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Stump and Site Factor Analysis After Sanitary Logging of Bark Beetle-Infested Forests

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ABSTRACT

Coniferous forests cover 41% of Bosnia and Herzegovina, with Norway spruce (*Picea abies*) being an ecologically and economically important species. Bark beetles, especially the European spruce bark beetle (*Ips typographus*), pose a major threat, often causing large-scale dieback. Factors such as wind, drought, terrain exposure, and slope can increase susceptibility to outbreaks. This study aimed to assess the influence of these factors on forest health in bark beetle outbreak areas, based on stump measurements after sanitary logging.

Fieldwork was conducted in spring 2024 on five known bark beetle hotspots managed by "Šumsko privredno društvo Zeničko-dobojskog kantona" d.o.o. Zavidovići. Data collected included stump diameter, wood decay, bark thickness, tree coordinates (via AlpineQuest), exposure, and slope. Analyses were performed in STATGRAPHICS Plus using one-way ANOVA and Bonferroni correction.

A total of 507 stumps were analyzed. About 81% were in diameter classes 31–50 cm and 51–80 cm and nearly 48% showed central wood decay. Terrain exposure and slope significantly influenced stump diameters, with the largest averages on SW exposure and 2–5% slopes. Stump diameter also significantly affected decay size, while bark thickness showed no significant variation across exposure or slopes.

This research confirmed that Norway spruce in diameter size categories 31–50 cm and 51–80 cm is most vulnerable to bark beetle attacks. This susceptibility is further intensified if trees are located on south-facing, moderate slopes. Central wood decay was present in nearly half of the observed tree stumps, leading to the conclusion that its presence is another predisposing factor for bark beetle attacks. Bark thickness on the observed tree stumps did not vary significantly on different terrains, which is a result that differed from the results obtained in other similar studies.

Keywords: bark beetle outbreak; Norway spruce; bark beetles; stumps; forest stand

INTRODUCTION

According to available data from the Second National Forest Inventory in Bosnia and Herzegovina, forests and forest land take up 3.231.500 ha (roughly 60%) of the total country area. In terms of tree species, conifers make up 41%, while broadleaf trees account for 59% of all forest trees. Norway spruce wood accounts for 32% of the total conifers' volume, and its share in the total timber stock of high forests in the public sector is 13% (Begović 1973). The vitality of forest trees depends on a number of abiotic and biotic factors, and the effects of harmful forest pests have a particularly significant role in this regard (Jactel et al. 2009).

Some of the most important pests in coniferous forests are bark beetles (Coleoptera: Curculionidae: Scolytinae) (Lieutier et al. 2004), capable of killing a large number of trees at once. As a crucial part of forest ecosystems, bark beetles have an important ecological role in picking out weakened trees and partaking in the initial stages of wood decomposing. However, they often pose a serious problem in forest management, since they can develop large populations and cause severe damages, which tend to be hard to mitigate (Wermelinger 2004). Damaging potential of the species has increased in the past decade with climate warming and more frequent occurrences of extreme weather events (Hartmann et al. 2025).

The emergence of a bark beetle gradation is conditioned by the state of forest cover and the population density of bark beetles. A higher bark beetle population density increases the mortality rate of forest trees (Christiansen 1985). Forest stand and habitat characteristics are significant factors influencing the intensity of tree mortality in specific areas identified as bark beetle "hotspots".

Forest stand events such as windthrows, snowbreaks, uprooting and droughts contribute to an accumulation of physiologically weakened trees, susceptible to bark beetle attacks (Gutowski and Krzystofiak 2005, de Groot et al. 2019, Jactel et al. 2019, Pernek et al. 2019). If climatic and stand conditions provide a sufficient number of susceptible hosts, large-scale outbreaks can develop rapidly (Christiansen and Bakke 1988). In this way, bark beetles can easily cause dieback of forest stands and forest complexes containing a greater share of Norway spruce as their host species (Hlásny et al. 2021). The latest research clearly shows that conifer-dominated forests are becoming increasingly vulnerable to wood- and bark-boring insects, particularly the spruce bark beetle (Hlasny et al. 2025)

The formation of bark beetle hotspots in forest stands largely depends on the level of sunlight exposure at the site. A higher degree of insolation leads to an increase in temperatures under the tree bark, creating favorable conditions for bark beetles. As a result, trees at stand edges, especially those on south-facing slopes, are more vulnerable to attacks (Jakuš 1998, Berthelot et al. 2021). Similarly, topography plays a significant role in the spatial variability of insolation, meaning that the terrain on which the stand is located largely determines which areas are at a higher risk of becoming infestation hotspots (Mezei et al. 2019).

According to Jakuš (1998), the level of air pollution plays a crucial role in determining the capability of Norway spruce to resist abiotic stress, and thus bark beetle overpopulation.

The risk of strong infestation is further increased by forest stand factors such as canopy, tree age, and the proportion of Norway spruce in mixed stands (Kärvemo et al. 2023). Intensified competition among tree species due to excessive stand density can limit the availability of soil resources (Zabihi et al 2023, Thomas et al. 2024), which affects the biosynthesis of various substances that serve as a tree's defence strategy against bark beetle attacks (Baier 1996, Rohde et al. 1996, Dautbašić and Mujezinović 2018, Erbilgin et al. 2021).

The presence of other, non-host tree species in stands at lower altitudes results in less frequent and intense sanitary felling compared to pure spruce stands with a low proportion of other species (de Groot 2023).

Greater crown height and higher tree volume of Norway spruce also increase the risk of bark beetle attacks. Trees under 15 meters in height are less exposed to bark beetle attacks, and the risk progressively increases with the further increase of average crown height, gradually stabilizing around the height of 25 meters (Kärvemo et al. 2023).

Forest structures vary depending on altitude, terrain slope, and exposure, with altitude playing a key role in tree dieback during all phases of spruce bark beetle, *Ips typographus* L. (Coleoptera, Curculionidae) attacks (Mezei et al. 2014). For example, trees tend to be more densely distributed at lower altitudes (Zabihi et al. 2021). This difference in tree density due to varying altitude also impacts the characteristics of trees and their bark (Zabihi et al. 2021), which are important factors determining tree susceptibility to bark beetles. Since topography and spacing between trees significantly influence the functions of forest ecosystems, strategies of forest management should be adjusted to take these variables into consideration in order to improve overall health and resilience of secondary Norway spruce forests (Zabihi et al. 2021, Thomas et al. 2024). Regarding tree age, it has been found that susceptibility of Norway spruce to bark beetle attacks is increased for trees over 70, and especially for those over 100 years of age (Becker and Schröter 2000).

Altitude and soil nutrients such as nitrogen, phosphorus and magnesium may have significant impact on the intensity of *I. typographus* bark beetle attacks (Dutilleul et al. 2000). Consequently, limitations in soil resources availability could affect many plant functions such as resin secretion, photosynthesis and biosynthesis of carbon-dependent defensive substances, which increases the likelihood of bark beetle attacks (Erbilgin et al. 2021).

The aim of this research is to determine the effects of different spruce forest stand and habitat characteristics on the decrease of tree vitality in certain areas of the forest stands marked as spruce bark beetle hotspots. The analysis was conducted through the inspection and measurement of tree stumps following sanitary logging and after the removal of trees infested by bark beetles.

MATERIALS AND METHODS

The determination of the impact of certain forest stand factors and habitat characteristics on the occurrence of bark beetle hotspots was carried out in the area of the public company "Šumsko privredno društvo Zeničko-dobojskog kantona" d.o.o. Zavidovići, forest management area "Gornjebosansko", management unit "Gornja Stavnja", forest sections 41/a, 40/b, 4/a, 96/b and 67/a. The observed forest stands belong to the following management classes: 1211 – Beech and fir forests with spruce on predominantly deep calcareous cambisols, luvisols and their combinations on solid limestone and dolomite, and 1226 – Secondary fir and spruce forests in the beech and fir with spruce forest belt on predominantly deep district cambisols, luvisols, pseudogleys and podzols on silicate and silicate-carbonate sedimentary substrates and acidic volcanic rocks (Table 1).

Fieldwork data collection took place in the spring of 2024.

In the stated forest sections, bark beetle hotspots were identified in places where trees were removed due to a bark beetle outbreak (Figures 1–4). On the specified areas, data was collected on forest stand characteristics and other habitat parameters which influence tree dieback and the formation of hotspots. Specifically, the following measurements and assessments were conducted in the field:

Measurement of tree stump diameters, wood decay diameters (if decay was present), tree bark thickness (where remnants of tree bark were present). The grouping of stump diameters into diameter classes with defined intervals represents a standard practice in forestry, as it reduces the number of categories and facilitates comparisons between groups, provides a clear representation of diameter distribution within the population of trees or stumps (van Laar and Akça 2007), and allows for the application of statistical analyses (e.g., ANOVA, χ^2 tests) by working with classes rather than individual values. The following classes were used: 11–20; 21–30; 31–50; 51–80; 80<.

Determination of individual tree coordinates, exposure and terrain slope in bark beetle hotspot locations. Field coordinates were recorded using the AlpineQuest application, while the terrain exposure was determined on maps. Terrain slopes were assessed based on the existing terrain slope categories, according to Demek (1972).

Assessment of tree and soil damage (soil compaction) caused by felling and extraction of the attacked trees, as well as the implementation of proper debris management.

After the conducted fieldwork where all the necessary parameters were measured, the obtained data was imported and analysed in the statistics software STATGRAPHICS Plus, through the method of one-way ANOVA. By setting the null-hypothesis, the impact of certain parameter categories on the chosen variable was determined. In case of a statistically significant difference being shown, the significance of such difference was determined via the Bonferroni correction.

Table 1. Overview of objects for data collection.

Research object	Management class	Terrain exposure category		Terrain incline category		Number of measured stumps
		a	b	a	b	
Plot 1	1211	SW (85.71%)	E (14.29%)	2–5% (85.71%)	12–32% (14.29%)	35
Plot 2	1211	NW (100%)		2–5 (100%)		34
Plot 3	1226	NE (100%)		12–32% (67.29%)	32–55% (32.71%)	107
Plot 4	1226	S (100%)		32–55% (100%)		204
Plot 5	1226	NW (100%)		32–55% (100%)		127

Figures 1–4. Forest stand and habitat characteristics on a bark beetle hotspot.

RESULTS

A total of 507 tree stumps were analysed and sorted into 5 distinct categories according to their diameter size. Within each diameter category, we recorded the number of tree stumps with present wood decay (Figure 5).

In the five observed experimental plots (P1 to P5), all analysed stumps were separated into two categories depending on presence of wood decay – tree stumps with and tree stumps without any wood decay. Wood decay was recorded on: 14 (40%) out of the total 35 tree stumps on P1, 12 (27.3%) stumps on P2, 38 (25.5%) on P3, 104 (51%) on P4 and 75 (59.05%) tree stumps on the experimental plot P5.

For each experimental plot, we recorded the mean elevation (Table 2).

All observed tree stumps were further divided into categories according to the terrain slope and exposure of their locations (Table 3, 4).

Finally, the analysed healthy, standing trees on the edges of observed bark beetle hotspots were divided into groups according to Kraft's tree classification (Figure 6).

Statistical significance of the impact that terrain exposure and inclination had on the diameters of observed tree stumps was analysed through one-factorial analysis of variance (one-way ANOVA). This test showed a statistically significant impact of the terrain slope on tree stump diameter size, with the terrain slope category 2–5% most significantly impacting stump diameters (Table 5).

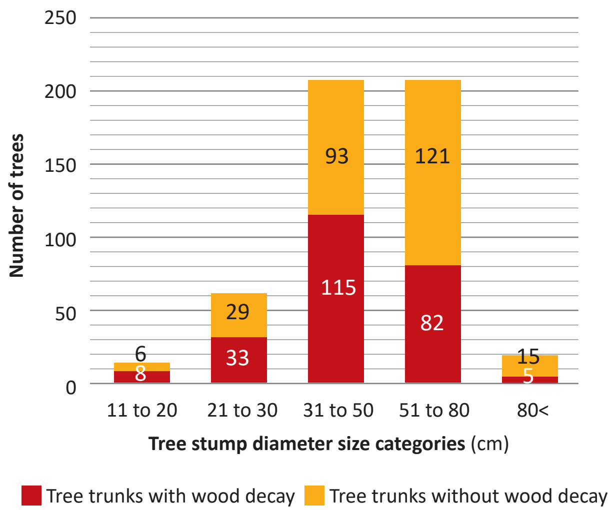

Figure 5. Cumulative distribution of the observed tree stumps into categories based on diameter size and presence of wood decay.

Table 2. Experimental plots mean elevation.

Experimental plot	Elevation [m]
P1	1277
P2	1146
P3	896
P4	1091
P5	1034

Table 3. Cumulative distribution of tree stumps into categories according to terrain sloping.

Terrain slope category	Number of trees
2–5%	64
5–12%	0
12–32%	35
32–55%	408
55%<	0

Similarly, terrain exposure was also proved to have a statistically significant impact on the observed tree stump diameter sizes. The tree stumps on terrains of a south-western exposure had the largest average diameter, while those on north-eastern exposure terrains had the smallest average diameter (Table 6).

Analysis of central wood decay diameters in the observed tree stumps showed a statistically significant impact of different experimental plots, stump diameter categories, terrain exposure and terrain slopes on the central wood decay diameters. According to the conducted one-way ANOVA and the subsequent Bonferroni correction,

Table 4. Cumulative distribution of tree stumps into categories according to terrain exposure.

Terrain exposure	Number of trees
NE	107
E	5
S	204
SW	30
NW	131

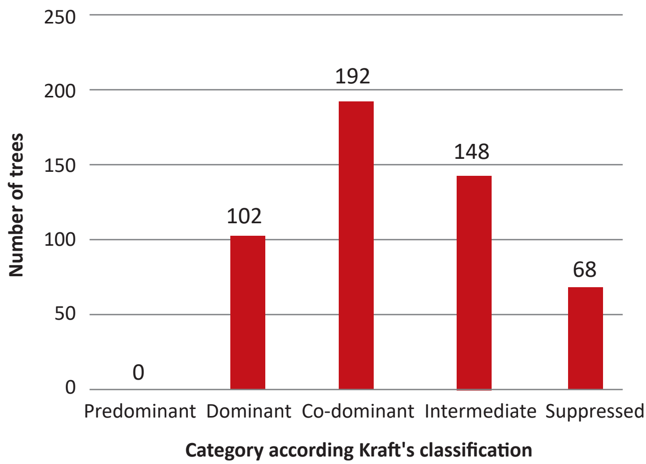

Figure 6. Distribution of the number of observed vital standing trees into categories according to Kraft's tree classification.

Table 5. Representation of homogenous groups in the assessment of tree stump diameter sizes depending on terrain slope.

Terrain slope category	Number of trees	Mean (cm)	Homogenous groups
12–32	35	42.22	X
32–55	408	47.60	X
2–5	64	64.12	X

Table 6. Representation of homogenous groups in the assessment of tree stump diameter sizes depending on terrain exposure.

Exposure	Number of trees	Mean (cm)	Homogenous groups
NE	107	41.43	X
S	204	48.87	X
NW	161	52.18	X
E	5	52.20	XXX
SW	30	64.50	X

central wood decay diameters statistically significantly varied amongst experimental plots P2 and P3, P2 and P4, P3 and P5 and P4 and P5.

We compared the basal areas of the observed tree stumps with the measured basal area of their recorded wood decay. Figure 7 shows the proportion of the average measured wood decay area in the average basal area of the stump, across the five experimental plots.

The impact of the observed stump diameter categories on the presence and diameter sizes of central wood decay in those stumps was analysed in a similar manner. Our analysis showed that there is a statistically significant difference between the presence of central wood decay and diameters depending on the stump diameter size category, for all observed categories. The average central wood decay diameter was significantly different in each stump diameter category, with the smallest average diameter (10.75 cm) calculated in the stump diameter category 11–20 cm, and the largest (63.4 cm) in the category >80 cm. As previously shown in Figure 5, the largest number of stumps with central wood decay (115) was recorded in the 31–50 cm stump diameter category.

The same type of statistical analysis showed a statistically significant impact of terrain exposure on the diameter of the observed stump' central wood decay. Tree stumps with the largest central wood decay diameters were identified on eastern (average diameter 44.66 cm) and north-western (average diameter 41.87 cm) terrain exposure, while the smallest average diameters of central wood decay were measured in stumps on a north-eastern exposure (average diameter 31.1 cm).

Terrain slope categories were proven to have a statistically significant impact on central wood decay diameters in the same way as terrain exposures. The conducted post-hoc test (Bonferroni correction) showed that tree stumps on 2–5% slopes had the largest average central wood decay diameters. These diameters were the smallest for stumps in locations with 12–32% terrain slopes (average wood decay diameter 29.28 cm).

According to the conducted analysis, the variability of bark thickness of the observed tree stumps was not statistically significant depending on different terrain exposure. Similarly, bark thickness did not statistically significantly vary between the observed experimental plots.

DISCUSSION

Forest damage caused by windthrows, wildfires, insects, and diseases has substantially increased in recent decades (Patacca et al. 2023, Hlasny et al. 2025). As climate change continues to accelerate, disturbance dynamics may intensify even further, though these effects can exhibit significant geographical variability and different responses between individual agents (Seidl et al. 2017). Continental forests in Europe will continue to exist since they are dynamic systems that must rearrange themselves as their surrounding environment changes (Hartmann et al. 2025). In this research we contribute to the understanding of forest damage caused by sudden increases in bark beetle populations. Understanding the habitat conditions that increase the risks of attack is our focus here, and this should help forestry practitioners in managing spruce forests.

During epidemic periods, altitude and the proportion of spruce exerted a stronger influence than during non-epidemic periods (de Groot et al. 2019). Altitude had a negative effect on sanitary felling, whereas a higher proportion of Norway spruce increased its occurrence, particularly at lower elevations during outbreaks (de Groot et al. 2019). Interactions between altitude, spruce proportion, and outbreak periods were observed. Altitude showed a negative correlation with sanitary felling (Ogris and Jurc 2010, Mezei et al. 2014, Pasztor et al. 2014) and was associated with lower temperatures.

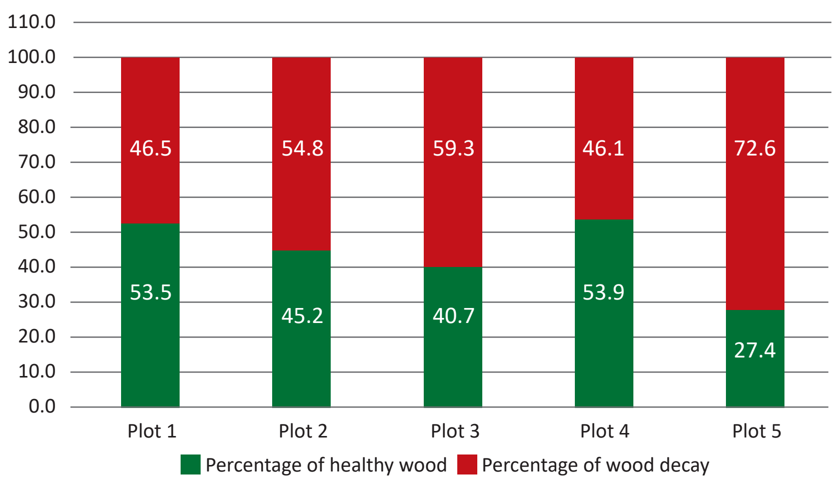

Figure 7. The ratio of average wood decay basal area to the average stump basal area across plots.

Elevated temperatures weaken Norway spruce, especially outside its natural distribution range, thereby increasing its susceptibility to bark beetles (Levanič et al. 2009). Moreover, the reproduction of *I. typographus* is influenced by degree days, with lower temperatures at higher altitudes reducing outbreak frequency (Öhrn et al. 2014). Although outbreaks are currently less frequent at higher elevations, rising temperatures are expected to increase infestation risk (de Groot et al. 2019).

De Groot et al. (2023) reported that the intensity of sanitary felling decreased with greater diversity of non-host tree species, particularly at lower elevations, although this effect weakened with increasing proportions of Norway spruce. Thus, species diversity alone does not determine outbreak risk, but enhances biotic resistance when host availability is reduced under less favorable abiotic conditions (de Groot et al. 2023). Sanitary felling was most frequent at lower altitudes and during outbreak periods, increasing with forest cover and spruce dominance (de Groot et al. 2023). Norway spruce stands were most vulnerable at low-elevation sites with high forest cover. However, tree species diversity did not significantly reduce spruce susceptibility to bark beetles or the likelihood of sanitary felling (de Groot et al. 2023). Higher spruce density at lower altitudes correlated with increased sanitary felling, consistent with previous findings (de Groot et al. 2019, Nardi et al. 2023). The largest number of stumps of attacked trees was recorded on southern exposure, somewhat fewer on northwestern exposure, and only a few on eastern exposure.

Altitude revealed a distinct pattern, with bark beetles preferring areas below 2000 m and above 4000 m. South- and west-facing slopes (100–300º) likely provide a warmer microclimate and suitable habitats for host trees, which is consistent with previous research showing that white spruce concentrated on south-facing slopes (Viereck and Little 2007, Ohse et al. 2009).

Mezei et al. (2019) observed that bark beetle infestations began in sun-exposed areas, peaking with the strongest response to solar radiation, and gradually spreading to less exposed sites. They also noted that topography influences insolation through variations in elevation, slope, aspect, and shading, thereby affecting microclimatic factors such as temperature, evapotranspiration, snowmelt, soil moisture, and light availability. Since temperature strongly affects bark beetle dynamics, topographic variables (aspect, slope, elevation) are key predictors. South- and west-facing slopes, in particular, increased infestation risk (Wermelinger and Seifert 1999, Baier et al. 2007, Jönsson et al. 2011).

Lausch et al. (2011) found that slope and aspect were not decisive for the dispersal of *I. typographus*, which contradicts Wulder et al. (2006), who improved their model by including slope. Jurc et al. (2006) reported a strong correlation between high *I. typographus* density and northeastern exposure, with greater trap catches on western and eastern slopes, while southern and northern exposure had minimal captures. Warmer west-facing slopes were more prone to wider spatial spread of infestation.

Blomqvist et al. (2018) identified aspect as a key factor in infestation severity: eastern and northeastern slopes were the most vulnerable, whereas southern and southwestern slopes had the lowest risk of severe infestation but a higher probability of moderate infestation when combined with other site factors.

South- and west-facing slopes are also vulnerable to *I. typographus* (Jakuš 1998), as drought-stressed trees in these areas are more susceptible to attack (Kaiser et al. 2013). Jurc et al. (2006) recorded higher beetle trap catches on eastern and northeastern slopes, suggesting favorable conditions in these aspects.

Statistical analysis showed that the largest average stump diameter occurred on the southwestern exposure, while the smallest was found on the northeastern exposure. The Bonferroni correction confirmed significant differences across five pairs: south and southwest, south and northeast, southwest and northeast, southwest and northwest, and northeast and northwest.

Further statistical analyses were performed to determine the extent of central wood decay in the observed stumps, considering plot, stump diameter class, exposure, and slope. The results indicated statistically significant differences in central wood decay diameter across these parameters.

Zahirović et al. (2018) found that the highest number of infected silver fir and spruce trees occurred in the 30–50 cm diameter class. Zahirović (2017) observed that in spruce, the length and volume of decay increased with breast height diameter. Similarly, Zahirović et al. (2016) reported significant differences in the presence of stump decay among diameter classes, with the greatest occurrence in trees of 30–79.9 cm, likely due to long-term damage from felling and extraction. Zahirović (2012) noted that infection rates in spruce increased with tree diameter, suggesting a gradual spread of decay fungi.

The relationship between stump basal area and the basal area of central wood decay contributes to a better understanding of the dynamics of decay development in spruce. Critical thresholds of stem diameter at which significant shifts in decay progression occur were identified. These findings hold practical relevance for forest management, particularly in decisions regarding tree harvesting, as they can help reduce economic losses and improve the quality of harvested timber.

It is unlikely that future forests will resemble the ones we appreciate today (Hartmann et al. 2025). Current host tree–insect/pathogen systems will develop new dynamics that we cannot predict with certainty. These changes may cause some of the currently dominant forest tree species to decline and become minor components of future forests. In some cases, adaptive management efforts may fail, at least from a utilitarian perspective. That is why investigations into the conditions and causes of forest damage are extremely important.

CONCLUSIONS

This study demonstrated that bark beetle outbreaks in uneven-aged Norway spruce stands are not random but strongly associated with site and tree-level factors. Trees in the diameter classes 31–50 cm and 51–80 cm were most frequently attacked, particularly on south-facing slopes with moderate inclinations, confirming the importance of stand structure and topography in shaping infestation hotspots. Nearly half of all analysed stumps contained central wood decay, which proved to be closely related to tree size and site conditions, highlighting its role as an additional predisposing factor for bark beetle attacks.

These findings underline that effective forest protection strategies must consider not only stand density and exposure but also the presence of internal stem decay when assessing vulnerability to bark beetle outbreaks. Integrating decay assessments into monitoring protocols could improve the early identification of susceptible stands and help prioritize sanitation logging.

From a management perspective, reducing the proportion of overmature spruce and minimizing mechanical damage during harvesting operations may lower the risk of both decay fungi and bark beetle infestations. In addition, adapting silvicultural practices to site-specific conditions—especially slope and exposure—can strengthen stand resilience and mitigate economic losses.

Finally, the demonstrated interaction between central wood decay and bark beetle susceptibility suggests that future research should focus on the combined effects of biotic and abiotic stressors, including *Heterobasidion* and *Armillaria* infections, drought stress, and stand composition. Understanding these complex interactions will be essential for designing adaptive management strategies under changing climatic conditions.

Author Contributions

OM and SM conceived and designed the research; OM and SM carried out the field measurements; KZ performed laboratory analysis; KZ, NG, DP and SI processed the data and performed the statistical analysis; MD and MP secured the research funding, supervised the research and helped to draft the manuscript; all authors wrote the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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