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Stand Density Effects on Stem Diseases and Mortality in Spruce and Pine Forests

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Abstract

Norway spruce (*Picea abies* (L.) H. Karst.) and Scots pine (*Pinus sylvestris* L.) are among the most valuable tree species in the Lithuanian forests. Pure stands, which comprise approximately one-quarter of Lithuania's forest area, provide an important framework for studying tree responses to thinning and susceptibility to species-specific diseases and damage. This study investigated stem health and quality in two experimental Scots pine stands (32 and 39 years old) and four experimental Norway spruce stands (36–43 years old) to assess the influence of the initial stand density and thinning intensity. Each stand consisted of five plots with different initial densities and was subjected to varying thinning regimes from stand establishment. Tree locations were mapped using the pseudolite-based positioning system TerraHärp, and local tree density was calculated. Stem health and damage were assessed using ICP-Forests methodology. Our results showed that across initial densities of 1000–4400 trees ha^{-1}, tree dimensions (diameter and height) were similar, regardless of thinning intensity. The highest levels of stem damage and competition-induced mortality occurred in the densest, unthinned stands, with deer browsing and scraping from fallen trees being the most common damage agents. In contrast, thinned stands exhibited a higher incidence of stem rot (*Heterobasidion annosum* (Fr.) Bref.), particularly for Norway spruce. Finally, stand density alone did not consistently explain the patterns of tree mortality in either the pine or spruce stands. These findings suggest that cultivating Scots pine and Norway spruce at lower initial densities with minimal thinning may reduce the damage and losses caused by fungal infection. Finally, novel techniques, such as the pseudolite-based positioning system for geolocating trees and drone imaging for assessing tree health, have proven valuable in facilitating field surveys.

Keywords: forest management; disease incidence; stand density; forest damage; tree positioning

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1. Introduction

The production of high-quality timber presents numerous challenges owing to its diverse applications [1,2]. Stem quality and tree health can be managed through the regulation of stand density and thinning regimes [1–4]; however, forest health has been declining worldwide, often as a result of past forestry practices [5–10]. Homogeneous, even-aged stands, which are managed under rotational forestry systems with the main objective of maximizing the volumes and quality of the final timber products, remain common because they are cost-effective for managing and facilitating consistent silvicultural operations [2]. However, such stands are more vulnerable to pests and diseases than mixed-species forests [11–13].

Stand density plays a key role in timber quality and forest resilience. Dense stands promote slender stems and thinner branches, whereas thinning enhances radial growth [14–17]. Specific thinning regimes are widely used to improve stem form, yet they can also stress trees and increase their susceptibility to damage. The incidence of disease and injury is particularly high in stands with high pre- and post-thinning densities [18]. Moreover, forest operations can facilitate fungal infections, such as *Heterobasidion* spp., which colonize freshly cut stumps and wounds [8]. Scots pine (*Pinus sylvestris* L.) was found to be more resistant to fungal damage than Norway spruce (*Picea abies* (L.) H. Karst.) [6], whereas mixed stands of spruce showed lower susceptibility to *Heterobasidion annosum* (Fr.) Bref. compared with that of pure spruce stands [7]. Other studies have shown that both the number of damaged trees and severity of damage increase over time [17,19]. The extent of damage during thinning or felling is strongly influenced by multiple factors, including season, tree species, care in harvest planning, and experience of machine operators [20,21].

More recently, forest decline has been increasingly driven by rising populations and expanded distributions of insect pests and pathogens [22]. Bark beetles, including *Ips acuminatus* (Gyllenhal) and *I. typographus* (Linnaeus), have growing impacts on spruce forests [23,24], although knowledge of these processes remains limited in the Baltic region.

Climate change frequently favors invasive pest species, imposing additional stress on trees. Choat et al. and Bose et al. [25,26] showed that the primary cause of tree mortality during drought is the catastrophic failure of plant hydraulic systems, yet the long-term impacts of drought on tree vitality remain uncertain. The wind is another major disturbance factor. Studies on Scots pine have highlighted the financial consequences of wind-induced damage [27,28], consistently linking wind events to reduced forest health and productivity. Valinger and Fridman [28] reported that the most severe wind damage occurs in dense mature stands dominated by Norway spruce, as well as in recently thinned dense mature stands, where trees are suddenly exposed to higher wind loads. Similarly, the increasing proportion of Norway spruce in mixed stands has been associated with greater wind vulnerability [29,30].

Therefore, increasing diameter growth through repeated thinning is a complex compromise, as it can increase the sensitivity of trees to mechanical and physiological stress. What initially appears to be a benefit may, in fact, lead to higher mortality rates. To better understand and predict forest responses to multiple stressors, advances in remote sensing technologies and the broader use of high-resolution data—derived from both field observations and satellite monitoring—should play an indispensable role [31–33]. Such integration would enable a more accurate assessment and resolution of current challenges associated with realistic predictions of tree mortality events [31]. Moreover, as the climate continues to warm, it will become increasingly important to account for changing interactions among trees, insects, and the microbiome, particularly those driven by the invasion of new species [34–36]. These insights will allow forest managers to make more informed decisions, set clear management priorities, and optimize resource allocation.

Against this background, the present study aimed to evaluate how initial stand density and thinning intensity influence the prevalence of disease and damage in Scots pine and Norway spruce stands aged 30–40 years. Identifying the drivers of forest degradation and establishing appropriately structured stands may enhance ecological sustainability [22,28]. Although climate change exerts global effects, its impacts have pronounced regional dimensions. Consequently, region-specific monitoring of forest health is essential for establishing forestry policy priorities at both regional and global levels. The findings of this study may help anticipate the disease risks associated with thinning and provide guidance for avoiding management practices that compromise stand resilience.

We asked the following research questions: How does initial stand density influence tree growth (diameter and height) in Scots pine and Norway spruce, independent of thinning intensity? How does thinning intensity affect the balance between reducing competition and increasing vulnerability to fungal infection? What silvicultural strategies (in terms of initial stand density and thinning regimes) best minimize losses from stem damage, mortality, and fungal infection? In addition to our experimental observations, we evaluate the applicability of modern tree-mapping and drone-imaging technologies as tools to facilitate similar investigations.

2. Materials and Methods

2.1. Study Area

Four Norway spruce and two Scots pine sites were selected within a long-term experimental area established between 1990 and 1992 to study stand growth under different thinning regimes. These sites represent distinct regions of Lithuania (Figure 1). Both species were cultivated at five initial stand densities and subjected to thinning from below using a semi-mechanized method: Trees were felled with chainsaws and logs transported by a small forwarder. The plantations were established by planting 2-year-old seedlings, and the first thinning, during which different density variants were formed, was conducted in 1990–1992, 4–12 years after planting. The initial density of the densest (V) variant is the planting density of the stands before the first thinning. Forest health and damage were assessed in 2020, when spruce trees were 36–43 years old and pine trees were 32–39 years old (Table 1).

Pine stands grew on *Dystri-Haplic Arenosol* and *Hapli-Albic Arenosol* soils, while spruce stands grew on *Epidystric Planosol*, *Hapli-Calc(ar)ic Luvisol*, and *Orthi-Haplic Luvisol* soils. According to the Food and Agriculture Organization of the United Nations [37], these are among the most suitable soil types for establishing productive pine and spruce stands.

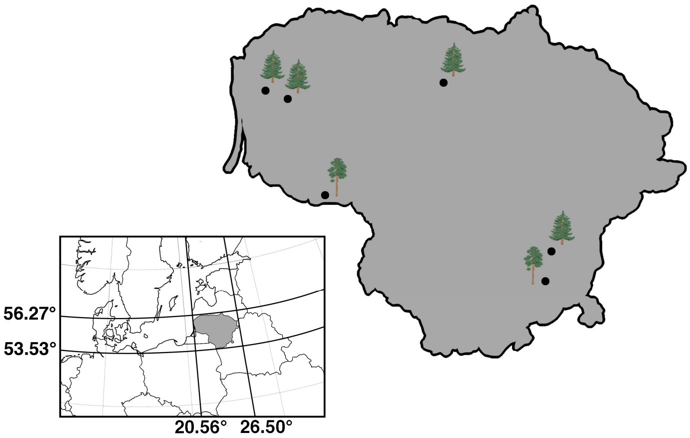

Figure 1. Geographic location of the selected study sites in Lithuania (🌲—*Picea abies* (L.) H. Karst. (100%); 🌳—*Pinus sylvestris* L. (100%)).

Table 1. Description of study plots chosen within a long-term experimental area established be-tween 1990 and 1992 (SP—Scots pine (*Pinus sylvestris* L.), NS—Norway spruce (*Picea* abies (L.) H. Karst.)).

Initial Stand Density Variant Number	Initial Stand Density Established in the First Thinning, Trees ha^{-1}	Number of Thinning	Principle Stand Age at Thinning Year	Area of Test Plots, ha		Total Number of Trees at Assessment, Tree		Mean Tree Height at Assessment, m		Mean Diameter of Trees at Assessment, cm	
				SP	NS	SP	NS	SP	NS	SP	NS
V	4038–5400	No thinning	-	0.58	0.64	1364	2025	17.5	19.5	16.1	18.0
IV	3000–4400	4	8, 15, 21, 34	0.56	0.63	576	608	17.7	21.2	19.3	22.8
III	2000–2400	3	8, 15, 34	0.57	0.92	529	795	17.7	21.0	20.2	23.7
II	1000–1200	2	8, 34	0.58	0.91	482	778	17.6	21.3	21.3	24.1
I	500–600	1	8	0.66	0.94	389	514	17.2	21.2	23.8	28.7

Due to the relatively small geographic area of the country, the climatic conditions across the nation and at the study sites can be considered similar. The long-term average air temperature is approximately +7.5 °C, and the long-term mean annual precipitation is 695 mm. The territory of Lithuania is predominantly lowland, with the exception of hilly plains in the east and west, which do not exceed 300 m above sea level. The elevation of the study sites ranges from 80 to 129 m above sea level. During the study period, the measured groundwater depth did not exceed 250 cm.

2.2. Assessment of Tree Health and Damage

Tree health and damage were evaluated using the International ICP-Forests methodology [38]. The assessment focused on the tree trunks and recorded the location of damage (LD), damage symptoms (SD), causal factors (FD), and damage intensity (ID, expressed as a percentage) (Table S1).

To link the initial forest health and damage assessment conducted in 2020 with the most recent field survey conducted in 2024, the sites were selected. The presence and damage status of the affected trees were confirmed and adjusted visually by analyzing the orthorectified images and 3D laser point clouds. For that, the study sites were first surveyed using a DJI Matrice 350 RTK platform equipped with a DJI Zenmuse L2 sensor, yielding an average point density of 260 points m^{-2}. Point cloud processing and ground point classification were performed in DJI Terra software (version 4.5.0, SZ DJI Technology Co., Ltd., Shenzhen, China). A canopy height model (CHM) was subsequently derived using LAStools (version 241210, Rapidlasso GmbH, Gilching, Germany), and segmented with the watershed algorithm to delineate individual tree crowns. Tree centers and heights were extracted from the segmented CHM and manually aligned with existing tree maps to ensure spatial correspondence.

Complementary multispectral data were acquired with a MicaSense RedEdge-P sensor (AgEagle Aerial Systems Inc., Wichita, Kansas, United States), producing imagery with a ground sampling distance of 6.9 cm. Following radiometric calibration, the imagery was used to generate an orthophoto mosaic comprising the Blue, Green, Red, RedEdge, and near-infrared (NIR) bands. The detection and condition status of affected trees were validated and, where necessary, corrected through visual interpretation of the orthorectified imagery in conjunction with the classified 3D point clouds.

2.3. Assessment of Tree Density

Tree density in the study plots was assessed by mapping the spatial locations of all trees using the TerraHärp system integrated with Masser ExCaliper II calipers [39]. This pseudolite-based positioning system relies on a network of base stations with known positions in the local coordinate system. Tree positions were determined by measuring the distance between the caliper and base stations. Sixteen base stations were installed within the study plots. The local coordinates were subsequently transformed into the Lithuanian National Coordinate System (LKS94) using conventional GNSS receivers positioned in open areas. Preliminary unpublished results indicate that the positional accuracy of tree locations was within a root mean square error of 0.4 m.

For each tree, the number of neighboring trees within a 5.64 m buffer (equivalent to an area of 100 m^2) was calculated. To minimize edge effects, trees located within 5.64 m of the plot boundary were excluded from the subsequent analyses. The plot boundary was delineated as the minimum bounding geometry enclosing the mapped tree positions for each thinning treatment. GIS processing was performed using ArcGIS Pro (version 3.5.3. Esri Inc., Redlands, CA, USA).

2.4. Statistical Analysis

For statistical analyses, the Cochran–Armitage trend test was applied to evaluate associations between test plot density and the proportion of damaged trees [40]. These analyses were conducted using the PROC FREQ procedure in the SAS software. To assess the strength and direction of the associations between stand density and damage symptom categories, Somers' d test (non-parametric) was employed, enabling the evaluation of relationships between ordinal dependent and ordinal independent variables. Two-sided *p*-values were computed to test whether the mean values exhibited monotonic increases or decreases across the row variable levels [41]. The Cochran–Mantel–Haenszel (QCMH) test was applied to determine the relationship between the damage types and initial stand density. All statistical computations were performed using SAS software (version 9.4; build 1.0.22621; SAS Institute Inc., Cary, NC, USA).

Graphical representations were produced to complement statistical tests. The relationship between SD and initial plot density was visualized using a heat map, whereas the associations of FD, LD, and ID with initial plot density were depicted in bar charts generated using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA). Overlapping variants of damage types were presented using combined visualizations: bar charts indicating absolute frequencies and pie charts indicating relative percentages.

The effect of stand density on tree mortality was assessed separately for Scots pine and Norway spruce trees. Descriptive statistics (n, mean, SD) for each species × variant × condition (healthy/dead) group were calculated using PROC MEANS. The differences between healthy and dead individuals for each variant were checked using a two-sample *t*-test (PROC TEST) and one-way ANOVA (PROC GLM, Quantity × condition in each density variant). The PROC SGPANEL procedure was used for the visualizations.

3. Results

3.1. Dependence of Tree Damages on Stand Density

In this study, the proportion of damaged trees differed by approximately 9% between the Norway spruce and Scots pine test plots. Damage was observed in 20.2% of the trees in the Norway spruce plots and 11.2% in the Scots pine plots (Figure 2).

For both species, a general decrease in the proportion of damaged trees was observed with decreasing stand density, except for test variant III for Norway spruce, where damage levels declined compared with the adjacent density classes. The mosaic plot (Figure 2) illustrates an increasing trend in damage with higher stand density for both Norway spruce and Scots pine. In Norway spruce stands, the lowest level of damage was recorded in test variant III, in which 12.92% of the trees were affected. The proportion of damaged spruce trees increased from 14.3% in test variant I to 25.91% in test variant V. In the Scots pine stands, the increase was less pronounced, ranging from 1.6% in test variant I to 19.84% in test variant V.

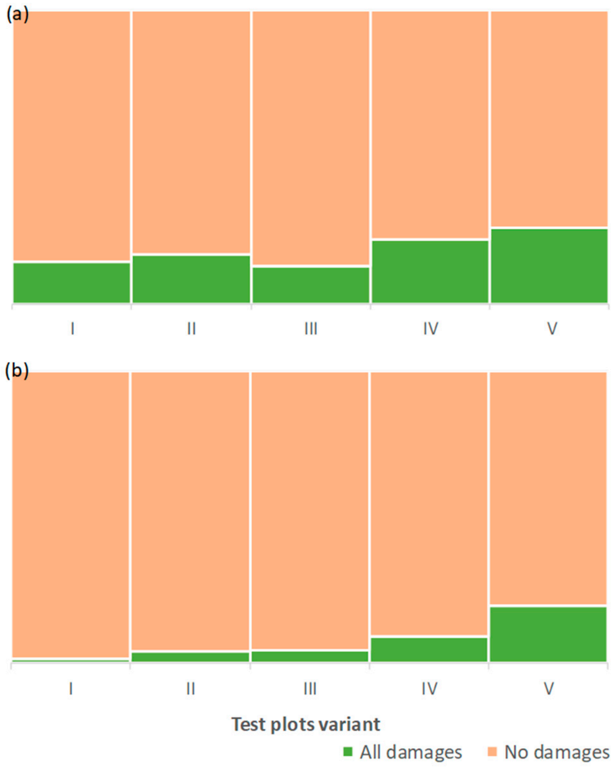

Figure 2. Mosaic plot graph of distribution of stem damages within Norway spruce (**a**) and Scots pine (**b**) test plots based on tree density (trees ha^{-1}).

Somers' d values indicated a stronger association for Scots pine (d = 0.41) than Norway spruce (d = 0.17). The asymptotic Somers' test confirmed a positive association between stand density and damage in both species. The results of the Cochran–Mantel–Haenszel test further supported this relationship, with χ^2 values of 79.87 (Norway spruce) and 187.10 (Scots pine), suggesting that the association was approximately twice as strong in Scots pine (Tables S2 and S3).

The highest proportion of damaged trees was recorded in the control plots (without thinning). For example, 25.91% of all trees in Norway spruce stands and 19.84% of trees in Scots pine stands exhibited visible damage (Figure 2, Tables S2 and S3).

3.2. Distribution of Tree Damages Symptoms (SD) According to Initial Stand Density

Analysis of damage symptoms showed that broken stems or branches were the most frequent symptom in Scots pine stands, affecting 1.8% of all observed trees. The most common damage symptoms in Norway spruce stands were decay or rot (7.13%). Other types of damage (parasitic, bacterial, and competitive) were also relatively frequent, affecting approximately 6% of the trees in both species, followed by wounds and resin flow (3.06% of trees) and signs of fungi (1.7%) (Table 2).

In Norway spruce stands, the lowest number of damaged trees was recorded in test variant III, whereas in Scots pine stands, the lowest values were observed in the lowest-density variant I (Figure 2). In spruce, decay and rot were most frequent in test variant IV (12% of all trees), whereas "other" symptoms were most common in control variant V (12.98%). Fungal symptoms were absent in the lowest-density variant I. In Scots pine stands, the SD across all variants was generally low (0%–1%), with the exception of decay or rot in variant II (2.1%), fungal symptoms in variants III and IV (2.5%–5.6%), broken stems (3%), and "other" symptoms (15%) in variant V.

The association between SD and initial plot density, assessed using the Cochran–Mantel–Haenszel (QCMH) test, was approximately five times stronger for Scots pine (QCMH = 73.55) than for Norway spruce (QCMH = 14.90) (Tables S4 and S5).

Table 2. Heat table depicting the percentage of all tree damages symptoms for all test plot variants by forest type (Norway spruce and Scots pine) and initial density (no symptoms—dark green, most symptoms—red).

Damage Symptom	**Test Plots Variant**					
Norway spruce						
	V	**IV**	**III**	**II**	**I**	**Total**
Tilted and fallen	0.11	0.82	0.38	1.41	0.97	0.57
Deformations	0.7	0.33	0.5	0.9	1.36	0.73
Signs of insects	1.3	2.47	0.88	0.13	0.19	1.06
Broken	1.14	1.15	1.51	2.57	1.36	1.47
Signs of fungi	2.16	2.96	0.38	2.06	0	1.69
Wounds and resin flow	4.38	2.8	2.52	2.44	0.39	3.06
Other signs (Parastitic, Bacteria, Competition)	12.98	0.99	0.13	0.51	3.5	5.97
Decay/rot	4.33	12.17	7.92	7.97	8.74	7.13
Without symptoms	72.9	76.32	85.79	82.01	83.5	78.37
Scots pine						
	V	**IV**	**III**	**II**	**I**	**Total**
Signs of insects	0	0.17	0	0.19	0	0.06
Deformations	0.22	0.17	0	0.38	0.52	0.24
Wounds and resin flow	0.15	1.22	0.21	0.19	0	0.33
Decay/rot	0.66	0.17	2.07	0.19	0	0.63
Tilted and fallen	1.17	1.04	0.83	0.19	0	0.81
Sign of fungi	0	5.56	0.21	2.46	0	1.38
Broken	3.01	1.04	1.04	0.76	1.03	1.8
Other signs (Parastitic, Bacteria, Competition)	14.88	0.35	0.21	0.19	0.26	6.23
Without symptoms	79.91	90.28	95.44	95.46	98.2	88.53

3.3. Distribution Factors (FD), Intensity (ID), and Location of Damages (LD) in Relation to Stand Density

FD distribution varied according to species and stand density. Game and grazing damage were unevenly distributed across Norway spruce density classes but was absent in Scots pine (Figure 3). Insect damage was recorded only in Scots pine variants III and IV (4% and 2% of total FD, respectively), whereas in Norway spruce, it ranged from 2% to 11% in all variants. Fungal FD accounted for 4–13% of the total FD in spruce variants and up to 60% in Scots pine variants III and IV. The highest proportion of abiotic FD was found in the lowest-density variants I and II, reaching 25–26% of the total FD in spruce and 43–46% in pine stands. Damage attributable to human activity was negligible (~9%). In the control/densest variant (V), the majority of damages were attributed to "other" FD (parasitic, bacterial, competitive, etc.), comprising 57% of Norway spruce and 85% of Scots pine stands. A considerable proportion of damages with no identified FD was recorded in Norway spruce variants I–IV, ranging from 44 to 55%.

The association between FD and initial stand density, assessed using the modified Cochran–Mantel–Haenszel test, was approximately six times stronger for Scots pine (QCMH = 59.14) than for Norway spruce (QCMH = 8.74) (Tables S6 and S7).

The ID also differed between species. In Norway spruce, 42% of all damaged trees were dead, with 71.4% of these occurring in variant V. Mortality was higher in Scots pine, with 74.9% of damaged trees dead and 76.0% of them in variant V (Tables S6 and S7). The proportion of trees with whole-trunk damage in spruce ranged from 1.2% to 28.3%, with the lowest proportion in variant III (12% of the damaged trees). In Scots pine, the lowest proportions of fully damaged trees were observed in variants I and II (41–43%) (Figure 3). The association between ID and initial stand density was slightly stronger in Norway spruce (QCMH = 29.72) than in Scots pine (QCMH = 22.91).

Norway spruce

Scots pine

Figure 3. Percentage distribution of factors (FD), intensity (ID), and location (LD) of damages in Norway spruce and Scots pine stands at different initial densities (tree ha^{-1}). Assessments of primary stand density (Table 1).

Within the Norway spruce test variants, the most common LD was along the trunk, particularly between the collar and crown, accounting for 50.3% of all damaged trees (Tables S6 and S7). The most prevalent LD in Scots pine variants was the trunk of dead trees, representing 72.8% of all affected individuals in this study. The lowest proportions of dead trees were observed in variant III for Norway spruce and in variants I and II for Scots pine. The association between LD and initial stand density, assessed using the Cochran–Mantel–Haenszel test, was more than twice as strong in Norway spruce (QCMH = 67.27) than in Scots pine (QCMH = 24.71).

3.4. High-Precision Tree Mapping for Assessing the Effect of Stand Density on Tree Mortality

All thinning experiments resulted in relatively similar stand densities on the present date (Figure 4). The only exception was the control variant, which retained maximum initial densities and showed no thinning, leading to substantially higher tree numbers in the plots. An assessment of tree density across all variants showed no statistically significant differences between the growth densities of the living and dead trees. Thus, the results do not support the conclusion that a higher stand density directly determines tree mortality.

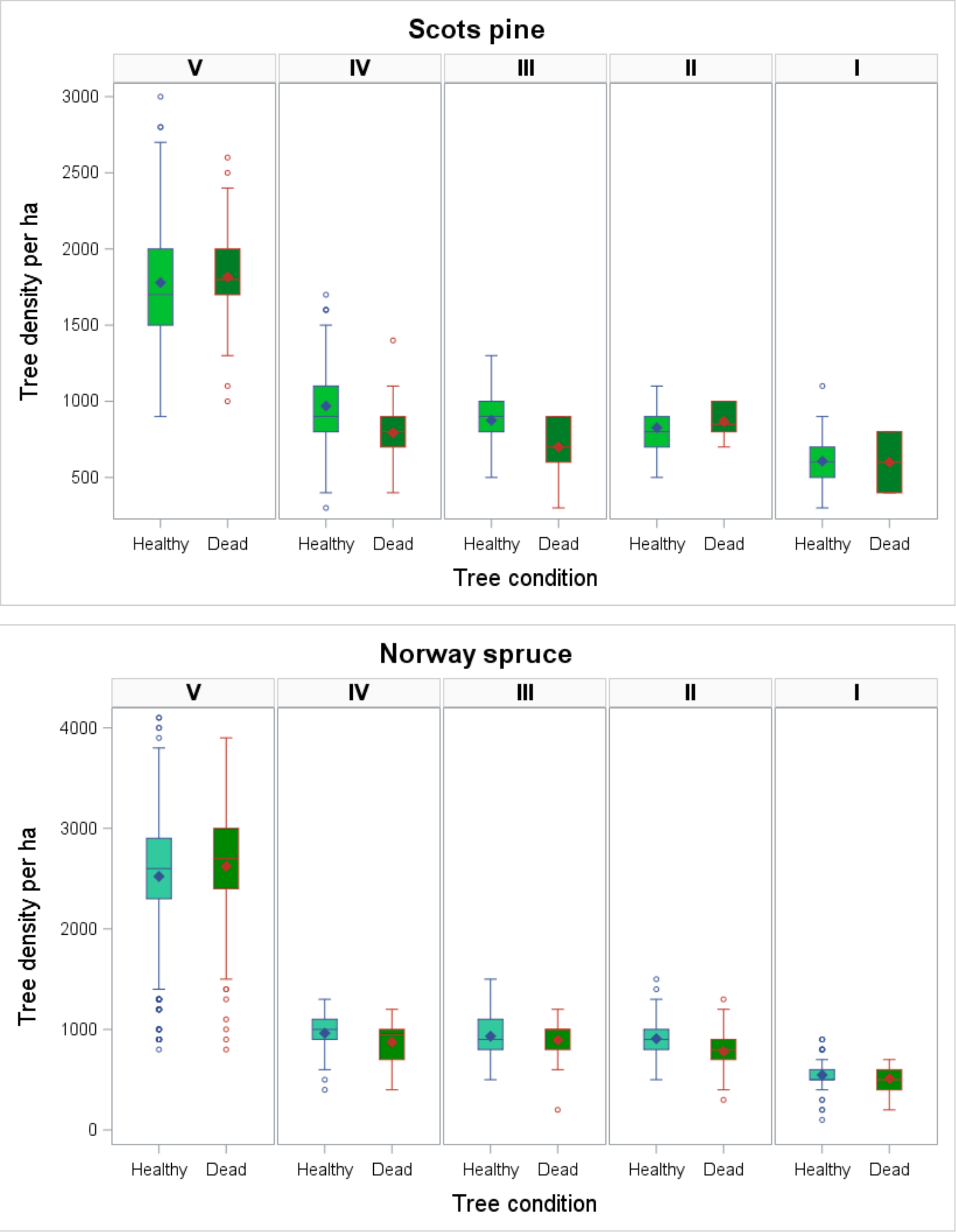

Figure 4. One-way ANOVA results in a boxplot form on in every density variant.

In pine stands, the number of neighboring living trees was generally higher than that of dead trees, except for the densest variants V and II, where the differences were not statistically significant. In contrast, significant differences between living and dead trees in terms of the number of surrounding trees were observed for variants III and IV. This pattern suggests that in these density variants, tree mortality is driven more by the spread of diseases than by stand density (Table 3).

Table 3. Univariate statistics (n—number of trees; Mean—number of neighboring trees within a 5.64 m buffer; SD—standard deviation of the mean; Diff—difference between the means of neighboring trees of living and dead trees; and *p*-value) describing the relationship between tree condition and the number of neighboring trees.

Variant	Healthy Trees			Dead Trees			Diff	*p* (*t*-test)	*p* (ANOVA)
	n	Mean	SD	n	Mean	SD			
Scots pine									
I	186	6.1	1.2	2	6.0	2.8	0.1	0.9778	0.9376
II	200	8.3	1.3	6	8.7	1.2	−0.4	0.4640	0.4748
III	199	8.8	1.7	15	7.0	1.9	1.8	0.0031	0.0001
IV	169	9.7	2.6	31	7.9	2.1	1.8	0.0001	0.0004
V	410	17.8	3.7	57	18.2	3.2	−0.4	0.4285	0.4736
Norway spruce									
I	123	5.5	1.4	27	5.1	1.2	0.3	0.1839	0.2317
II	240	9.1	1.7	54	7.8	2.1	1.3	<0.0001	<0.0001
III	300	9.3	1.8	19	8.9	2.3	0.4	0.5042	0.3979
IV	162	9.6	1.6	22	8.7	2.1	0.9	0.0653	0.0186
V	632	25.2	6.2	129	26.2	5.6	−1.0	0.0687	0.0860

In spruce stands, living trees in variant II had significantly more neighbors than dead trees, whereas no significant differences were observed in the remaining variants. Overall, living trees tended to be surrounded by more neighbors than dead trees. This finding supports the assumption that disease outbreaks occur within stands, leading to a reduced number of neighbors around dead individuals.

4. Discussion

The demand for softwood remains high; however, the cultivation of stable stands is increasingly challenged by extreme weather events, such as storms and droughts [3,42]. Mixed-species stands of varying ages are generally considered more resilient [43], whereas in pure, even-aged stands, appropriate thinning regimes may enhance their profitability and adaptability to changing conditions [4].

The results of this study highlight the complexity of thinning outcomes, particularly in relation to species- and site-specific responses. We examined the stability and disease susceptibility of pure pine and spruce stands, with particular attention paid to the initial stand density and thinning history. Our results indicated that stands established at initial densities between 1000 and 4400 trees ha^{-1} and aged 32–43 years exhibited very similar tree densities, mean diameters, and heights, irrespective of stand formation or thinning intensity. Differences in the mean tree diameter were observed only in the lowest- and highest-density variants (±4 cm relative to the overall average). The growth dynamics of these stands have been described in previous studies [44,45], and these findings suggest that forest management strategies could be adjusted to enhance both economic efficiency and forest sustainability. These findings suggest that thinning intensity within the tested range had limited long-term effects on stem dimensions, although it appears to influence tree health.

Trunk damage was observed in 11.2% of pine trees and 21.5% of spruce trees across all the study sites. These values are broadly consistent with national forest statistics, which report that 21.8% of Scots pine and 22.2% of Norway spruce were damaged in Lithuania in 2023 [46]. While the observed spruce damage rates align with national trends, the pine stands in the present study appeared to be in comparatively better condition. The inclusion of additional sites from other regions may have yielded more representative results.

Damage distribution patterns further indicated that in Norway spruce, the most frequently affected portion of the stem was located between the stump and crown, which is typically considered the most valuable timber. Minor damage (0–10% intensity) predominated, accounting for 27% of the spruce damage and 9% of the pine damage. In contrast, the most severe category (100% intensity, corresponding to dead trees) was concentrated in the densest stand variants, accounting for 42% and 74% of spruce and pine mortality, respectively.

Three characteristic groups of stand structure and associated damage could be distinguished: (i) dense, unthinned stands (4038–5400 trees ha^{-1}); (ii) heavily thinned stands (500–600 trees ha^{-1} after one thinning); and (iii) moderately thinned stands (1000–4400 trees ha^{-1}, with varying intensities of thinning).

4.1. The Densest Stand Variants

Unthinned stands exhibited elevated stem damage and mortality, which was largely attributable to natural competition. Shade-induced mortality was more pronounced in pines than in spruces. Although mortality is expected in high-density stands, the occurrence of dead trees in thinned variants may indicate suboptimal thinning practices or pathogen activity. Dense stands also showed greater susceptibility to wind damage, including broken stems and trunk wounds. Such injuries, particularly in Scots pine (3.01% of observed trees in variant V), not only reduce mechanical stability but also create infection pathways for fungal pathogens [47,48].

4.2. The Rarest Stand Variants

Early heavy thinning accelerated diameter growth and crown expansion, producing thicker stems that may confer greater resilience to climatic stress. Previous research has demonstrated that intensive thinning can increase root volume, thereby enhancing drought resistance [49,50]. However, despite these potential benefits, mortality due to unknown causes and wind-induced breakage are still observed.

4.3. Thinning Stands with Different Intensities

In stands thinned at intermediate densities (3000–4400 trees ha^{-1}), damages frequencies were the highest: 9% in pine and 22% in spruce (Figure 3). Previous studies have shown that frequent thinning maximizes economic returns, whereas less frequent but more intensive thinning can reduce both wood quality and profitability [51]. Other studies have indicated that reduced stand density increases windthrow risk [9,10], which is consistent with our observation of greater wind damage in less frequently thinned stands.

Stem rot fungi, particularly *Heterobasidion annosum* (Fr.) Bref., were the most prevalent in repeatedly thinned variants. In a four-times-thinned spruce stand (initial density 3000–4400 trees ha^{-1}), infection rates reached 12.17% in spruce and 5.56% in pine stands. Fruiting bodies confirmed the presence of *H. annosum*, and although thinning wounds themselves accounted for only 0.8% (spruce) and 0.5% (pine) of the observed damage, they likely contributed to pathogen spread via the stumps of felled trees. Previous studies have indicated that *H. annosum* clones can persist and expand for 7–8 years after infection [5–7,19]. Moreover, decay may remain undetected in apparently healthy trees [5], suggesting that the prevalence of infection in the present study area is likely underestimated. This could also account for the relatively high proportion of mortality cases with undetermined causes. In other words, the high number of dead trees, even in regularly maintained, cleaned, and thinned stands, cannot be explained by inter-tree competition. Nevertheless, without more detailed laboratory analyses, the precise cause of mortality in these trees cannot be determined.

4.4. Current Stand Density and Mortality

In many thinning trials, density reduction is expected to lower mortality [52]; however, the results of our study indicate that stand density alone does not consistently explain patterns of tree mortality in either pine or spruce stands. While some density variants showed significant differences between living and dead trees, in many cases, no such relationship was observed. This suggests that factors other than competition, particularly pathogen spread, play a substantial role in driving mortality. The observation that dead trees tended to have fewer neighbors than living individuals further supports the interpretation that mortality events are not primarily density-dependent but rather reflect localized disease outbreaks that reduce the number of surrounding trees. Species-specific responses were also evident: in pine, the density effects on mortality were more pronounced in variants III and IV, whereas in spruce, significant differences occurred only in variant II. These differences may be linked to contrasting ecological strategies and susceptibilities to stressors, with pine being less shade-tolerant but more resistant to certain pathogens than spruce. From a management perspective, the findings imply that thinning alone may not be sufficient to mitigate mortality risk, and that attention should also be directed toward disease monitoring and sanitation measures. Long-term studies are required to assess whether density-related mortality emerges more clearly as stands mature and competition intensifies, or whether disease-driven mortality remains the dominant factor. The present study was limited to pure pine and spruce stands, many of which were established on former agricultural land. Therefore, stand dynamics and health responses may differ from those in naturally regenerated or mixed-species forests.

4.5. Directions for Future Studies

Future studies could benefit from integrating physiological models that capture tree-level responses to changing resource availability and environmental stress. Such models would improve also our current understanding of how thinning and mortality interact to shape stand density over time. The Stand Density Index (SDI) could also serve as a valuable tool for evaluating the relationship between tree density and growth potential, helping to identify optimal densities for sustainable management [53]. Combining SDI with physiological modeling could provide forest managers with more precise guidance in selecting thinning regimes that balance growth increase with mortality risk, thereby improving forest productivity and resilience. In addition, emerging technologies—such as pseudolite-based positioning systems and laser scanning for geolocating trees, alongside drone imaging for assessing tree health—hold strong potential for advancing understanding of tree- and stand-level dynamics under natural and management-driven processes.

5. Conclusions

This study demonstrated that a high initial stand density combined with frequent thinning increases the risk of stem rot and wounding in Scots pine and Norway spruce, despite maintaining similar stem dimensions across thinning regimes. While such management can sustain high productivity in the short term, the long-term impacts of fungal infection and wind damage may offset these potential gains.

We recommend establishing Scots pine and Norway spruce at lower initial stand densities and applying thinning less frequently to reduce susceptibility to fungal diseases and associated yield losses. Management strategies that balance stand density and thinning intensity are essential for maintaining productivity and resilience under changing climatic conditions.

In the future, broader studies across diverse site conditions and mixed-species stands are required to test whether these findings hold beyond pure stands on former agricultural land. Long-term monitoring of fungal spread in relation to thinning regimes would help refine management guidelines.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f16101606/s1. Table S1: The tree damages assessment protocol used to evaluate Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) stands, based on Eichhorn et al. [38]. Table S2: Summary statistics for categories by the density of damage symptoms in Norway spruce stands. Table S3: Summary statistics for categories by the density of damage symptoms in Scots pine stands. Table S4: Cochran-Mantel-Haenszel Statistics of symptoms damages association of density of Norway spruce test plots. Table S5: Cochran-Mantel-Haenszel Statistics of symptoms damages association of density of Scots pine test plots. Table S6: Factors (FD), intensity (ID), and location (LD) statistics of all damaged trees in Norway spruce plots with different primary densities (trees ha^{-1}). Table S7: Factors (FD), intensity (ID), and location (LD) statistics of all damaged Scots pine plots with different primary densities (trees ha^{-1}).

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