Journal of Forestry Research (2025) 36:94
https://doi.org/10.1007/s11676-025-01889-w

ORIGINAL PAPER

Outer appearance of bark-beetle-infested stands of Norway spruce after different standing storage durations: a case study in the Harz Mountains, Germany

Jan-Frederik Trautwein[1] · **Laurenz Rudolf Rohde**[1] · **Holger Militz**[1] · **Christian Brischke**[2]

Received: 10 January 2025 / Accepted: 4 March 2025

Abstract Norway spruce (*Picea abies* (L.) Karst.) in the Harz Mountains National Park (Germany) has experienced widespread mortality (> 97% of trees in the study stands) due to infestation with the large spruce bark beetle (*Ips typographus* L.). The dead trees (snags) remain standing in the forest for 2–5 years before harvesting. It is important to identify trees that can still produce quality timber, which may be achieved by examining their outer appearance using selected characteristics. The aim of this study was to identify possible correlations between the standing storage duration and defined external characteristics of the snags. The mean tree height at compartment level was calculated using a vegetation height model, based on light detection and ranging data from 2018, to derive the stem breakage proportion. The condition of the crown and the bark and presence of fungi, wood rot, stem cracks and bark stripping damage were also assessed. The majority of the snags were broken at least once. Windthrows were less likely compared to living spruce trees because of reduced resistance to the wind as a result of needle loss and breakage. The mean stem breakage proportion increased significantly with the duration of the standing storage; however, prolonged storage durations did not always lead to complete breakage. The occurrence of fungal fruiting bodies was significantly correlated with a higher proportion of stem breakage, and the longer the storage, the more snags had fungal fruiting bodies. The condition of the crown, assessed by the presence of branchlets, was a good indicator of the duration of the standing storage. If trees had few or no branchlets, they had been standing for at least 4 years. Overall, this initial description of the external appearance of spruce trees that have been stored standing for many years suggests that time significantly influences the tree condition and breakage intensity, which is reflected by certain tree characteristics. Future studies should examine these aspects in greater depth, particularly with regard to utilization options and safety during timber harvesting.

Keywords Snag · Stem breakage proportion · *Ips typographus*

Introduction

In recent years, calamities affecting forests in Central Europe have had a strong impact on forest management and forest research. In Germany, the amount of salvage logging among the total timber harvest has risen from 17.8% in 2012 to a temporary peak of 81.4% in 2021 (Destatis 2023b). The large-scale dieback can be attributed to a combination of storm events and high physiological stress due to summer droughts (Eichhorn et al. 2021). In particular, even-aged monoculture conifer stands have been severely affected in various regions since 2018.

Project funding: This study was supported by the German Federal Ministry of Food and Agriculture (BMEL) and the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) via the Agency for Renewable Resources (FNR) (GRANT no. 2220WK49E3).

The online version is available at https://link.springer.com/.

Corresponding editor: Tao Xu.

✉ Jan-Frederik Trautwein
jan-frederik.trautwein@uni-goettingen.de

[1] Faculty of Forest Sciences and Ecology, University of Göttingen, Wood Biology and Wood Products, Buesgenweg 4, 37077 Goettingen, Germany

[2] Thünen Institute of Wood Research, Leuschnerstr. 91d, 21031 Hamburg, Germany

These conditions have been ideal for bark-breeding beetles and led to high populations and a massive standing infestation. In 2022, around 99% of insect infestations took place in coniferous stands (Destatis 2023b).

Forestry companies affected by a calamity are immediately faced with a central challenge, which comprises an economic and a logistical component. On the one hand, the company must make high investments in reforestation measures and climate-adaptive forest conversion (Möhring et al. 2022). On the other hand, unplanned felling due to a calamity correlates with declining raw timber prices (Schwarzbauer 2006; Toth et al. 2020). The sale of timber is often the main source of income, especially for private forestry companies (von Arnim et al. 2021); thus, storing the affected wood until the timber market recovers might be more profitable. The total coniferous timber harvest in Germany increased by an average of 21% due to damaging events in the years 2018–2021, compared to the long-term average for 2008–2017 (Jochem et al. 2023). Between 2018 and 2022, ongoing calamity led to a total salvage logging of 233.45 million m^3 in coniferous wood (Destatis 2023a). Affected forestry companies had to process and store large amounts of timber within a short time (Brischke et al. 2024).

In general, the storage methods for round wood can be divided into wet storage and dry storage (Wauer et al. 2013). Wet storage can preserve the wood quality if done properly, but requires high infrastructural requirements and additional expenditures (Wauer 2007; Lutze 2023; Rauch and Kogler 2023). Short-term dry storage in piles next to the forest roads is the favored method for round wood storage in Central Europe (Kuera and Katušák 1993).

During calamity involving high timber volumes, it is not possible for forest owners and the raw timber processing industry to work without long-term storage on a large scale. However, such storage concepts also requires sufficient space. It has become apparent that forest owners have switched to standing storage for logistical reasons (Brischke et al. 2024). From the economic perspective, the aim of standing storage is to temporarily store the dead trees (snags) until the cost of timber production has normalized and higher timber revenues can be expected. Therefore, standing storage of snags could represent a possible solution for overcoming economic and logistical storage challenges.

The aim of this study was to investigate changes in the outer appearance of bark beetle infested spruce trees over time during standing storage. Therefore correlations between specific characteristics assessed in dead trees in spruce stands and age since damage had occurred were investigated.

The predefined tree characteristics were fungal fruiting bodies, decay, cracks, branchlets, bark stripping damage and general bark condition and proportion of stem breakage.

Materials and methods

Study area

In September 2023, this study took place in the Harz Mountains National Park, which is the second largest forest national park in Germany, with a total area of 24,732 ha. The study area comprised 3503 ha, mainly in the Oderhaus district. In addition, a 1-km-wide buffer was included in the neighboring national park districts of Torfhaus and Acker to increase the proportion of deadwood areas surveyed in 2018. In total, the spruce deadwood area of 1639 ha covered at least 47% of the study area. Dying spruce stands developed from the north to the south and from the montane to the sub-mountainous vegetation stage. Here, we refer to the Oderhaus study area as including the buffer areas. The majority of spruce trees in the study area were originally planted and managed in pure stands until the study area was excluded from forestry use on January 1, 1994 (BfN 2022). Over the past 30 years, the forest areas have developed in a near-natural way, with extensive dead or dying forest areas in the last few years.

Selection of sample points

Stratification by standing storage duration

The selection of the sample points in the study area were based on the evaluation of an aerial image time series from 2000 and 2003 to 2021 which was carried out by the Harz Mountains National Park administration in cooperation with the Northwest German Forest Research Institute (NW-FVA) to document and monitor progression of the bark beetle infestation and damage (Nationalparkverwaltung 2021). Images from 2001 and 2002 were not included in the database because the digitalization of the aerial images had not been completed when the investigation took place. The National Park Administration (Nationalparkverwaltung 2021) delineated deadwood areas by digitizing features on orthophotos (20 cm resolution) from 2008. Infested areas mapped prior to 2008 were added later to the digital overall representation. Additive mapping was used to record infested areas that had a minimum size of 0.05 ha, a canopy cover of recently dead spruce of less than 30%, and a remaining proportion of living spruce of 10% of the total stem number (Nationalparkverwaltung 2021). The true cause of mortality for each area could not be identified during the image analysis, but due to the bark beetle dynamics in Harz Mountains National Park, the observed deadwood areas were assumed to be exclusively caused by bark beetles (Nationalparkverwaltung 2021).

The aerial surveys of the national park area took place in autumn, at the end of the annual cycle of the spruce bark beetle. Therefore, mortality was mapped from autumn of the previous year to autumn of the current year. Based on these data, the deadwood area of each mapped year and the area-weighted mean altitude were determined using the open-source geoformation software QGis 3.28 (2022). The analyses began with dead spruce stands that had been mapped in 2018. The standing storage duration was linked to the year that the area was identified as dead. In the next step, the standing storage duration was used as stratification for selecting the sampling points.

Area selection

The center points of spruce stands with the same standing storage duration were recorded, since they were probably influenced by approximately the same climatic factors. These factors were essentially dependent on the dynamics affecting the deadwood surface and were not additionally influenced by a living stand edge. For each stratum, the mapped deadwood areas were filtered according to the minimum size (1 ha) available in QGis 3.28 (2022), and the area centers were created using the processing tool Polygon Centroid. Then the polygons were visually compared with the ESRI satellite image of the reference area (Fig. 1). Polygons that included, for example, non-forest land (paths/waters/wild meadows) were corrected manually. At the same time, it was checked whether the infested spruce had been felled as part of the national park's abiotic forest protection measure in the "safety strip". After completing the correction and verification, the areas were filtered again. A random sample of $n = 10$ per stratum was drawn from the center points of the areas using the simple random sampling.

The plot design followed a stem distance method as a variation of the k^{th} tree sample, in which the closest 10 trees to the center point were recorded. The distance between the selected trees and the center point was determined using ultrasonic measurement technology from the manufacturer Haglöf Sweden AB (Langsle), model Vertex IV with the transponder T3. A Haglöf 360° adapter was used so that the ultrasonic signal emitted by the transponder was evenly scattered, and distances were measured in a circle (Haglöf Schweden 2007). Ten plots

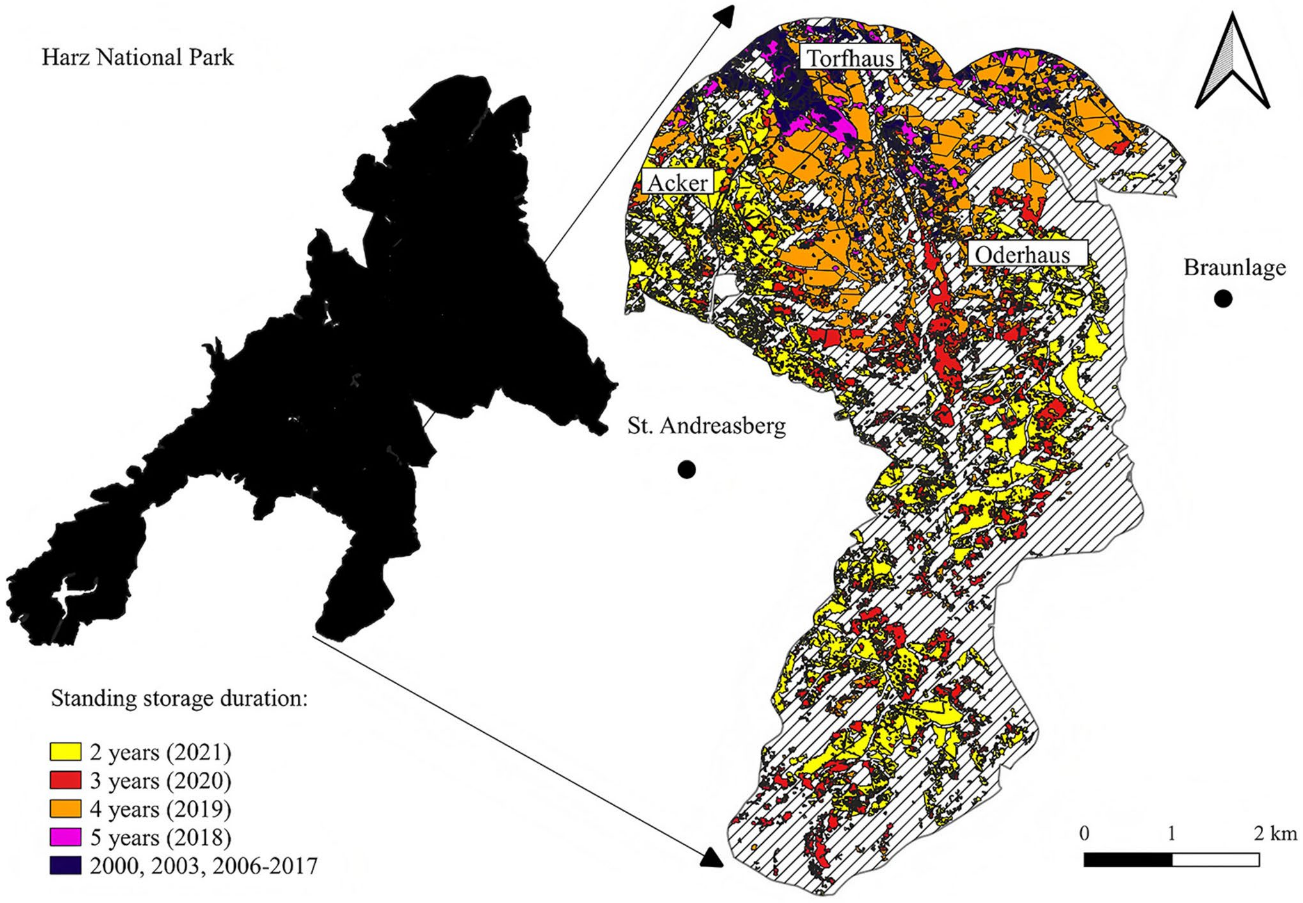

Fig. 1 Visualised deadwood area by standing storage duration in the study area. Data from Nationalparkverwaltung Harz 2021

per standing storage duration (2–5 years) were selected, with 10 trees per plot for a total of 400 recorded trees. The DBH of all spruce trees with DBH ≥ 7 cm (coarse wood limit) were recorded. The DBH-measurements were carried out with a circumference tape to an accuracy of 0.1 cm. Tree heights were measured to an accuracy of 0.1 m using the Vertex IV's integrated horizontal distance measurement method.

Recording tree characteristics for individual trees

To locate the sample points, an Alpha 100 positioning device and GNSS systems GPS and GLONASS (Garmin Ltd 2014, Schaffhausen, Switzerland) was used. The open-source application ForisCollect was used to record the data (Open Foris 2024).

On each tree, the same characteristics were recorded and visually assessed by two people. Fungal fruiting bodies, visible decay, stem cracks, branchlets and stripping damage were assessed as present or absent. Stem cracks were assessed as present if they had a minimum width of 1 cm and a minimum length of 1 m.

Branchlets refers to the smallest branching unit on which needles and leaves are attached. In general, branchlets comprise woody parts of a tree with a diameter of less than 7 cm (Bartsch et al. 2020). Even on dead spruce trees, branchlets are easily recognizable and were used to describe the condition of the tree crown. The examples in Fig. 2 illustrate the characteristics of the branchlets in the crown for the different trees states: snag without breakage (A, B) and snag with breakage (C, D).

The bark condition was categorized as the proportion that remained on the trunk: A = ≥ 90%; B = 90% < x > 10%; C = ≤ 10%.

Stem breakage proportion

The amount of the standing stored tree remaining was determined by calculating the stem breakage proportion using the ratio between the measured height and the mean tree height at the reference age in 2018. The rate can therefore be between 0 and 100%; trees with 100% stem breakage were rated as thrown, and 0% were rated as a whole standing tree. The intermediate range $0 < x < 100\%$ described the breakage rate. Calculations for the canopy height model (CHM) were based on light detection and ranging point clouds from the Office for Geoformation and Land Surveying of Lower Saxony (LGLN) and on the forest management plan from 2003. Due to the fact that the study area was managed by the Lower Saxony State Forestry Administration until the establishment of the national park, this complete forest management plan from 2003 was available. Compartment boundaries and stand ages were extracted from this plan and used for calculations. Twelve aerial surveys of the Harz Mountains National Park were carried out between February 2018 and April 2018 using a RIEGL LMS-Q780 scanner on behalf of the LGLN (2018). The CHM was calculated using the R package lidR (Roussel et al. 2020; Roussel and Auty 2024). In the first step, a normalized terrain surface model (digital terrain model) was calculated using the functions rasterize_terrain and normalize_height. In the second step, the function rasterize_canopy was used to calculate the CHM with a spatial resolution of 20 cm. Using the CHM, the tree tops were identified using the function locate_trees. The algorithm was set so that localized trees had a minimum height of 10 m to prevent excessive bias in the mean height calculation. The sampling points could be assigned to an area unit at the sub-compartment to subsurface level. The identified tree tops were plotted for each area unit, and the arithmetic mean height was calculated for the reference age in 2018.

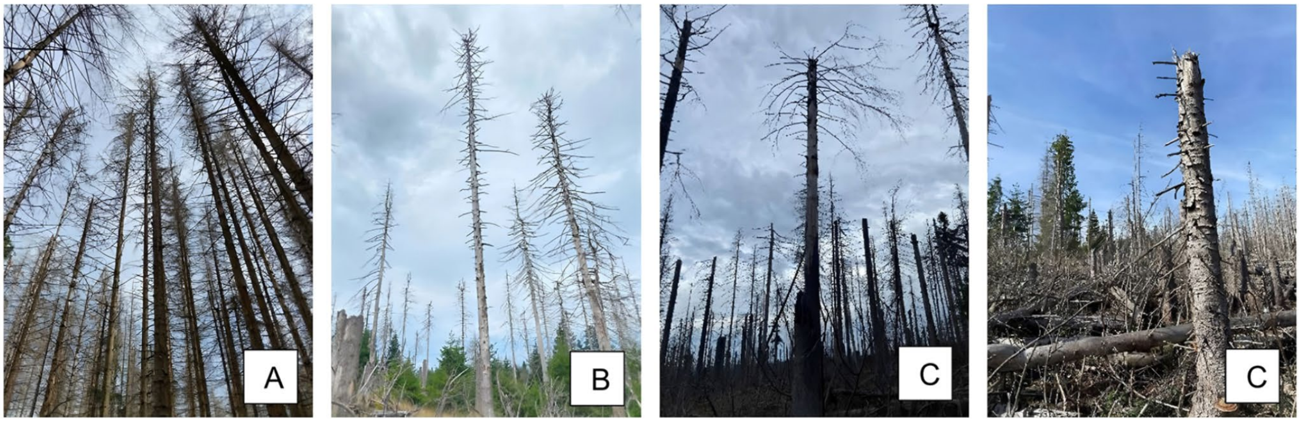

Fig. 2 Occurrence of branchlets. **A** Standing dead whole tree with branchlets. **B** Standing dead whole tree without branchlets. **C** Standing dead broken tree with branchlets. **D** Standing dead broken tree without branchlets

Statistical analyses

R Version 4.3.2 (R Core Team 2023) was used for all statistical analyses. Contingency tables were set up to test for an association between the different proportions of tree states and the considered tree characteristics using a χ^2 test. The components of these results were further analyzed using a post-hoc pairwise comparison. If expected frequencies < 5 occurred in the contingency tables, Fisher's exact test was used for the comparison (Mangiafico 2016).

A point-biserial correlation analysis was used to test for a directional correlation between all tree characteristics (except the bark) and the stem breakage proportion. The tree characteristic bark condition was not included because the analyzed characteristic could not have more than two categories. The test procedure for a possible correlation was also carried out for the tree states by subdividing the stem breakage proportion into three classes: breakage $\leq 33\%$ (low intensity), $> 33\%$ to 67% (medium intensity), $> 67\%$ (high intensity). A correlation analysis was used to determine whether the mean proportion of tree characteristics was correlated with the standing storage duration and whether the breakage proportion was correlated with the occurrence of a tree characteristic. The residuals of each combination of tree characteristic and standing storage duration were first tested for normal distribution using the Shapiro–Wilk test. If the distribution was normal, then data were analyzed using Pearson's product–moment correlation coefficient. If the distribution was not normal, data were tested using Spearman's nonparametric rank correlation. The correlations were also tested for significance using the base functions in R 4.3.2 (R Core Team 2023). The significance level in the statistical analyses was $\alpha = 0.05$. The strength of the relationship in the correlation analyses was determined using the standard values of Kuckartz et al. (2013).

Results and discussion

Tree states

Most of the trees were classified as snags with breakage (71%), followed by snags without breakage (24%), living trees (3%) and thrown trees (2%) (Fig. 3). Only 12 spruce trees were identified as living, and nine trees were thrown. This low number of living spruce trees resulted from mass propagation of the spruce bark beetle, which usually halts only when there are no more host trees.

The factors contributing to the resistance or resilience of individual spruce trees is the subject of current forest research (van Loo et al. 2019; Isopp 2020). In this study, the majority of the living spruce trees came from natural regeneration. Approximately 59% of all living spruce were recorded on just one sample point. The existing 157-year old spruce stand had already been thinned and provided suitable light conditions for natural regeneration. The young spruce trees had an average DBH of 16.8 cm. Because the spruce bark beetle favors larger trees, the young spruce were less attacked. The low number of nine thrown trees (2%) was noticeable because spruce generally has a high risk of windthrow due to its shallow root system. Starting from windthrow on smaller groups; older, single trees from damaged stands can be completely thrown after storms (Schmidt-Vogt 1989). Such a scenario was not observed at any sampling point, but it cannot be ruled out in the study area. Regarding the risk of windthrow, 97% of the spruce had already died, no longer had foliage, and some had already broken off. Early needle loss reduces wind resistance, and crown break-offs reduces the area of tree exposed, which improves stability (Hütte 1983). The lower windthrow risk of dead spruce trees was confirmed by the results of the study.

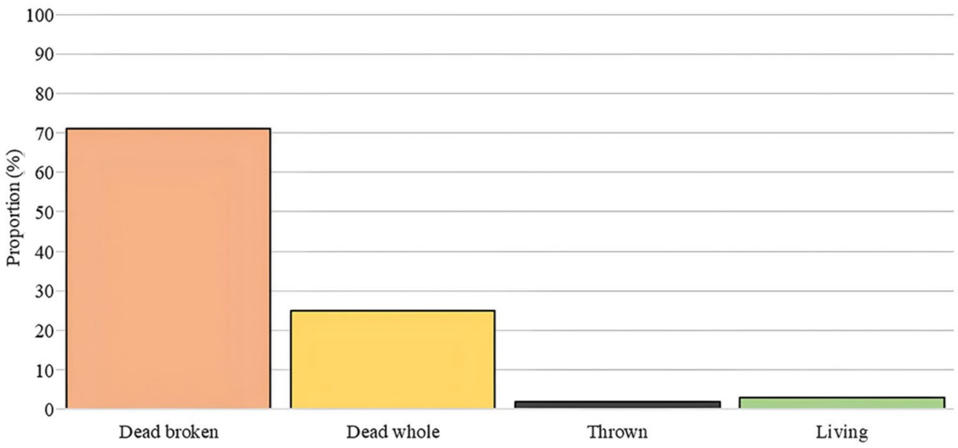

Fig. 3 Proportion of the 400 trees in each tree state

Stem breakage proportion

The average breakage significantly increased with increased standing storage duration (Fig. 4) and the relationship was moderately correlated ($\rho = 0.456$; $P < 0.001$). After 2 years of storage, spruce trees had an average breakage proportion of 23%, and half of the trees had no breakage. After 5 years, the average stem breakage increased to 68% (median = 87%).

Due to the conical stem shape of the spruce, the wood volume is highest in the center stem area (Kramer and Akça 2008), which means that a loss of the crown (25% breakage proportion) has less effect on the wood volume than higher breakage proportions do.

Bauer (2002) observed that decomposition of spruce snags is high within the first 2 years of tree death and is mainly characterized by flaking off of the bark and breaking of the stem at least once. This study confirms that prolonged standing storage up to 5 years does not always lead to complete collapse. In some cases, trees had a breakage proportion of over 90% after 2 years, while others were still standing without any breakage after 5 years. Ammann (2006) also found that trunk height of 10-year-old dead spruce trees varied greatly (2.6–20.4 m). Past local events such as wind or snow breaks could have led to greater breakage, but were not taken into account in the present study (Bauer 2002). These factors should be taken into account when interpreting breakage proportions, especially since crowns break more frequently at higher altitudes due to stronger storms and heavier snow loads. In the Harz Mountains, this effect is enhanced by the broad-crowned lowland provenance that was planted (Ellenberg and Leuschner 2010).

Tree characteristics

Fungal fruiting bodies

The proportion of trees with fungal fruiting bodies was significantly positively correlated with standing storage duration ($r = 0.693$; $P < 0.001$) and increased from 19% after 2 years to 71% after 5 years (Fig. 5B). The relation between the presence or absence of the fruiting bodies and tree state was also significant ($P < 0.001$). Figure 5A shows that 90% of the fruiting bodies were on dead broken trees. In contrast, 37% of dead whole trees did not contain any fungal fruiting bodies. More of the trees that had fruiting bodies were broken off compared with those without fungal fruiting bodies ($r = 0.591$; $P < 0.001$). This trend was also observed over the duration of standing storage (Fig. 5C, D). After 2 years, the mean breakage proportion of trees without fungal fruiting bodies was 18%, and 42% for three with fungal fruiting bodies. After 5 years, the breakage proportion increased to 27% for trees without fungal fruiting bodies and to 85% for those with fungal fruiting bodies.

Fomitopsis pinicola Sw. P. Karst. was predominantly found on the studied trees. This polypore is a typical brown rot pathogen in spruce wood (Dörfelt and Ruske 2018). The wood degradation induced by fungal infestation causes a decrease in structural integrity and fungi that cause brown rot cause a greater and faster loss in mass and strength than those causing white rot (Bariska et al. 1983; Brischke et al. 2008). There is also a significant correlation between rot in dead spruce trees and stem breakage (Ammann 2006). The correlation between stem breakage and the presence of fungal fruiting bodies indicates advanced wood rot because the reproductive fruiting bodies often only become visible after years of mycelial growth in the wood (Dörfelt and Ruske 2018; Rigling 2021; Schweiger et al. 2021). This relationship explains the higher breakage proportion as more fruiting

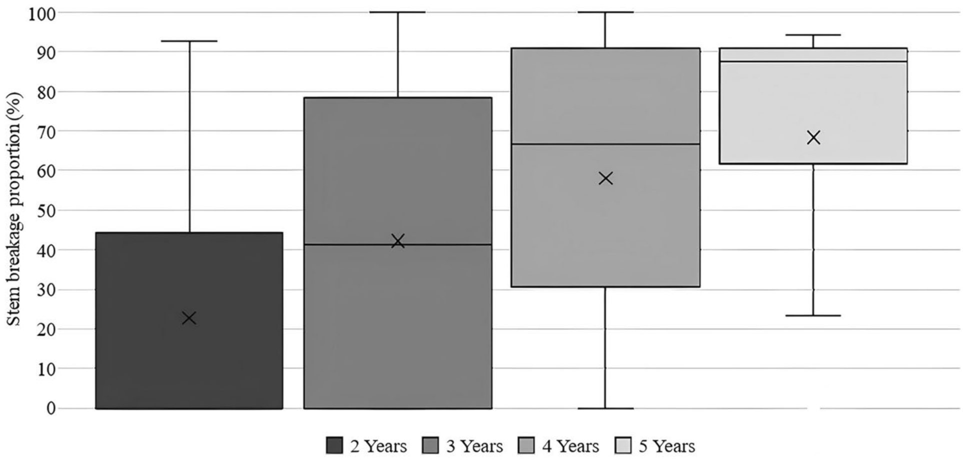

Fig. 4 Proportion of trees with stem breakage by standing storage duration (100% equals a thrown tree; 0% is a whole standing tree). For boxplots in B–D, X marks the mean; horizontal lines on the box mark the 75th, 50th and 25th percentile. Vertical bars mark minimum and maximum values; circular points mark outliers

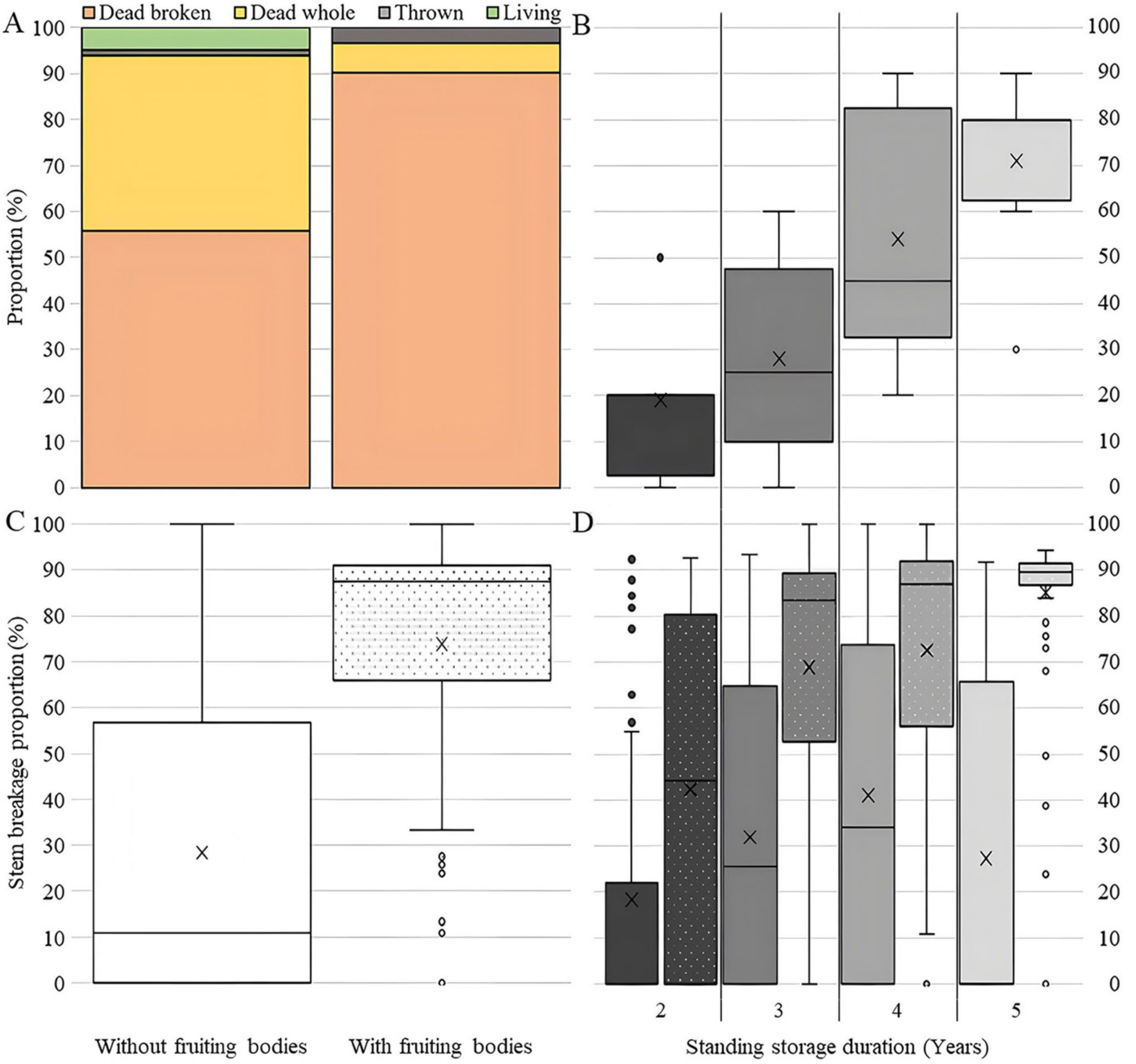

Fig. 5 Presence of fungal fruiting bodies: **A** Proportion of tree states as a function of fruiting bodies. **B** Proportion of trees with fruiting bodies as a function of standing storage duration. **C** Mean stem breakage proportion as a function of fruiting bodies absence or presence. **D** Mean stem breakage proportion as a function of the standing storage duration and presence or absence of fruiting bodies. For boxplots in B–D, X marks the mean; horizontal lines on the box mark the 75th, 50th and 25th percentile. Vertical bars mark minimum and maximum values; circular points mark outliers. Dot patterns in D: fruiting bodies present

bodies develop during prolonged standing storage and fungal colonisation. These extent of the resulting decay is thus a critical factor in the usability of the wood and thus its economic viability. This study focused exclusively on the external appearance of snags (see also Chapter 4.3.2) and did not assess internal decay. However, the extent of decay in standing stored wood is part of an ongoing NUKAFI project to determine the maximum duration of standing storage and address potential uses this wood can be applied to and whether it remains economically viable. Furthermore, it is necessary to determine and monitor whether and how standing stored trees can be harvested. On the one hand, harvesting methods must comply with occupational health and safety regulations. On the other hand, the wood must be processed in a way that prevents breakage into economically unviable small sections, so researchers are working together with foresters.

Visible decay

A low positive but non-significant correlation was found between rot and standing storage duration ($r = 0.2327$; $P = 0.1485$) (Fig. 6B). In Fig. 6A, a significant positive correlation between visible decay and thrown spruce trees ($P < 0.001$) was found. No differences in visible decay were found between the proportions of snags without breakage and snags with breakage (Fig. 6A). However, there was a significant, low positive correlation between the stem breakage proportion and the presence of visible decay ($r = 0.232$; $P < 0.001$). Trees with visible decay had a higher mean breakage proportion (60%) than trees without visible decay (42%) (Fig. 6C). This trend continued over the standing storage durations. After 2 years, on average, 35% of the trees with visible decay were broken, but only 19% of trees without visible decay were broken. After 5 years, on average, 80% of the trees with visible decay

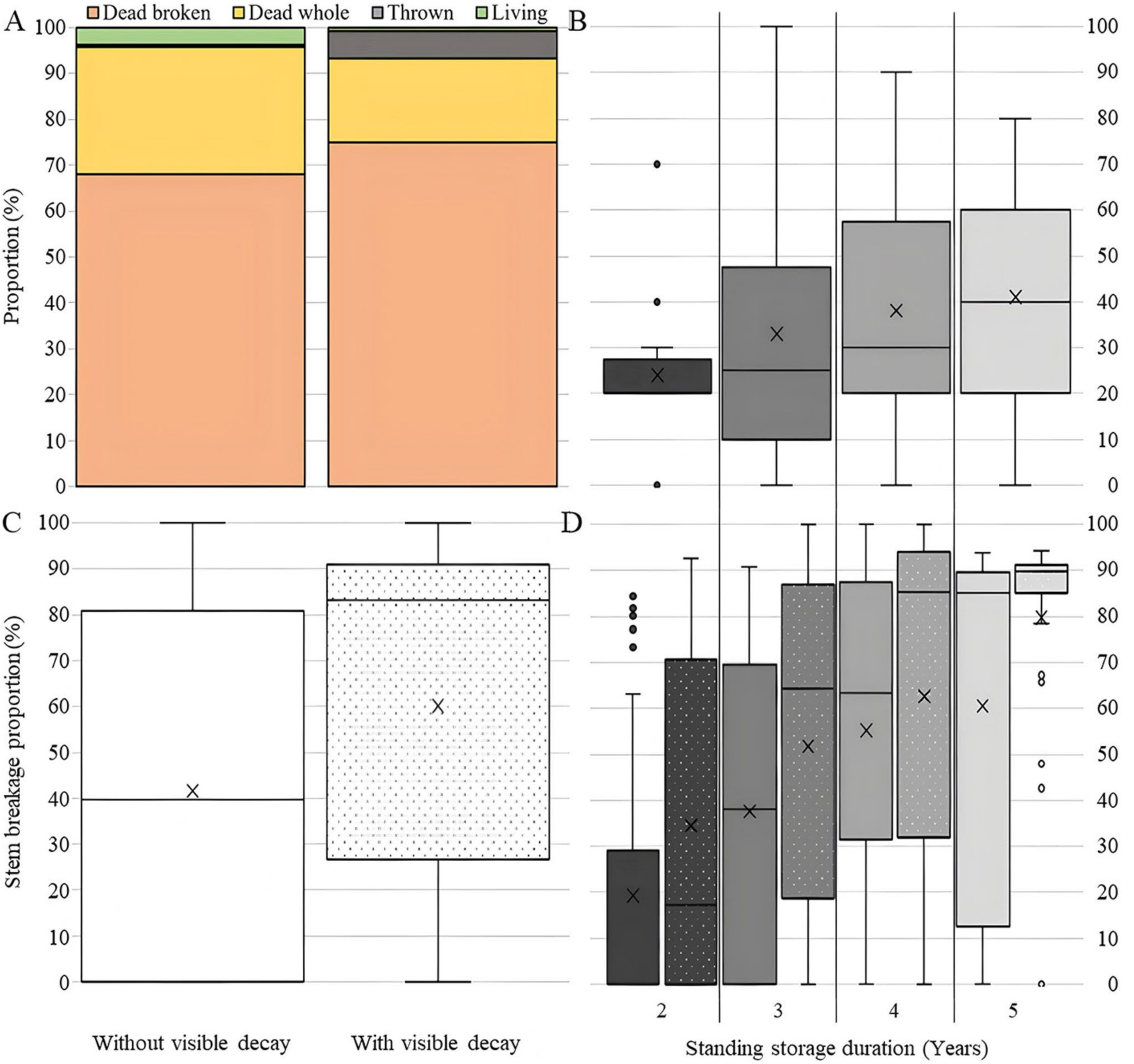

Fig. 6 Presence of visible decay and its relationship to tree state and standing storage duration. **A** Proportion of tree states as a function of visible decay. **B** Proportion of trees with visible decay as a function of the standing storage duration. **C** Mean stem breakage proportion as a function of visible decay. **D** Mean stem breakage proportion as a function of the standing storage duration and visible decay. For box-plots in B–D, X marks the mean; horizontal lines on the box mark the 75th, 50th and 25th percentile. Vertical bars mark minimum and maximum values; circular points mark outliers. Dot patterns in D: Visible decay was present

were broken, but only 60% of trees without visible decay were broken (Fig. 6D).

The presence of rot is directly dependent on the presence of wood-decaying fungi, but the correlations were less pronounced compared to the presence of fungal fruiting bodies. This difference could be explained by the survey method, since visible decay was often seen at the break point of the trunk, which means that there is a dependency on the break height and breakage proportion of the tree. This dependency was also reflected in the lack of association between visible decay and the proportion of snags with breakage and snags without breakage.

Stem cracks

The overall low negative correlation between the proportion of stem cracks and the standing storage duration was not significant ($\rho = -0.2968$, $P = 0.063$). The mean proportion of trees with stem cracks increased from the 2- to 3-year standing storage duration (Fig. 7B). Excluding the 2-year standing storage duration, the occurrence of stem cracks resulted in a significant, negative correlation ($\rho = -0.6603$, $P < 0.001$) with a decrease in the mean proportion from 85 to 42%. Stem cracks showed a significant dependence from the tree states ($P < 0.001$). While 87% of the trees without stem cracks were snags with breakage, 33% of trees with stem cracks were snags without breakage. Living trees did not show any stem cracks (Fig. 7A). Overall, there was a significant moderate negative correlation between stem cracks and breakage proportion ($r = -0.3678$; $P < 0.001$). Trees with stem cracks were on average less broken (37%) than those without stem cracks (66%) (Fig. 7C). The breakage proportion increased significantly from 33 to 78% for trees without stem cracks between the second and third year of storage and increased slightly to 79% after 5 years of storage (Fig. 7D). The breakage proportion of trees with stem cracks also increased with the duration of standing storage, but was always less than the percentage of trees without stem cracks (Fig. 7D).

With increasing storage time, stem cracks decreased, which can be explained by the increasing stem breakage proportion. The probability that a crack at least 1 cm wide and 1 m long was detectable on individual trees decreased with increasing stem breakage proportion. This correlation was illustrated by the sharp increase in the breakage proportion of individual trees without stem cracks, between 2 and 3 years of standing storage. After the spruce tree dies, the wood begins to dry during standing storage, where it is influenced by changing ambient humidity and temperatures, precipitation, UV radiation and wind. Cracks along the grain are usually the result of tension stresses that occur after drying and shrinking of the wood (Niemz and Sonderegger 2017). The crack size and depth increase as the cross-sectional area increases (Plößl 2008). In this study, no drying cracks were detected on living trees, but this does not prove the absence of such cracks on the analyszed spruce stands. Drying cracks can also form in living spruce trees as a result of extreme climatic conditions such as severe drought (Klädtke et al. 2004). In dry conditions, the sorption stress between root and crown can exceed the pressure of the tracheid, leading to cell collapse (Grabner et al. 2001). These cracks occur mainly in young spruce trees on nutrient- and water-rich sites, where above-average growth leads to large annual ring widths with low wood density (Klädtke et al. 2004). In turn, drying cracks provide openings for infection and colonization by wood-discoloring and wood-destroying fungi and wood-breeding insects, which promote wood degradation during vertical storage (Nördlinger 1878). After just 2 years in storage, many trees showed cracks in the mantle that were 1 cm wide and 1 m long. The number of trees with stem crack increased up to the 3-year storage period. The actual devaluation of the wood depends on the crack depth, which can only be systematically addressed on lying round wood (Larsen et al. 2011; RVR 2023).

Branchlets

There was a significant correlation between the presence of branchlets and the tree states ($P < 0.001$). The group snags with breakage and thrown trees did not differ for the presence branchlets; both were predominantly devoid of branchlets. When branchlets were present, 48% were snags without breakage, but for trees without branchlets, 84% were snags with breakage (Fig. 8A). The mean proportion of trees with branchlets fell from 77% after 2 years of standing storage to 0 after 5 years (Fig. 8D). There was a significant, high negative correlation between the proportion of trees with branchlets and the duration of standing storage ($\rho = -0{,}684$; $P < 0.001$), so that after 5 years of storage, no branchlets remained in the crowns of unbroken trees (Fig. 8C). There was a significant, high negative correlation ($r = -0.609$; $P < 0.001$) between the stem breakage proportion and presence of branchlets. Trees without branchlets broke off at a higher height on average (mean 64%) than those with branchlets (14%) (Fig. 8C). The proportion of trees with branchlets decreased with increasing duration of standing storage and with stem breakage proportion (Fig. 8D). Even after 2 years of storage, the breakage proportions differed significantly. On average, only 12% of the trees with branchlets were broken off, while 66% of trees without branchlets had already broken off (Fig. 8C). Overall, the stem breakage proportion increased over time, although there were differences between tree states (Fig. 8D).

The crowns with a high proportion of branchlets, which were often still brownish in color, appeared denser than those without branchlets. Loss of branchlets was especially

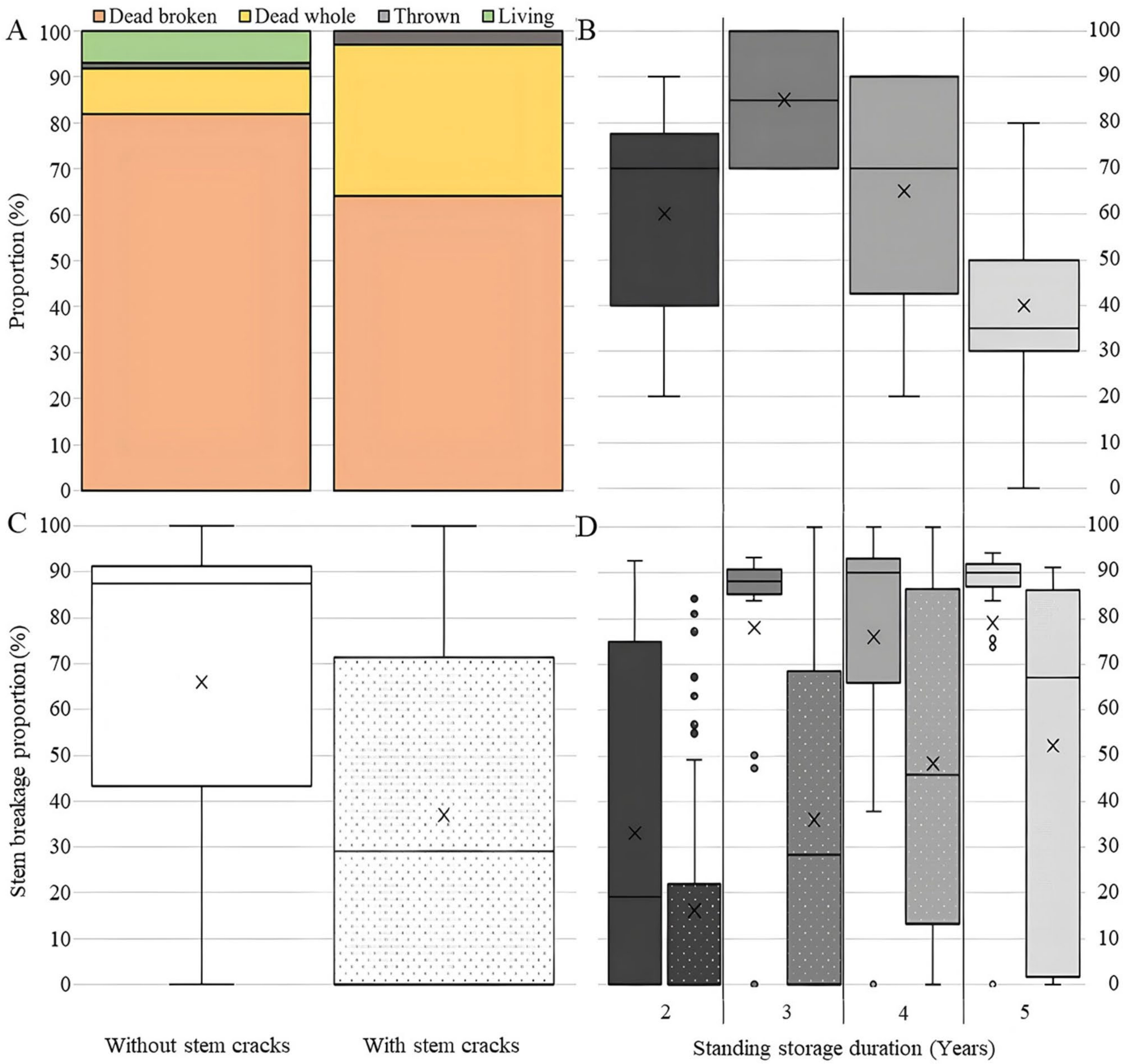

Fig. 7 Presence of stem cracks and its relationship to tree state and standing storage duration. **A** Proportion of tree states without and with stem cracks. **B** Proportion of trees without and with stem cracks as a function of the standing storage duration. **C** Mean stem breakage proportion as a function of stem cracks. **D** Mean stem breakage proportion as a function of the standing storage duration and stem cracks. For boxplots in B–D, X marks the mean; horizontal lines on the box mark the 75th, 50th and 25th percentile. Vertical bars mark minimum and maximum values; circular points mark outliers. Dot patterns in D: stem cracks were present

severe between 2 and 3 years of standing duration. Therefore, a high proportion of branchlets indicates a storage duration of 2 years or less, while almost no branchlets indicates a standing storage duration of more than 4 years. Therefore, the proportion of branchlets on a spruce snag is a simple, external metric to easily and effectively estimate standing storage duration.

Bark stripping damage

The mean proportion of bark stripping damage showed a significant negative correlation ($\rho = -0.462$; $P = 0.003$), and dropped from 48% after 2 years to 12% after 5 years of standing storage (Fig. 9B). In addition, bark stripping damage was significantly correlated with tree state

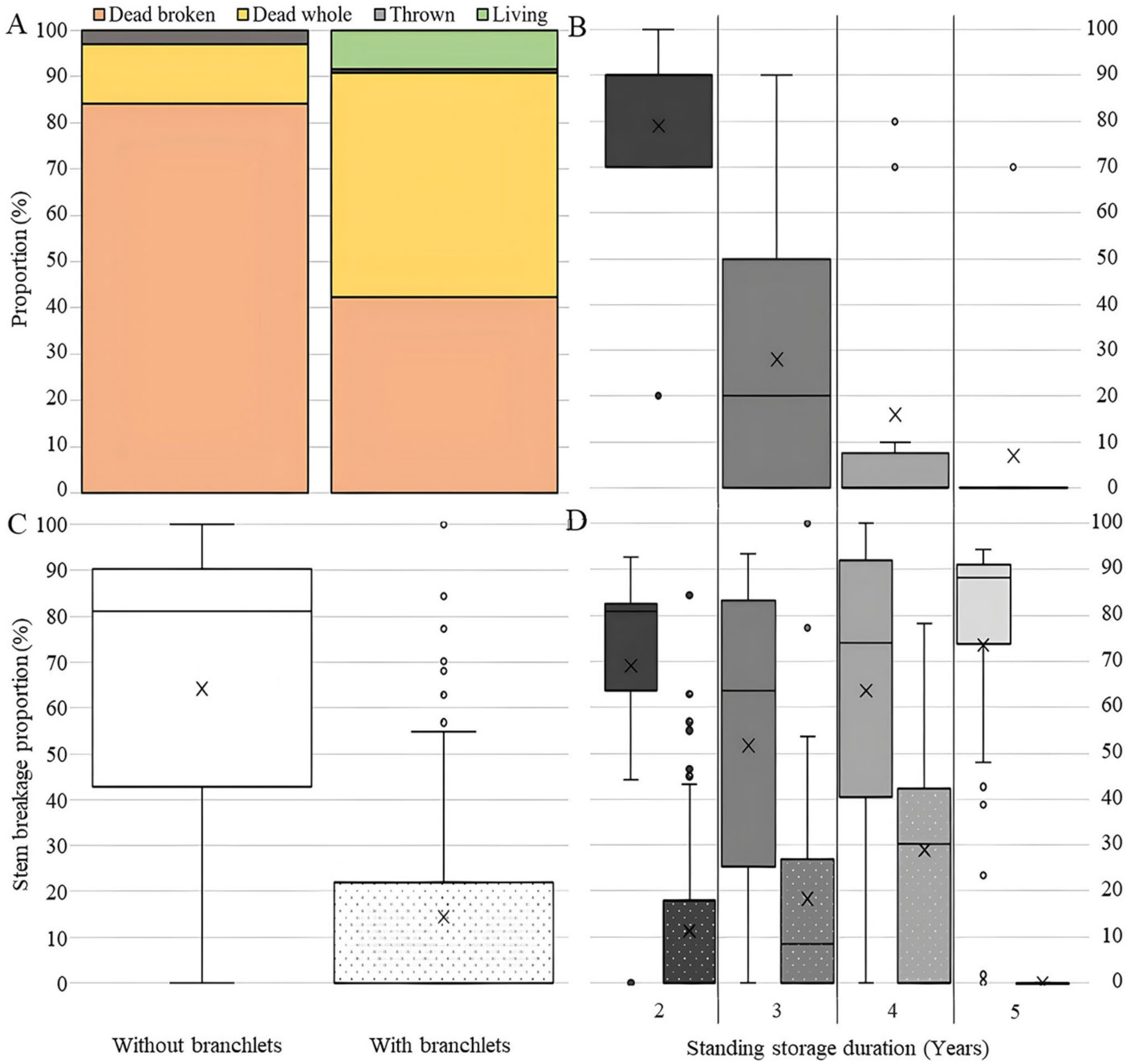

Fig. 8 Proportion of trees with branchlets and its relationship to tree state and standing storage duration. **A** Proportion of tree states without and with branchlets. **B** Proportion of trees with branchlets as a function of the standing storage duration. **C** Mean stem breakage proportion as a function of branchlet presence. **D** Mean stem breakage proportion as a function of the standing storage duration and branchlet presence. For boxplots in B–D, X marks the mean; horizontal lines on the box mark the 75th, 50th and 25th percentile. Vertical bars mark minimum and maximum values; circular points mark outliers. Dot patterns in D: branchlets present

($P < 0.001$). Undamaged trees were more frequently classified as "snags with breakage" (Fig. 9A). There was a significant, low negative correlation between stem breakage proportion and the occurrence of bark stripping damage ($r = -0.236$; $P < 0.001$). Individual trees with bark stripping damage had an average lower stem breakage proportion (34%) than trees without bark stripping damage (54%) (Fig. 9C). This trend continued over the standing storage duration (Fig. 9D). Bark stripping damage can be seen as an indicator of red rot, which is typical for spruce (Bartsch et al. 2020) and caused by white rot fungi whose spores cause rot in wounded areas, which can spread within the trunk's core (Kohnle 2015; Rohmeder 1937). Von Bazzigher (1973) identified *Heterobasidion parviporum* (Niemelä & Korhonen) as the dominant wound rot fungi and Kohnle (2015) considered it as the most important core rot pathogen of spruce. Pechmann et al. (1973) found that bark damage caused wound infections in half

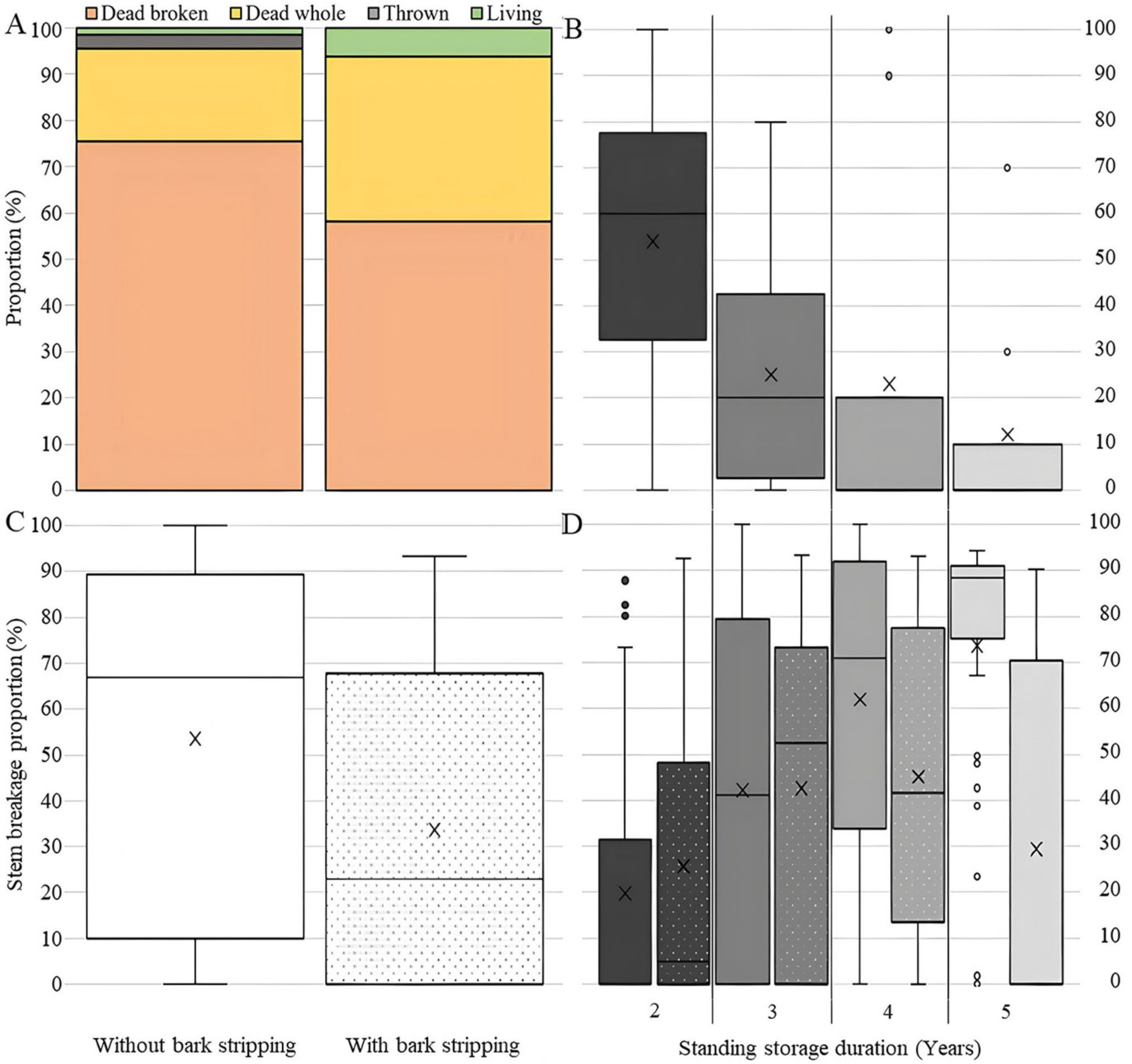

Fig. 9 Bark stripping damage and its relationship to tree state and standing storage duration. **A** Proportion of tree states without and with bark stripping and **B** Proportion of trees with bark stripping damage as a function of standing storage duration. **C** Mean stem breakage proportion as a function of bark stripping. **D** Mean stem breakage proportion as a function of standing storage duration and bark stripping. For boxplots in B–D, X marks the mean; horizontal lines on the box mark the 75th, 50th and 25th percentile. Vertical bars mark minimum and maximum values; circular points mark outliers. Dot patterns in D: bark stripping present

of the investigated stem rots. Against expectations, bark stripping was observed more frequently on snags without breakage, and there was a negative correlation between bark stripping damage and stem breakage proportion. One reason could be that the stems had broken off below the damaged area so that bark stripping damage was no longer be recordable. Based on this study, old stripping damage should not be interpreted as stabilizing the stem breakage behavior of dead spruce stands.

Bark condition

The bark condition was assessed according to the amount of bark remaining on the trunk: A (≥ 90%), B (> 10 to < 90%), C (≤ 10%). All living trees were assigned to condition A, but this condition was not limited to living trees; some trees that were dead had peeling bark with > 90% of the bark intact. The mean proportion of trees in category A and C showed no significant correlation with the standing storage duration, but there was a significant mean negative correlation with category B ($\rho = -0.411$; $P < 0.001$) (Fig. 10B). The tree state showed a significant correlation on bark condition ($P < 0.001$). With increasing bark loss, the proportion of snags without breakage increased, whereas the proportion of snags with breakage decreased. The breakage proportion was also significantly correlated with bark condition ($P < 0.001$). Trees in category A had a higher mean breakage proportion (64%) than trees in categories B or C (Fig. 10C). The breakage proportion of trees in category A increased from 36% after 2 years to 83% after 3 years of standing storage (Fig. 10D), and the proportion remained high with increasing storage duration.

During spruce bark beetle propagation, reddish-colored crowns and peeling bark are clear signs of infestation. If the bark falls off, the spruce is in the dying process, as the bark is loosened by the feeding and mulching of the young beetles (Nierhaus-Wunderwald and Forster 2004; Rohe 2020). The

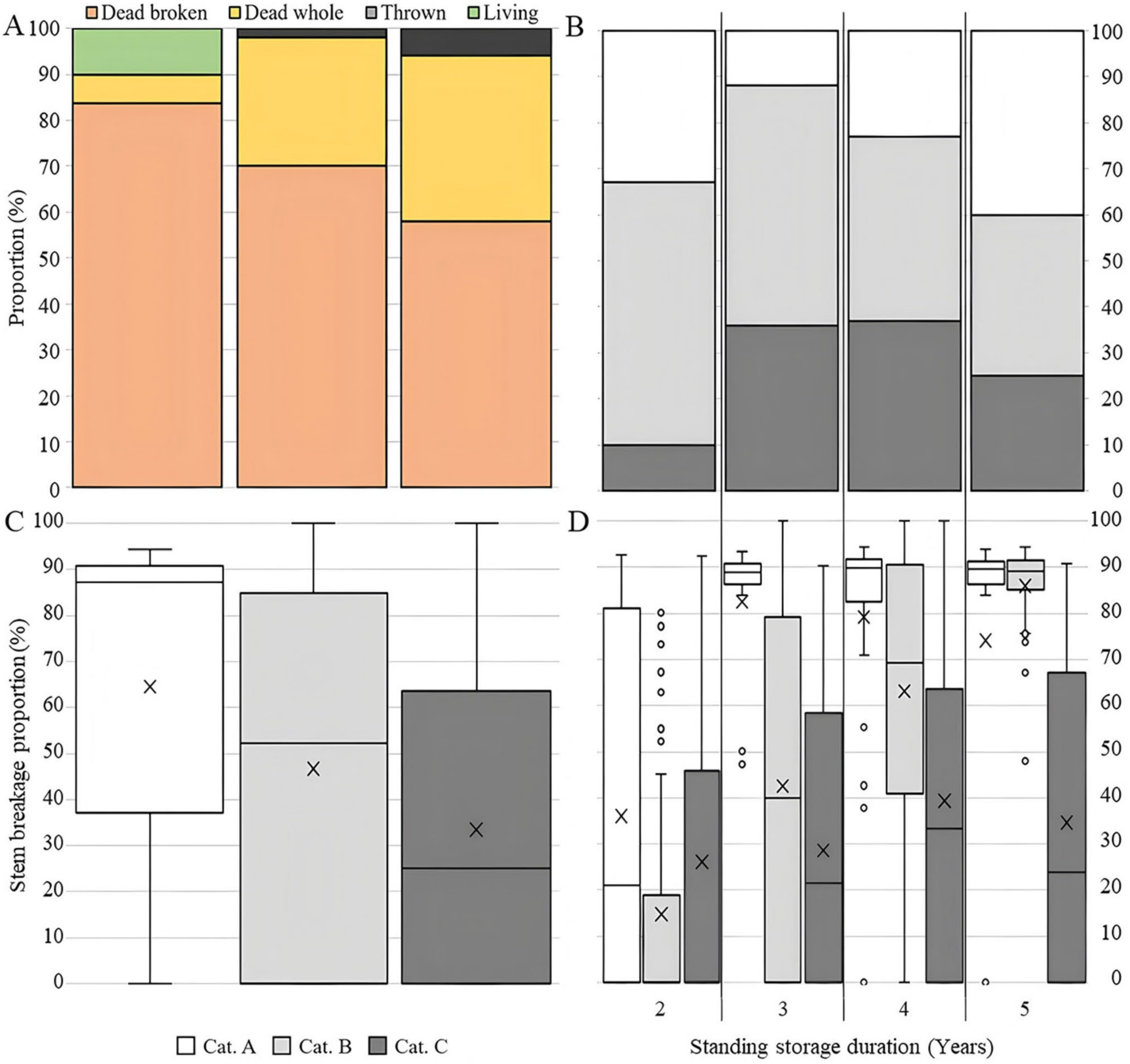

Fig. 10 Condition of bark. **A** Proportion of tree states by amount of remaining bark (category A ≥ 90%; B > 10 to < 90%; C ≤ 10%). **B** Proportion of trees in each bark category as a function of the standing storage duration. **C** Mean stem breakage proportion as a function of bark category. **D** Mean stem breakage proportion as a function of the standing storage duration and bark category. For boxplots in B–D, X marks the mean; horizontal lines on the box mark the 75th, 50th and 25th percentile. Vertical bars mark minimum and maximum values; circular points mark outliers

bark may already start to fall off when the crown is green, so that the tree remains attractive to the spruce bark beetle (LWF 2020). The analysis of the bark condition over the standing storage period showed an apparent "improvement"; more trees were categorized as A as the standing storage duration increased. This is due to the recording methodology, in which the bark condition was recorded as the proportion of bark still visible on the trunk. Many trees still had intact bark at the base of their trunks, which was presumably preserved by contact with the ground, roots or low wind loads. Intensively broken trees with bark remaining at the base of the trunk were assigned to category A, which makes the bark condition appear to be more of an indicator of the breakage proportion. In addition, knotty, especially young spruce trees often showed bark residue at the branch bases and between the branch whorls.

Critical evaluation of the methodology

Sample design

Based on the deadwood inventory of the Harz Mountain National Park (Nationalparkverwaltung 2021), the total population of possible study areas was stratified according to the standing storage duration. The aim of stratification is homogenization within defined subgroups (strata) of a population, whereby there is still heterogeneity between the subgroups to minimize distortions (Högel 2014). Samples were taken from 10 stands for each standing storage duration. The sample area design was based on a modified form of the six-tree sample according to Prodan (1968) or the *k*-tree sample (Kramer and Akça 2008), in which the size of the sample area is determined by the distance to the k^{th} tree. This method leads to different sample plot sizes within an inventory. The *k*-tree sample is a rational method of forest inventory (Gadow 2005; Kramer and Akça 2008), but it is not unbiased for parameters such as stock or stem number per hectare (Kleinn et al. 2009). The lack of unbiased results from the different inclusion probability of the sample tree was due to varying sample plot sizes and the lack of random distribution of the stems (Staupendahl 2006; Kleinn et al. 2009). In even-aged forests, such as those in the study area before the establishment of the national park, the stem distribution is not random due to artificial regeneration measures. A random distribution of the number of trees is not expected until the next forest generation in the national park. This distortion has a stronger effect in horizontally heterogeneous stands (Kramer and Akça 2008). Therefore, no conclusions should be drawn from the data collected about stocks or stem numbers in the study area.

Calculation of tree heights

The algorithm of Roussel and Auty (2024) calculates the height of individual tree tops by identifying local maxima in the canopy height model (CHM), which is particularly suitable for determining the heights of spruce trees, as their monopodial growth forms a clear crown maximum (Ackermann et al. 2020). This method uses a normalized digital terrain model as a reference surface and visually demonstrates a high level of positional accuracy when calculating tree heights (Ackermann et al. 2020). Figure 11 shows the tree tops in the Oderhaus study area, exemplarily for subcompartment 585a, based on the CHM. The accuracy of the tree-top segmentation depends on the quality of the source material (Light Detection and Ranging point cloud) and the stand structure (Ackermann et al. 2020). Conventional measuring methods, such as trigonometric measuring devices, also exhibit errors (Kramer and Akça 2008). Ginzler and Hobi (2016) reported deviations of ± 3 m between tree heights from CHMs and conventional measurements. Terrestrial laser scanning does not provide a more precise estimation than light detection and ranging point clouds (Sibona et al. 2017). Because current tree height measurements were

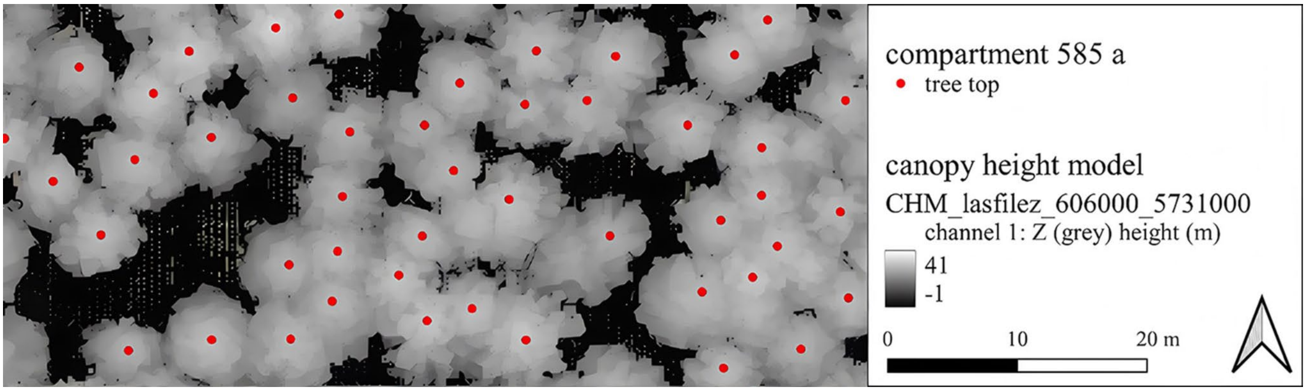

Fig. 11 Extraction from the canopy height model (CHM) of the Oderhaus study (Compartment 585a) area with localised tree tops. Data basis: LGLN 2018

not available for the study area and the stands were already dead at the time of the survey, remote sensing was chosen to determine tree heights in 2018 as a suitable reconstruction method. Iterative methods with surface segments and defined minimum heights (here 10 m) have proven to be effective for determining stand heights (Ackermann et al. 2020). Minimum heights defined for each area unit could lead to more precise estimates and allow parameters such as Weise's top height (Weise'sche Oberhöhe) to be derived (Ackermann et al. 2020). On the other hand, the arithmetic mean height is susceptible to bias due to management practices and should therefore only be used for biological statistical analyses (Kramer and Akça 2008). For the aims of this study, the arithmetic mean height appeared suitable for analyzing trends and correlations in pure spruce stands with trees of the same age that are exposed to the same external influences. This restriction should be taken into account for further stock estimates and deriving stock parameters.

Conclusion

Observations of the tree condition and the stem breakage proportion of spruce snags after different durations offered valuable insights into the standing storage of spruce calamity wood. The low proportion of living spruce trees was explained by the low probability of survival after mass reproduction of spruce bark beetles and was primarily due to offspring from natural regeneration at some sample points. Nearly all trees were dead, either broken or whole, and a few were thrown or still living; the living trees were from natural regeneration at just a few sample points. Nearly all fungal fruiting bodies, which belonged to the brown rot species, *Fomitopsis pinicola*, occurred on dead, standing trees. So the presence of fruiting bodies can be interpreted as the main external indicator of stands with stored standing spruce. Stem cracks decreased with longer standing storage durations, which indicates the lower probability of development in the case of higher proportions of stem breakage. The presence of branchlets could prove useful for estimating the standing storage duration, since a significant decrease was correlated with increasing storage durations. Bark stripping damage, on the other hand, was implausible in terms of its effect on the tree state and stem breakage proportion. Hence, it should not be interpreted as having a stable effect on spruce stands. However, the bark condition could have an influence on the stem breakage proportion, but further investigations are required to confirm this effect. Longer standing duration increased the stem breakage proportion. After 2 years, a critical threshold was reached when significant changes in the external appearance of the trees were evident. In practice, it is important to clarify whether spruce wood stored standing is still safe and economically usable after prolonged storage, as the risk of breakage and the associated risks increases.

Acknowledgements The authors sincerely thank the Administration of the Harz National Park, particularly Marlene Düngelhoef and Kai Bauer, for their invaluable support in conducting this study and for providing essential data and logistical assistance. We also extend our gratitude to Dr. Marc Overbeck from the Forest Planning Office of Lower Saxony (NFP) for providing site and forest management data and to the Office for Geoinformation and Land Surveying of Lower Saxony (LGLN) for providing map data and expert guidance, which played a significant role in the success of this work. Additionally, we appreciate the scientific expertise and valuable input provided by the partners of the NUKAFI project. Financial support was received from the Open Access Publication Funds of the University of Göttingen.

Funding Open Access funding enabled and organized by Projekt DEAL.

Data availability Data of this study are available from the corresponding author upon reasonable request.

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