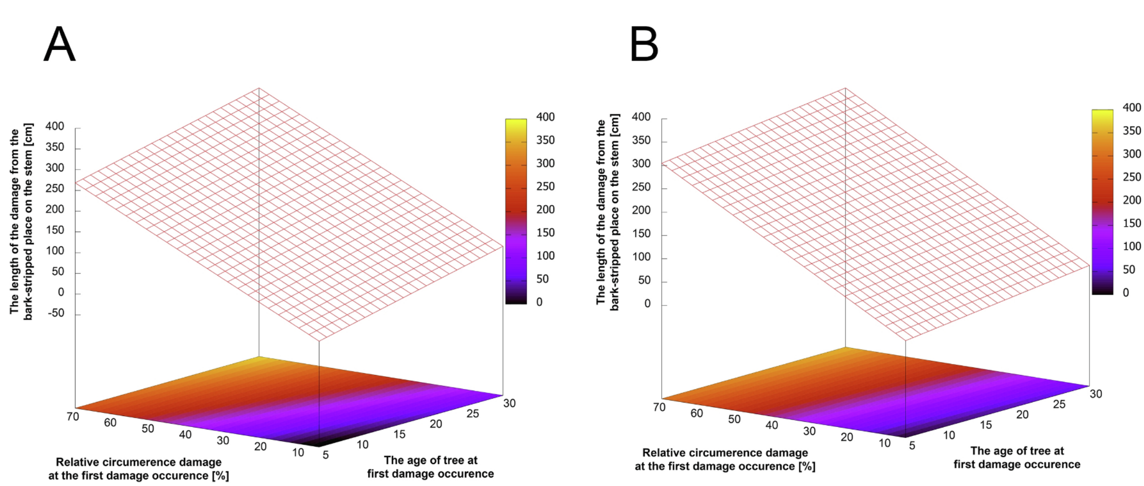

Fig. 7. Graphic depiction of a linear model for the estimation of the extent of stem-rot damage based on the first trunk damage parameters (age and bark-stripped girth at the first occurrence of bark stripping damage); location A – Stříbro (sika deer), location B – Klášterec nad Ohří (red deer).

Table 2
Characteristics of tree-ring width chronologies of the spruce of healthy trees (HT), trees with minor damage (MD) and with extensive damage (ED) in Stříbro (sika deer) and Klášterec nad Ohří (red deer).

ID	No. trees (pcs)	Mean RW (mm)	Mean σ	MS	R-bar	SNR	EPS	Negative pointer years
Stříbro								
HT	23	3.666	1.520	0.352	0.417	6.442	0.892	2003, 2015
MD	23	3.371	1.590	0.378	0.301	5.258	0.881	2003, 2015
ED	22	3.019	1.684	0.412	0.212	4.570	0.852	1998, 2003, 2015
Klášterec n. Ohří								
HT	24	3.021	1.306	0.292	0.211	5.195	0.856	2003, 2013, 2018
MD	24	2.965	1.350	0.410	0.221	4.651	0.876	2003, 2013, 2018
ED	24	2.295	1.414	0.316	0.189	3.321	0.845	1996, 2003, 2013, 2018

Notes: No. trees – number of analyzed and used core samples, RW – tree-ring width, σ – standard deviation, MS – mean sensitivity, R-bar – interseries correlation, SNR – signal-to-noise ratio, EPS – expression population signal.

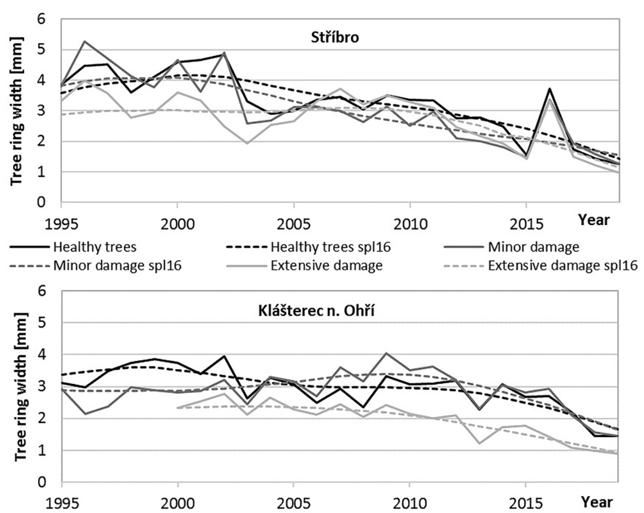

Fig. 8. Annual tree-ring width of Norway spruce for healthy trees (1), trees with minor damage (2) and with extensive damage (3) in the Stříbro location (sika deer) and the Klášterec nad Ohří location (red deer) and relevant smoothing 16-year spline; only the ring width series with EPS value ≥ 0.85 are displayed.

significant month being February (9 significant correlations).

4. Discussion

In this study, the differences in production parameters of Norway spruce stands in relation to bark damage were confirmed. The main indicator – the mean stem volume was 71% lower in heavily damaged trees in Klášterec and by 50% in Stříbro compared to healthy trees. Similar results were reported from older Norway spruce stands where the stand volume of heavily damaged trees was almost half (Cukor et al., 2019a). Lower characteristics were also observed in the other characteristics, like height and DBH of the tree. However, bark stripping does not affect only the tree growth, but consequently also the wood quality, by allowing fungal pathogens to enter. Root rot is also found in the stem of visually healthy trees. Surprisingly, no significant differences between the diameter growth of trees with root rot and healthy trees were observed in spruce stands in Estonia (Allikmäe et al., 2017). No significant differences in the volume of wood decayed by *Heterobasidion* spp. were confirmed in a study from Sweden (Rönnberg et al., 2013) as well. These facts indicate that the differences in growth characteristics are caused by a lower circumference, which transports water with nutrients into the upper parts of the tree. Conversely, significant losses in diameter growth were observed in trees in Sweden infected by fungal pathogens in the range of 9–20% without damage caused by deer. The spread of root rot in the stem increased with the stand age (Bendz-Hellgren and Stenlid, 1995), similar to our case.

Vertically, the stem rot reached a maximum height of 4.52 m (mean 1.92 m) inside the stem in Stříbro and 6.04 m (mean 3.07 m) in Klášterec. Similarly, (Čermák et al., 2004b) documented a decay range from 2.5 to 4.5 m in a stand of a comparable age. Another study from the Czech Republic describes the average rot development from 1.25 m in the third age class to 4.38 m in the seventh age class in Norway spruce stands (Šafránek et al., 2016). The average height of the decay column was 4 m in older spruce stands at the total stand age of 74–75 years in Sweden (Rönnberg et al., 2013), however, these trees were not bark-stripped by ungulates. The average speed of rot spreading upwards through the stem was observed to be 5.65 cm yr^{-1} in the Stříbro location and 9.59 cm yr^{-1} in the Klášterec location. The results from Klášterec are totally consistent with the mean progress of rot 9 cm yr^{-1} in Moravia (Czech Republic), for example. The damage was also caused by red deer in this location (Čermák et al., 2004b) as was the case in the Klášterec area. The annual rot progress depends on the age of stands. In younger stands the rot growth was 11.8 cm yr^{-1} and in the older stands (6th and 7th age class) it was 2.7 cm yr^{-1} (Šafránek et al., 2016). Other studies (e.g. Čermák and Strejček, 2007) determined progress of the rot caused by *Stereum sanguinolentum* ranged from 13.3 to 19.5 cm yr^{-1}, also depending on the age of the trees.

The results suggest that the stem rot was highly developed in the area where the damage was caused by red deer. This fact is probably related to the different body condition of both deer species. The sika deer is a small to medium-sized *Cervidae* species with a shoulder height between 94 (female) to 105 cm (male). The body mass ranges from 102.8 to 151.0 kg in adult males and 68.0 and 99.8 kg in adult females according to seasonal fluctuations. However, these data are reported from Japan (Suzuki et al., 2001). The sika deer individuals seem to be smaller in Central Europe than in their native range. The average shoulder height reaches 95 cm in the Czech Republic, and the average body mass around 55 kg (Červený, 2003). More accurate data from our area of interest (FMU Stříbro) were published by Hanzal et al., (2018) when the average body weight was about 42 kg when the five year old males have 88 kg on average. On the other hand, the shoulder height of red deer males is about 150 cm and body weight up to 250 kg, while the weight of does is less by a third (Červený, 2003). This also corresponds with the height of the center of damage on the stem, which was 87.9 cm above ground in the Stříbro location (damage caused by sika deer) and 128.2 cm in the Klášterec location (red deer). However, the center of the bark stripping caused in winter could also be affected by snow cover at higher altitudes. General information describes the height of damage on the stem in a ratio between 50 and 100 cm (Gill, 1992) without a detailed distinction of deer species which caused the damage. The length of the damage (along the stem) was observed to be 39.0 cm in Stříbro and 73.7 cm in the case of Klášterec. Moreover, the initial damage caused by sika deer was observed in forest stands aged 11 years on average and in 14 years old stands in locations with red deer population. The damage can be initiated when the density of branches decreases with age and the stem becomes accessible to deer (Gill,

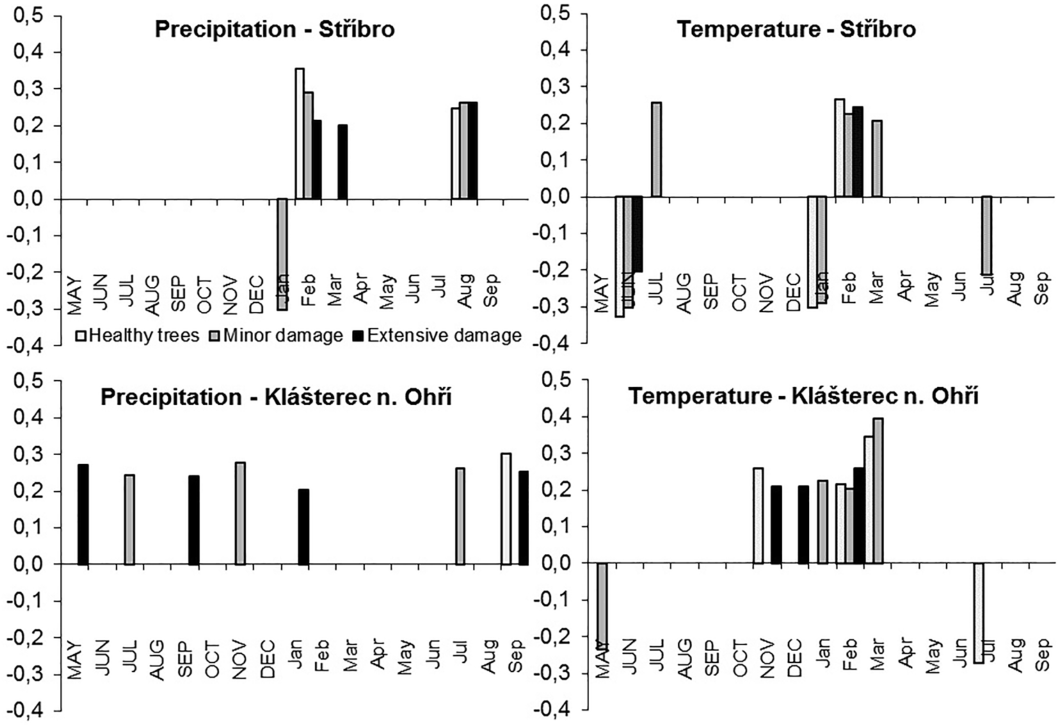

Fig. 9. The values of the correlation coefficients of the standardized tree-ring width chronology with the monthly precipitation and temperatures from May of the previous year (capital letters) to September of the current year (small letters) for the period 1995–2019 for Norway spruce in Stříbro (sika deer) and Klášterec nad Ohří (red deer); correlation coefficients with statistically significant values ($\alpha = 0.05$) are displayed.

1992). Therefore, the stem seems vulnerable earlier for smaller *Cervidae* species – sika deer in the case of our study.

In general, more than 20% of the total volume of harvested timber was damaged by stem rot at the beginning of 21st century in the Czech Republic (Půlpán, 2001). Similar rates of stem rot damage are reported from Scandinavia, where about 14% of Norway spruce is damaged by root rot at the stump height, according to Swedish National Forest Inventory (Thor et al., 2006). In our case, the main fungal pathogen causing wood rot was *Stereum sanguinolentum*, similar to other studies in the Czech Republic (Čermák et al., 2004a, 2004c) and also in other countries (Mäkinen et al., 2007). The average volume of economic losses due to the spread of rot in the Czech Republic is increasing (Malík and Karnet, 2007). In the European Union, annual losses attributed to growth reduction and degradation of wood are estimated at € 790 million, of which about € 120 million are accounted for by Sweden and Finland (Woodward et al., 1998; Pukkala et al., 2005). Specifically, rot damage caused by *Stereum sanguinolentum* create an economic loss amounting to € 2.5 thousands per hectare of forest stands (Čermák et al., 2004c) while total losses caused by bark stripping reached an average of € 10.2 thousands per hectare in the Czech Republic (Simon and Kolář, 2001). Other sources estimate the loss caused by root rot damage by *Heterobasidion* species annually amount to € 0.5–1 billion for the whole of Scandinavia (Bendz-Hellgren and Stenlid, 1995; Rönnberg et al., 2013). So far, despite its biological and economic importance, *Stereum sanguinolentum* and *Heterobasidion annosum* have been largely overlooked in practical forest planning (Čermák et al., 2004a; Thor et al., 2006). Conclusively, early thinning appears to be more important for the disease development than subsequent multiple thinning. To restrict the disease development in the stand later during the rotation period, it is of the utmost importance that the earlier thinning is done during winter, or otherwise properly protected against fungal spore infection (Rönnberg et al., 2013). The importance of responsible thinning of heavily bark-stripped trees followed by lower timber production was confirmed in previous studies (Cukor et al., 2019a, 2019b).

Game damage must be assessed in relation to ongoing environmental changes, especially global climatic change. In relation to the increasing threat of climate change, European forests have faced several unprecedented weather events in recent years (Seidl et al., 2014; Nagel et al., 2017). Tree growth is strongly affected and limited by ongoing warming, uneven distribution of precipitation, more frequent droughts, wind disturbances and other climatic extremes (Primicia et al., 2015; Seidl et al., 2017). Similarly, the limiting factors of radial growth in the studied area were especially extreme droughts, and synergism of high temperatures and a lack of precipitation. In all cases, a significant decrease was observed in 2003 due to extreme low precipitation and high temperatures in the growing season, similar to other spruce stands in the Czech Republic (Šrámek et al., 2008; Rybníček et al., 2010). Conversely, a late frost and extreme snow cover had a negative effect on radial growth as well. The highest effect of climate factors on radial growth was observed in February, followed by January, March and August of the current year. A positive effect of temperature from January to May (especially March) was also observed in other spruce stands at comparable altitudes (Rybníček et al., 2010; Petráš and Mecko, 2011; Mikulenka et al., 2020). On the other hand, these studies documented the most significant month in relation to precipitation as June and July, however in our case, it was August. Wimmer and Grabner (1997) observed significant effects of climatic factors on radial growth and resin duct density of Norway spruce from June to August. This can be explained by climatic conditions in this period, when a great part of radial increment is produced (Putalová et al. 2019). Regarding xylem formation and stem radius increase in May, the fastest daily increments were recorded in June and July, with a slowdown in August (Mäkinen et al. 2003).[3] Temperature had a higher effect on radial growth in the study area compared to precipitation. Similarly, a prevalent positive effect of temperature was observed in other submontane and montane areas in Europe (Král et al., 2015; Sidor et al., 2015; Vacek et al., 2015a, 2017b). The limiting effect

[3] (Mäkinen et al., 2003)

of low temperatures was more significant on high-altitude sites, while the importance of precipitation increased with decreasing altitude (Mäkinen et al., 2002; Savva et al., 2006).

Bark stripping had a significant effect on both variability/stability of radial growth and sensitivity to climatic factors. Other research from eastern Czechia (Cukor et al., 2019a) and southern Finland (Mäkinen et al., 2001) also confirmed higher sensitivity of damaged trees to the climate factors compared to healthy trees. In our case, drought and a lack of precipitation were significant limiting factors for growth of extensively damaged trees, while the effect of precipitation was low in healthy trees. Conversely, increased temperature had a higher effect on healthy trees due to sufficient water supply, but differences among variants were lower compared to precipitation. Damaged trees also showed higher variability in radial growth. Similarly, in Switzerland (Meyer and Brker, 2001) and in other parts of Czechia (Cukor et al., 2019a), precipitation had a larger effect on the radial growth of damaged trees compared to healthy trees. On the other hand, higher temperatures were associated with increasing growth in the healthy trees, but not in the damaged ones (Mäkinen et al., 2001). Higher drought stress in damaged trees (interfered hydraulic conductance of wood) with secondary rot infection significantly reduces not only mechanical stability of individual spruce trees, but of all forest stands, en masse (Čermák et al., 2004a; Krisans et al., 2020). The escalating frequency of droughts and windstorms in the last decades (Usbeck et al., 2010) significantly increases the susceptibility of these stands to disturbances, having already been damaged by bark stripping. Moreover, the losses in the Czech forestry sector due to climatic change and subsequent attacks on weakened Norway spruce stands by bark beetle reached around € 1.12 billion in 2019 (Toth et al., 2020).

5. Conclusion

Our study confirmed an urgent need for fundamental change in the management approach to commercial forests in the Czech Republic. In both study locations, game damage to the stands exceeded the acceptable economic and environmental limits. Due to the high density of sika deer and red deer, there was a high risk of game damage to young spruce forests stands by bark stripping and subsequent stem rot spread. With respect to production, trees with minor damage showed on average a 25–28% less stem volume than healthy trees, and in the case of heavily damaged trees, the stem volume reduction amounted to 50–71%. The mean decayed wood reached 30–39% of the merchantable volume. We also assume that the static stability of trees was significantly impaired, as damaged trees responded worse to the lack of precipitation and droughts compared to healthy trees. All of these factors lead to a higher susceptibility of forest stands to biotic and abiotic disturbances. Harmonization of hunting and silvicultural management should increase the resistance of forests to global climate change. The recommended hunting measures include a significant reduction in game numbers, and, possibly, the use of overwintering game enclosures. More intensive first tending interventions (increased tree spacing) leading to the formation of long and dense branches, which will prevent the game from accessing the stem. An increase in the share of palatable admixed tree species and individual protection will also decrease the probability of game damage on target trees.

CRediT authorship contribution statement

Zdeněk Vacek: Data curation, Resources, Writing - original draft, Writing - review & editing. **Jan Cukor:** Conceptualization, Data curation, Funding acquisition, Resources, Project administration, Methodology, Validation, Writing - original draft, Writing - review & editing. **Rostislav Linda:** Conceptualization, Data curation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **Stanislav Vacek:** Conceptualization, Methodology, Validation, Supervision, Writing - original draft. **Václav Šimůnek:** Data curation, Writing - original draft. **Jakub Brichta:** Data curation, Writing - original draft. **Josef Gallo:** Data curation, Writing - original draft. **Anna Prokůpková:** Data curation, Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Agnoletti, M., Emanueli, F., Corrieri, F., Venturi, M., Santoro, A., 2019. Monitoring traditional rural landscapes. The case of Italy. Sustain. 11, 6107. https://doi.org/10.3390/su11216107.

Akashi, N., Nakashizuka, T., 1999. Effects of bark-stripping by Sika deer (Cervus nippon) on population dynamics of a mixed forest in Japan. For. Ecol. Manage. 113, 75–82. https://doi.org/10.1016/S0378-1127(98)00415-0.

Allikmäe, E., Laarmann, D., Korjus, H., 2017. Vitality assessment of visually healthy trees in Estonia. Forests 8, 223. https://doi.org/10.3390/f8070223.

Ambrož, R., Vacek, S., Vacek, Z., Král, J., Štefančík, I., 2015. Current and simulated structure, growth parameters and regeneration of beech forests with different game management in the Lány Game Enclosure. Cent. Eur. For. J. 61, 78–88. https://doi.org/10.1515/forj-2015-0016.

Assandri, G., Bogliani, G., Pedrini, P., Brambilla, M., 2019. Species-specific responses to habitat and livestock management call for carefully targeted conservation strategies for declining meadow birds. J. Nat. Conserv. 52, 125757. https://doi.org/10.1016/j.jnc.2019.125757.

Arhipova, N., Gaitnieks, T., Donis, J., Stenlid, J., Vasaitis, R., 2011. Butt rot incidence, causal fungi, and related yield loss in Picea abies stands of Latvia. Can. J. For. Res. 41, 2337–2346.

Assefa, A., Abate, D., 2018. Assessment of wounding factors (natural and anthropogenic) of Juniperus procera and their relation to disease occurrence of Pyrofomes demidofffii in some afromontane forests of Ethiopia. For. Ecol. Manage. 409, 361–371. https://doi.org/10.1016/j.foreco.2017.11.031.

Baltzinger, M., Mårell, A., Archaux, F., Pérot, T., Leterme, F., Deconchat, M., 2016. Overabundant ungulates in French Sologne? Increasing red deer and wild boar pressure may not threaten woodland birds in mature forest stands. Basic Appl. Ecol. 17, 552–563. https://doi.org/10.1016/j.baae.2016.04.005.

Barančeková, M., Krojerová-Prokešová, J., Voloshina, I.V., Myslenkov, A.I., Kawata, Y., Oshida, T., Lamka, J., Koubek, P., 2012. The origin and genetic variability of the Czech sika deer population. Ecol. Res. 27, 991–1003. https://doi.org/10.1007/s11284-012-0992-y.

Barja, I., Rosellini, S., 2008. Does habitat type modify group size in roe deer and red deer under predation risk by Iberian wolves? Can. J. Zool. 86, 170–176. https://doi.org/10.1139/Z07-129.

Bendz-Hellgren, M., Stenlid, J., 1995. Long-term reduction in the diameter growth of butt rot affected Norway spruce, Picea abies. For. Ecol. Manage. 74, 239–243. https://doi.org/10.1016/0378-1127(95)03530-N.

Bílek, L., Vacek, S., Vacek, Z., Remeš, J., Král, J., Bulušek, D., Gallo, J., 2016. How close to nature is close-to-nature pine silviculture? J. For. Sci. 62, 24–34. https://doi.org/10.17221/98/2015-JFS.

Bílek, L., Vacek, Z., Vacek, S., Bulušek, D., Linda, R., Král, J., 2018. Are clearcut borders an effective tool for Scots pine (*Pinus sylvestris* L.) natural regeneration? For. Syst. 27, e010. https://doi.org/10.5424/fs/2018272-12408.

Biondi, F., Waikul, K., 2004. DENDROCLIM2002: A C++ program for statistical calibration of climate signals in tree-ring chronologies. Comput. Geosci. 30, 303–311. https://doi.org/10.1016/j.cageo.2003.11.004.

Bolte, A., Ammer, C., Löf, M., Madsen, P., Nabuurs, G.J., Schall, P., Spathelf, P., Rock, J., 2009. Adaptive forest management in central Europe: Climate change impacts, strategies and integrative concept. Scand. J. For. Res. 24, 473–482. https://doi.org/10.1080/02827580903418224.

Borkowski, J., Banul, R., Jurkiewicz, J., Hołdyński, C., Świeczkowska, J., Nasiadko, M., Załuski, D., 2019. High density of keystone herbivore vs. conservation of natural resources: Factors affecting red deer distribution and impact on vegetation in Słowiński National Park, Poland. For. Ecol. Manage. 450, 117503. https://doi.org/

10.1016/j.foreco.2019.117503.
Brang, P., Fontana, G., Innes, J.L., Cherubini, P., Dobbertin, M., Rigling, D., 2002. Tree-life history prior to death: two fungal root pathogens affect tree-ring growth differently. J. Ecol. 90, 839–850.
Brazaitis, G., Petelis, K., Žalkauskas, R., Belova, O., Danusevičius, D., Marozas, V., Narauskaite, G., 2014. Landscape effect for the Cervidaes Cervidae in human-dominated fragmented forests. Eur. J. For. Res. 133, 857–869. https://doi.org/10.1007/s10342-014-0802-x.
Bunn, A.G., 2010. Statistical and visual crossdating in R using the dplR library. Dendrochronologia 28, 251–258. https://doi.org/10.1016/j.dendro.2009.12.001.
Bunn, A.G., 2008. A dendrochronology program library in R (dplR). Dendrochronologia 26, 115–124. https://doi.org/10.1016/j.dendro.2008.01.002.
Caudullo, G., De Battisti, R., Colpi, C., Vazzola, C., Da Ronch, F., 2003. Ungulate damage and silviculture in the Cansiglio forest (Veneto Prealps, NE Italy). J. Nat. Conserv. 10, 233–241. https://doi.org/10.1078/1617-1381-00023.
Carden, R.F., Carlin, C.M., Marnell, F., McElholm, D., Hetherington, J., Gammell, M.P., 2011. Distribution and range expansion of deer in Ireland. Mamm. Rev. 41, 313–325. https://doi.org/10.1111/j.1365-2907.2010.00170.x.
Čermák, P., Glogar, J., Jankovský, L., 2004a. Damage by deer barking and browsing and subsequent rots in Norway spruce stands of Forest Range Mořkov, Forest District Frenštát p. R. (the Beskids Protected Landscape Area). J. For. Sci. 50, 24–30.
Čermák, P., Jankovský, L., Glogar, J., 2004b. Progress of spreading Stereum sanguinolentum (Alb. et Schw.: Fr.) Fr. wound rot and its impact on the stability of spruce stands. J. For. Sci. 50, 360–365.
Čermák, P., Jankovský, L., Lička, D., Beránek, J., Glogar, J., 2004c. Damage to spruce stands by deer barking and subsequent rots in Forest range Proklest, the Křtiny Training Forest Enterprise "Masaryk Forest" (the Drahany Upland). Acta Univ. Agric. Silvic. Mendel. Brun. 52, 165–174.
Čermák, P., Mrkva, R., Horsák, P., Špiřík, M., Beranová, P., Orálková, J., Plšek, J., Kadlec, M., Zárybnický, O., Svatoš, M., 2011. Impact of ungulate browsing on forest dynamics. Folia For. Bohem. 20, 80.
Čermák, P., Strejček, M., 2007. Stem decay by Stereum sanguinolentum after red deer damage in the Českomoravská vrchovina Highlands. J. For. Sci. 53, 567–572.
Červený, J., 2003. Encyklopedie myslivosti. Ottovo nakladatelství.
Côté, S., Rooney, T., Tremblay, J.-P., Dussault, C., Waller, D., 2004. Ecological impacts of deer overabundance. Annu. Rev. Ecol. Evol. Syst. 35, 113–147. https://doi.org/10.2307/annurev.ecolsys.35.021103.30000006.
Cukor, J., Linhart, L., Vacek, Z., Baláš, M., Linda, R., 2017. The effects of Alginite fertilization on selected tree species seedlings performance on afforested agricultural lands. Cent. Eur. For. J. 63. https://doi.org/10.1515/forj-2017-0001.
Cukor, J., Vacek, Z., Linda, R., Prasad, R.S., Vacek, S., 2019a. Afforested farmland vs. forestland: Effects of bark stripping by Cervus elaphus and climate on production potential and structure of Picea abies forests. PLoS One 14, 1–25.
Cukor, J., Vacek, Z., Linda, R., Vacek, S., Marada, P., Šimůnek, V., Havránek, F., 2019b. Effects of bark stripping on timber production and structure of Norway Spruce forests in relation to climatic factors. Forests 10, 13–17. https://doi.org/10.3390/f10040320.
Dobrowolska, D., Załuski, D., Dąbrowski, W., Banul, R., Borkowski, J., 2020. Factors affecting admixed pedunculate oak growth under heavy browsing by deer: benefits from inter- and intraspecific neighbourhoods. Eur. J. For. Res. 139, 155–167. https://doi.org/10.1007/s10342-020-01268-6.
El Atta, H.A., Hayes, A.J., 1987. Decay in Norway spruce caused by Stereum sanguinolentum Alb. & Schw. ex Fr. developing from extraction wounds. Forestry 60, 1–111.
Fattebert, J., Baubet, E., Slotow, R., Fischer, C., 2017. Landscape effects on wild boar home range size under contrasting harvest regimes in a human-dominated agro-ecosystem. Eur. J. Wildl. Res. 63, 32. https://doi.org/10.1007/s10344-017-1090-9.
Fritts, H.C., 1976. Tree rings and climate. Academic Press, New York.
Gallo, J., Bílek, L., Šimůnek, V., Roig, S., Bravo Fernández, J.A., 2020. Uneven-aged silviculture of Scots pine in Bohemia and Central Spain: Comparison study of stand reaction to transition and long-term selection management. J. For. Sci. 66, 22–35. https://doi.org/10.17221/147/2019-JFS.
Garbelotto, M., Gonthier, P., 2013. Biology, epidemiology, and control of heterobasidion species worldwide. Annu. Rev. Phytopathol. 51, 39–59. https://doi.org/10.1146/annurev-phyto-082712-102225.
Gill, R.M.A., 1992. A review of damage by mammals in north temperate forests: 1. Deer. Forestry 65, 145–169. https://doi.org/10.1093/forestry/65.2.145.
Gill, R.M.A., Beardall, V., 2001. The impact of deer on woodlands: The effects of browsing and seed dispersal on vegetation structure and composition. Forestry 74, 209–218. https://doi.org/10.1093/forestry/74.3.209.
Hagen, R., Heurich, M., Kröschel, M., Herdtfelder, M., 2014. Synchrony in hunting bags: Reaction on climatic and human induced changes? Sci. Total Environ. 468–469, 140–146. https://doi.org/10.1016/j.scitotenv.2013.08.022.
Hanzal, V., Košinová, K., Pokorný, R., Janiszewski, P., Hart, V., 2018. Weight parameters of body parts in sika deer (Cervus nippon nippon) from the Konstantinolázeňsko microregion, the Czech Republic. Cent. Eur. For. J. 64, 16–23. https://doi.org/10.1515/forj-2017-0027.
Jaedrzejewski, W., Spaedtke, H., Kamler, J.F., Jaedrzejewska, B., Stenkewitz, U., 2006. Group size dynamics of red deer in białowieża primeval forest, Poland. J. Wildl. Manage. 70, 1054–1059. https://doi.org/10.2193/0022-541x(2006)70[1054:gsdord]2.0.co;2.
Kiffner, C., Rößiger, E., Trisl, O., Schulz, R., Rühe, F., 2008. Probability of recent bark stripping damage by red deer (Cervus elaphus) on Norway spruce (Picea abies) in a low mountain range in Germany - A preliminary analysis. Silva Fenn. 42, 125–134.
Konôpka, B, Pajtík, J, Bošeľa, M, Šebeň, V, Shipley, LA, 2019. Modeling forage potential for red deer (Cervus elaphus): a tree-level approach. Eur. J. For. Res. https://doi.org/10.1007/s10342-019-01250-x.
Köppen, W., 1931. Grundriss der Klimakunde. (Zweite, verbesserte Auflage der Klimate der Erde.). Walter de Gruyter & Co., Berlin.
Kosmala, M., Suchocka, M., 2008. Influence of mechanical damage on the condition of trees.
Kraft, G., 1884. Beiträgezur zur lehre von den durchforstungen, schlagstellungen und lichtungshieben. Klindworth, Hannover, Germany.
Král, J., Vacek, S., Vacek, Z., Putalová, T., Bulušek, D., Štefančík, I., 2015. Structure, development and health status of spruce forests affected by air pollution in the western Krkonoše Mts. in 1979–2014. For. J. 61, 175–187. https://doi.org/10.1515/forj-2015-0026.
Králíček, I., Vacek, Z., Vacek, S., Remeš, J., Bulušek, D., Král, J., Štefančík, I., Putalová, T., 2017. Dynamics and structure of mountain autochthonous spruce-beech forests: Impact of hilltop phenomenon, air pollutants and climate. Dendrobiology 77, 119–137. https://doi.org/10.12657/denbio.077.010.
Krisans, O., Saleniece, R., Rust, S., Elferts, D., Kapostins, R., Jansons, A., Matisons, R., 2020. Effect of bark-stripping on mechanical stability of Norway spruce. Forests 11, 357. https://doi.org/10.3390/f11030357.
Levers, C., Butsic, V., Verburg, P.H., Müller, D., Kuemmerle, T., 2016. Drivers of changes in agricultural intensity in Europe. Land Use Policy 58, 380–393. https://doi.org/10.1016/j.landusepol.2016.08.013.
Lorz, C., Fürst, C., Galic, Z., Matijasic, D., Podrázký, V., Potocic, N., Simonic, P., Strauch, M., Vacik, H., Makeschin, F., 2010. GIS-based probability assessment of natural hazards in forested landscapes of central and south-eastern Europe. Environ. Manage. 46, 920–930. https://doi.org/10.1007/s00267-010-9508-0.
Mäkinen, H., Nöjd, P., Kahle, H.P., Neumann, U., Tveite, B., Mielikäinen, K., Röhle, H., Spiecker, H., 2002. Radial growth variation of Norway spruce (Picea abies (L.) Karst.) across latitudinal and altitudinal gradients in central and northern Europe. For. Ecol. Manage. 171, 243–259. https://doi.org/10.1016/S0378-1127(01)00786-1.
Mäkinen, H., Nöjd, P., Mielikäinen, K., 2001. Climatic signal in annual growth variation in damaged and healthy stands of Norway spruce [Picea abies (L.) Karst.] in southern Finland. Trees - Struct. Funct. 15, 177–185. https://doi.org/10.1007/s004680100089.
Mäkinen, H., Nöjd, P., Saranpää, P., 2003. Seasonal changes in stem radius and production of new tracheids in Norway spruce. Tree Physiol. 23, 959–968. https://doi.org/10.1093/treephys/23.14.959.
Mäkinen, H., Hallaksela, A.M., Isomäki, A., 2007. Increment and decay in Norway spruce and Scots pine after artificial logging damage. Can. J. For. Res. 37, 2130–2141. https://doi.org/10.1139/X07-087.
Malík, V., Karnet, P., 2007. Game damage to forest trees. J. For. Sci. 53, 406–412.
Månsson, J., Jarnemo, A., 2013. Bark-stripping on Norway spruce by red deer in Sweden: level of damage and relation to tree characteristics. Scand. J. For. Res. 28, 117–125. https://doi.org/10.1080/02827581.2012.701323.
Meyer, FD, Brker, OU, 2001. Climate response in dominant and suppressed spruce trees, picea abies (L.) karst., on a subalpine and lower montane site in switzerland. Ecoscience 8, 105–114. https://doi.org/10.1080/11956860.2001.11682636.
Mikulenka, P., Prokůpková, A., Vacek, Z., Vacek, S., Bulušek, D., Simon, J., Šimůnek, V., Hájek, V., 2020. Effect of climate and air pollution on radial growth of mixed forests: *Abies alba* Mill. vs. *Picea abies* (L.). Karst. 66, 23–36. https://doi.org/10.2478/forj-2019-0026.
Motta, R., 1996. Impact of wild ungulates on forest regeneration and tree composition of mountain forests in the Western Italian Alps. For. Ecol. Manage. 88, 93–98. https://doi.org/10.1016/S0378-1127(96)03814-5.
Nagaike, T., 2019. Effects of heavy, repeated bark stripping by Cervus nippon on survival of Abies veitchii in a subalpine coniferous forest in central Japan. J. For. Res. https://doi.org/10.1007/s11676-019-00940-x.
Nagel, T.A., Mikac, S., Dolinar, M., Klopcic, M., Keren, S., Svoboda, M., Diaci, J., Boncina, A., Paulic, V., 2017. The natural disturbance regime in forests of the Dinaric Mountains: A synthesis of evidence. For. Ecol. Manage. 388, 29–42. https://doi.org/10.1016/j.foreco.2016.07.047.
Näslund, M, 1937. Skogsförsöksanstaltens gallringsförsök i tallskog, Medd. Statens Skogsförsöksanstalt. Swedish Institute of Experimental Forestry.
Opała-Owczarek, M., Błaś, M., Owczarek, P., Sobik, M., Godek, M., 2019. A dendroclimatological study of east- and west-facing slopes in mountainous areas subjected to strong air pollution (the Sudetes, Central Europe). Phys. Geogr. 40, 186–208. https://doi.org/10.1080/02723646.2018.1547872.
Pérez-Espona, S., Pemberton, J.M., Putman, R., 2009. Red and sika deer in the British Isles, current management issues and management policy. Mamm. Biol. 74, 247–262. https://doi.org/10.1016/j.mambio.2009.01.003.
Petráš, R., Mecko, J., 2011. Effect of climatic factors on the dynamics of radial increments of Norway spruce, European beech and sessile oak. J. For. Sci. 57, 293–302. https://doi.org/10.17221/49/2010-jfs.
Petráš, R., Pajtík, J., 1991. Sústava česko-slovenských objemových tabuliek drevín. For. J. - Lesn. časopis 37, 49–56.
Piri, T., 1996. The spreading of the S type of *Heterobasidion annosum* from Norway spruce stumps to the subsequent tree stand. Eur. J. Plant Pathol. 26, 193–204.
Pitra, C., Lutz, W., 2005. Population genetic structure and the effect of founder events on the genetic variability of introduced sika deer, Cervus nippon, in Germany and Austria. Eur. J. Wildl. Res. 51, 95–100. https://doi.org/10.1007/s10344-005-0087-y.
Primicia, I., Camarero, J.J., Janda, P., Čada, V., Morrissey, R.C., Trotsiuk, V., Bače, R., Teodosiu, M., Svoboda, M., 2015. Age, competition, disturbance and elevation effects on tree and stand growth response of primary Picea abies forest to climate. For. Ecol. Manage. 354, 77–86. https://doi.org/10.1016/j.foreco.2015.06.034.
Pukkala, T., Möykkynen, T., Thor, M., Rönnberg, J., Stenlid, J., 2005. Modeling infection and spread of Heterobasidion annosum in even-aged Fennoscandian conifer stands. Can. J. For. Res. 35, 74–84. https://doi.org/10.1139/x04-150.
Půlpán, J., 2001. Vliv hospodaření na vznik hnilog. Zprávy Lesn. výzkumu 46, 135–136.

Putalová, T., Vacek, Z., Vacek, S., Štefančík, I., Bulušek, D., Král, J., 2019. Tree-ring widths as an indicator of air pollution stress and climate conditions in different Norway spruce forest stands in the Krkonoše Mts. Cent. Eur. For. J. 65, 21–33.

Quitt, E., 1971. Klimatické oblasti Československa [Climatic regions of Czechoslovakia]. Academia, Prague.

R Core Team, 2018. R: A Language and Environment for Statistical Computing.

Rönnberg, J., Berglund, M., Johansson, U., Cleary, M., 2013. Incidence of Heterobasidion spp. following different thinning regimes in Norway spruce in southern Sweden. For. Ecol. Manage. 289, 409–415. https://doi.org/10.1016/j.foreco.2012.10.013.

Rossell, C.R., Patch, S., Salmons, S., 2007. Effects of deer browsing on native and non-native vegetation in a mixed oak-beech forest on the Atlantic coastal plain. Northeast. Nat. 14, 61–72. https://doi.org/10.1656/1092-6194(2007)14[61:eodbon]2.0.co;2.

Rybníček, M., Čermák, P., Žid, T., Kolář, T., 2010. Radial growth and health condition of Norway spruce (*Picea abies* (L.) Karst.) stands in relation to climate (Silesian Beskids, Czech Republic). Geochronometria 36, 9–16. https://doi.org/10.2478/v10003-010-0017-1.

Šafránek, Z., Honzová, M., Vala, V., Dvořák, J., 2016. Sortimentace a zpeněžení smrkového dříví v závislosti na výskytu škod ohryzem a loupáním jelení zvěří -SORTING AND CONVERSION OF SPRUCE TIMBER INTO MONEY DEPENDING ON THE OCCURRENCE. Zpravy Lesn. Vyzk. - Reports For. Res. 61, 298–304.

Savva, Y., Oleksyn, J., Reich, P.B., Tjoelker, M.G., Vaganov, E.A., Modrzynski, J., 2006. Interannual growth response of Norway spruce to climate along an altitudinal gradient in the Tatra Mountains, Poland. Trees - Struct. Funct. 20, 735–746. https://doi.org/10.1007/s00468-006-0088-9.

Schindelin, J., Rueden, C.T., Hiner, M.C., Eliceiri, K.W., 2015. The ImageJ ecosystem: An open platform for biomedical image analysis. Mol. Reprod. Dev. 82, 518–529. https://doi.org/10.1002/mrd.22489.

Schwarz, O., Vacek, S., Podrázský, V., Kuś, J., Krkonošského, S., 2007. Vývoj stavu spárkaté zvěře a škod zvěří v bilaterální Biosférické rezervaci Krkonoše / Karkonosze Development of hoofed game stocks and damage caused by the game in the bilateral Biosphere Reserve Krkonoše / Karkonosze. Opera Corcon. 44, 453–464.

Schweingruber, F.H., Eckstein, D., Serre-Bachet, F., Bräker, O.U., 1990. Identification, presentation and interpretation of event years and pointer years in dendrochronology. Dendrochronologia 8, 9–38.

Seidl, R., Schelhaas, M.J., Rammer, W., Verkerk, P.J., 2014. Increasing forest disturbances in Europe and their impact on carbon storage. Nat. Clim. Chang. 4, 806–810. https://doi.org/10.1038/nclimate2318.

Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J., Ascoli, D., Petr, M., Honkaniemi, J., Lexer, M.J., Trotsiuk, V., Mairota, P., Svoboda, M., Fabrika, M., Nagel, T.A., Reyer, C.P.O., 2017. Forest disturbances under climate change. Nat. Clim. Chang. 7, 395–402. https://doi.org/10.1038/nclimate3303.

Sidor, C.G., Popa, I., Vlad, R., Cherubini, P., 2015. Different tree-ring responses of Norway spruce to air temperature across an altitudinal gradient in the Eastern Carpathians (Romania). Trees - Struct. Funct. 29, 985–997. https://doi.org/10.1007/s00468-015-1178-3.

Siegel, S., Castellan Jr., N.J., 1988. Nonparametric statistics for the behavioral sciences, 2nd ed., Nonparametric statistics for the behavioral sciences, 2nd ed. Mcgraw-Hill Book Company, New York, NY, England.

Simon, J., Kolář, C., 2001. Economic evaluation of bark stripping by red deer on the basis of analysis on a time growth series of spruce stands in the Hrubý Jeseník Mts. J. For. Sci. 47, 402–409.

Šimůnek, V., Vacek, Z., Vacek, S., Králíček, I., Vančura, K., 2019. Growth variability of European beech (*Fagus sylvatica* L.) natural forests : Dendroclimatic study from Krkonoše National Park. Cent. Eur. For. J. 65, 3–11. https://doi.org/10.2478/forj-2019-0010.

Slanař, J., Vacek, Z., Vacek, S., Bulušek, D., Cukor, J., Štefančík, I., Bílek, L., Král, J., 2017. Long-term transformation of submontane spruce-beech forests in the Jizerské hory Mts.: Dynamics of natural regeneration. Cent. Eur. For. J. 63, 212–224. https://doi.org/10.1515/forj-2017-0023.

Šrámek, V., Vejpustková, M., Novotný, R., Hellebrandová, K., 2008. Yellowing of Norway spruce stands in the silesian beskids - Damage extent and dynamics. J. For. Sci. 54, 55–63. https://doi.org/10.17221/795-jfs.

Štefančík, I., Vacek, Z., Sharma, R.P., Vacek, S., Rösslová, M., 2018. Effect of thinning regimes on growth and development of crop trees in fagus sylvatica stands of central Europe over fifty years. Dendrobiology 79, 141–155. https://doi.org/10.12657/denbio.079.013.

Stokely, T.D., Betts, M.G., 2020. Deer-mediated ecosystem service versus disservice depends on forest management intensity. J. Appl. Ecol. 57, 31–42. https://doi.org/10.1111/1365-2664.13532.

Suvanto, S., Nöjd, P., Henttonen, H.M., Beuker, E., Mäkinen, H., 2016. Geographical patterns in the radial growth response of Norway spruce provenances to climatic variation. Agric. For. Meteorol. 222, 10–20. https://doi.org/10.1016/j.agrformet.2016.03.003.

Suzuki, M., Onuma, M., Yokoyama, M., Kaji, K., Yamanaka, M., Ohtaishi, N., 2001. Body size, sexual dimorphism, and seasonal mass fluctuations in a larger sika deer subspecies, the Hokkaido sika deer (Cervus nippon yesoensis Heude, 1884). Can. J. Zool. 79, 154–159. https://doi.org/10.1139/z00-181.

Takarabe, K., Iijima, H., 2019. Contrasting Effect of Artificial Grasslands on the Intensity of Deer Browsing and Debarking in Forests. Mammal Study 44, 173. https://doi.org/10.3106/ms2018-0082.

Thor, M., Arlinger, J.D., Stenlid, J., 2006. Heterobasidion annosum root rot in Picea abies: Modelling economic outcomes of stump treatment in Scandinavian coniferous forests. Scand. J. For. Res. 21, 414–423. https://doi.org/10.1080/02827580600917338.

Thulin, C.G., Malmsten, J., Ericsson, G., 2015. Opportunities and challenges with growing wildlife populations and zoonotic diseases in Sweden. Eur. J. Wildl. Res. 61, 649–656. https://doi.org/10.1007/s10344-015-0945-1.

Toth, D., Maitah, M., Maitah, K., Jarolínová, V., 2020. The impacts of calamity logging on the development of spruce wood prices in Czech. Forestry 11, 283. https://doi.org/10.3390/f11030283.

Usbeck, T., Wohlgemuth, T., Dobbertin, M., Pfister, C., Bürgi, A., Rebetez, M., 2010. Increasing storm damage to forests in Switzerland from 1858 to 2007. Agric. For. Meteorol. 150, 47–55. https://doi.org/10.1016/j.agrformet.2009.08.010.

Vacek, S., Hůnová, I., Vacek, Z., Hejcmanová, P., Podrázský, V., Král, J., Putalová, T., Moser, W., 2015a. Effects of air pollution and climatic factors on Norway spruce forests in the Orlické hory Mts. (Czech Republic), 1979–2014. Eur. J. For. Res. 134, 1127–1142. https://doi.org/10.1007/s10342-015-0915-x.

Vacek, S., Vacek, Z., Bulušek, D., Putalova, T., Sarginci, M., Schwarz, O., Šrůtka, P., Podrázský, V., Moser, W.K., 2015b. European ash (*Fraxinus excelsior* L.) Dieback: Disintegrating forest in the mountain protected areas, Czech Republic. Austrian J. For. Sci. 132, 203–223.

Vacek, S., Černý, T., Vacek, Z., Podrázský, V., Mikeska, M., Králíček, I., 2017a. Long-term changes in vegetation and site conditions in beech and spruce forests of lower mountain ranges of Central Europe. For. Ecol. Manage. 398, 75–90. https://doi.org/10.1016/j.foreco.2017.05.001.

Vacek, S., Vacek, Z., Ulbrichová, I., Remeš, J., Podrázský, V., Vach, M., Bulušek, D., Král, J., Putalová, T., 2019. The effects of fertilization on the health status, nutrition and growth of Norway spruce forests with yellowing symptoms. Scand. J. For. Res. 34, 267–281. https://doi.org/10.1080/02827581.2019.1589566.

Vacek, Z., Vacek, S., Bulušek, D., Podrázský, V., Remeš, J., Král, J., Putalová, T., 2017b. Effect of fungal pathogens and climatic factors on production, biodiversity and health status of ash mountain forests. Dendrobiology 77, 161–175. https://doi.org/10.12657/denbio.077.013.

Vasiliauskas, R., 2001. Damage to trees due to forestry operations and its pathological significance in temperate forests: A literature review. Forestry 74, 319–336. https://doi.org/10.1093/forestry/74.4.319.

Vasiliauskas, R., Stenlid, J., Johansson, M., 1996. Fungi in bark peeling wounds of *Picea abies* in central Sweden. Eur. J. For. Pathol. 26, 285–296.

Vlad, R., Sidor, C.G., 2013. Research for the estimate of rotten stem wood volume in Norway spruce stand damaged by deer species. Rev. Pădurilor 128, 27–32.

Vospernik, S., 2006. Probability of bark stripping damage by red deer (Cervus elaphus) in Austria. Silva Fenn. 40, 589–601. https://doi.org/10.14214/sf.316.

Warren, G., Baines, P., Plamondon, J., Pitt, D.G., 2013. Effects of precommercial thinning on the forest value chain in northwestern New Brunswick: Part 1 – Roundwood production and stumpage value. For. Chron. 89, 446–457. https://doi.org/10.5558/tfc2013-086.

Welch, D., Scott, D., 2017. Observations on bark-stripping by red deer in a Picea sitchensis forest in Western Scotland over a 35-year period. Scand. J. For. Res. 32, 473–480. https://doi.org/10.1080/02827581.2016.1247464.

Welch, D., Staines, B.W., Scott, D., Catt, D.C., 1988. Bark-stripping damage by red deer in Sitka spruce in Western Scotland. II. Qound size and position. Forestry 61, 245–254.

White, T.C.R., 2019. The cause of bark stripping of young plantation trees. Ann. For. Sci. 76, 105–107. https://doi.org/10.1007/s13595-019-0888-x.

Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis.

Williams, T., Kelley, C., many others, 2019. Gnuplot 5.2: an interactive plotting program.

Wimmer, R., Grabner, M., 1997. Effects of climate on vertical resin duct density and radial growth of Norway spruce [*Picea abies* (L.) Karst.]. Trees 11, 271–276. https://doi.org/10.1007/PL00009673.

Woodward, S, Stenlid, J, Karjalainen, R, Hüttermann, A, 1998. Heterobasidion annosum: Biology, Ecology, Impact and Control. Oxford University Press, Wallingford.

Yamaguchi, D.K., 1991. A simple method for cross-dating increment cores from living trees. Can. J. For. Res. 21, 414–416. https://doi.org/10.1139/x91-053.