

Article

Tree Damage by Ice Accumulation in Norway Spruce (*Picea abies* (L.) Karst.) Stands Regarding Stand Characteristics

Silva Šēnhofa, Juris Katrevičs, Andis Adamovičs, Kārlis Bičkovskis, Endijs Bāders , Jānis Donis and Āris Jansons *

Latvian State Forest Research Institute Silava, Rigas Street 111, LV-2169 Salaspils, Latvia; silva.senhofa@silava.lv (S.Š.); juris.katrevis@silava.lv (J.K.); andis.adamovics@silava.lv (A.A.); karlis.bickovskis@silava.lv (K.B.); endijs.baders@silava.lv (E.B.); janis.donis@silava.lv (J.D.)

* Correspondence: aris.jansons@silava.lv

Received: 29 May 2020; Accepted: 11 June 2020; Published: 13 June 2020



Abstract: Freezing rain is a frequently occurring, but relatively rarely studied disturbance in Europe, although ice accumulation may occasionally cause severe damage for forestry. We aimed to characterize ice-accumulation damage to overstory trees in spruce stands, assess the probability of damage based on the stand and individual tree parameters, and define the most significant parameters that affect the probability of individual tree damage in all stands and in recently thinned stands. Among the studied stands, the proportion of damaged overstory spruce ranged from 1.8% to 60.9% and was higher ($p < 0.001$) in recently thinned stands ($27.8\% \pm 1.9\%$) than in the other stands ($20.4\% \pm 1.6\%$). Stem breakage was the prevalent ($98.5\% \pm 1.1\%$) damage type. At the stand level, the probability of damage decreased for older, less dense stands with a larger mean diameter. Within stands, overstory trees were more damaged ($23.5\% \pm 1.2\%$; $p < 0.001$) than those in the lower stand layers, but, within overstory, trees with larger dimensions and a higher social position (high relative diameter and low slenderness ratio) and a higher proportion of crown were less damaged. The probability of breakage to overstory trees was most accurately predicted using almost the same variables for all stands and recently thinned stands. The site type, tree height, relative diameter, and crown ratio were common for both, with the addition of mean diameter at breast height for all stands and the stand density for recently thinned stands. Our results indicate the importance of the tree and stand characteristics on the resistance of individual tree to ice accumulation and the need for management practices that balance increased growth and the stability of trees throughout the rotation.

Keywords: freezing rain; thinning effect; stem breakage; natural disturbance

1. Introduction

Natural disturbances strongly affect forest structure and the dynamics of forest stands with an effect on different types of provided ecosystem services [1], including economic activities [2] and carbon sequestration [3]. Among the disturbance types, wind, insects and fire are studied in the most detail across Europe [4,5] and in the hemiboreal forests [6–11], but damage from ice accumulation is relatively rarely studied.

Ice accumulation is most often caused by freezing rain (also called supercooled rain)—a liquid precipitation with a droplet temperature of below $0\text{ }^{\circ}\text{C}$ that may freeze on impact with solid objects [12]. Recently, several climatological studies of freezing rain have been done in Europe [13–15], including an estimation of its spatial and temporal occurrence [16]. Freezing rain is a common phenomenon in the region. Currently, central and eastern Europe typically undergo one to two events per year, and the

northern countries average 0.5 to 1.5 events per year [16] with the duration of a single event as long as three or more consecutive days [15,16]. On a global scale, the incidence of ice disturbances may decrease [17] but has been forecasted to undergo a poleward shift [18]. Accordingly, the projected occurrence of freezing rain under the future emission scenarios of RCP4.5 and RCP8.5 suggests a shift toward an increased possibility of low and moderate events (accumulation of 0 to 5 mm over 6 h) in northern and northeastern Europe [19]. Yet changes in the frequency of the more extreme events with high precipitation amounts (exceeding an accumulation of >5 mm per hour) and a long duration are challenging to forecast [19].

While high-intensity ice accumulation (commonly referred as an ice storm) is relatively rare, it has substantial effects on infrastructure and forestry. For instance, in January 2019, in Romania, freezing rain resulted in an ice layer of 2–4 cm on the tree branches, causing extensive damage in the capital city [15]. In 2014, in Slovenia, persistent freezing rain for four days resulted in ice accumulation of up to 6 to 9 cm [20], whereas nearly all of the measured 165 mm precipitation was freezing rain in the most affected region, creating an even thicker ice layer [21]. During this event, about 0.5 million hectares of forest were affected, with total costs including damage to infrastructure estimated at over 400 million euros [22].

Generally, forestry studies of such severe disturbances are hampered by the fact that they are occasional occurrences, that the damaged sites are often isolated, and that a limited time scale for study exists due to management pressure/priority to conduct salvage logging. Most studies concerning ice damage have been conducted in North America, where severe ice storms are more frequent (see [23,24]). However, a recent large-scale ice storm provided an opportunity to study this disturbance in European temperate forests. Several studies have been done, focusing on an assessment of the general forest damage [25], unmanaged stands [26], effects of the storm intensity and the species-specific susceptibility [27], and resulting hazards in damaged forests [28]. However, studies of the freezing rain and ice-accumulation damage in northern Europe and hemiboreal forests are scarce (for exception, see [29]).

The damage severity to forests depends on two sets of factors, the first related to meteorological processes, and the second to individual tree and stand parameters and the site physical conditions. The tree species is among the most important factors affecting the type and level of damage. Norway spruce and Scots pine, economically the most important tree species in northern Europe, are both more susceptible to ice damage compared to broadleaf species [27]. In addition, spruce is prone to several disturbances that can cumulate in increased susceptibility, such as prior damage from wind and root rot. These decrease stem and root endurance [30] and increase the risk of uprooting and breakage. Furthermore, stands damaged by ice become more prone to other types of disturbance mainly associated with the bark beetle *Ips typographus* (L.) [28].

Storms are impossible to prevent; however, stand resistance and resilience can be increased if critical conditions are understood and measures are taken to address them in forest management. Therefore, knowledge of the relation between the individual tree and stand parameters to the probability of damage is necessary to modify management if needed. Factors like age and site type cannot be directly modified but are important factors for deciding about the rotation length and site suitability for tree species. Other factors may be managed through low initial stand density [31] and thinning [32]. However, during the first following years, the susceptibility of thinned stands is increased [33,34].

2. Materials and Methods

We aimed to characterize ice-accumulation damage in Norway spruce stands, assess the probability of damage concerning the stand and individual tree parameters, and define the most significant parameters that affect the probability of individual tree damage in all stands and recently thinned stands. For this, we studied Norway spruce (*Picea abies* (L.) Karst.) stands in the eastern part of Latvia (Rēzekne, Balinava, Balvi and Kārsava municipalities) after freezing rain in December 2012 in unfrozen soil conditions. In Latvia, the season for freezing rain is from September to April, with the

peak in December [16]. The studied sites are located in the region of Latvia with the highest frequency of freezing rain events. During the period from 1940/1941 to 2009/2010, the mean number of days per year with ice (>5 mm) on surfaces in December was one in the western regions (Liepāja) and five in the eastern regions (Alūksne) [according to the data from the Latvian Environment, Geology and Meteorology Center]. Under the future emission scenarios of RCP4.5 and RCP8.5, a slight increase may occur [19].

We randomly selected 61 spruce stands where, according to stand inventory data, the proportion of spruce was at least 70% of the stand total growing stock and the area was ≥ 0.8 ha. No meteorological data are available for these stands at the occurrence of the incidence, but no significant wind was reported during the storm. The intensity of the disturbance is characterized by the amount of ice that increased the pressure on the trees. As an indicator of intensity, icing during the same event increased the tree mass by 1.5 times in nearby pine stands, compared to trees without ice [29].

According to stand inventory data gathered before the icing event, the age of selected stands (*Ast*) was 20 to 113 years. All measurements were done in winter 2012/2013. In each stand, we established 6 to 8 circular sample plots (200 m^2 ; $R = 7.96\text{ m}$), evenly distributed within the stand and offset at least 10 m from the stand edges. Site type (*ST*) was noted from the prior inventory data and was grouped according to the classification by Bušs [35] into mesic mineral soils, wet mineral soils and drained peat soils. In each plot, for spruce trees with a diameter at breast height (*DBH*) of ≥ 2.1 cm we noted the stand layer (overstory, understory and advance regeneration), incidence of damage and damage type (broken or other ice-caused damage, e.g., bent or uprooted). A tree was classified as ‘broken’ if the broken top was at least 15% of the tree height. For the overstory spruce, we determined *DBH*, tree height (*H*) and height of the crown, with height of the broken trees calculated using a regression equation based on the height/*DBH* relationships of the undamaged overstory spruce trees in the same stands. In total, 7581 spruce trees were measured on the plots, with 4672 situated in the overstory, 1965 in the understory and 944 in advance growth.

We then used these data to calculate the stand parameters: stand density (number of overstory trees per hectare (*Nst*)) and the mean *DBH* (*DBHst*) and height (*Hst*) of the overstory spruce. For each tree, the relative diameter (ratio between the individual tree and stand mean diameter (*Drel*)), crown ratio (ratio between the green crown length (cm) and tree height (m) (*CR*)) and stem slenderness ratio (ratio of the tree height (m) and *DBH* (cm) (*HD*)) were calculated. Based on the stand inventory data, stands were divided into (1) recently thinned—thinning done during the three years before the ice storm and (2) other stands—no thinning or thinning done more than three years before the icing event.

The age of the recently thinned stands was 20 to 75 years (median 53 years) and that of the other stands was 31 to 113 years (median 73 years). Stand parameters showed considerable variation with much overlap between the recently thinned and other stands (Table 1) in their common age range (31 to 75 years). No information on thinning intensity (number of trees, basal area or yield removed) was available to assess the direct effect of recent thinning. Therefore, we first assessed the probability of damaged and broken trees concerning the stand and individual tree parameters of all stands (age 20 to 113 years), and then developed assessment models for all stands and for the recently thinned stands.

Table 1. Stand parameters of the recently thinned and other stands at a common age range (31 to 75 years).

Stand Parameter	Recently Thinned	Other Stands
Number of trees per ha	385–1613	335–2375
Basal area, $\text{m}^2\text{ ha}^{-1}$	15–33	19–41

To assess the probability of breakage of individual spruce tree (binary data), each of the measured tree parameter was divided into levels, and in each level, the proportion of broken spruces was calculated. The generalized linear model based on the binomial distribution was applied to assess the relationship between the stand layer and site type as well as the tree *DBH*, height, relative diameter,

crown ratio and slenderness ratio on the proportions of damaged and broken trees. The one-way analysis of variance was used to assess the differences in the proportion of damaged and broken trees among the levels for each factor. The effect of stand density, mean DBH, and mean height on the proportion of broken trees were assessed using the generalized linear model based on the binomial distribution. The relation between these parameters was assessed using Spearman's rank correlation.

We used a cluster dendrogram to group mutually related factors with a height larger than 0.5. The layout of the dendrogram of all stands (Figure 1) was similar to that of the recently thinned stands. In both, the factors were divided into the same five groups. The probability of breakage was assessed using equations compiled with all possible combinations of one to five factors (one from each cluster). In total, 125 equations for each data set (all stands and the recently thinned stands) were evaluated. The selection of the best performing models was based on the comparison of the Akaike information criterion (AIC), the Bayesian information criterion (BIC) and the residual deviance between the models and the null model. All tests were performed at $\alpha = 0.05$, and the mean values and their confidence intervals are shown. All calculations were done in R 3.5.1 [36].

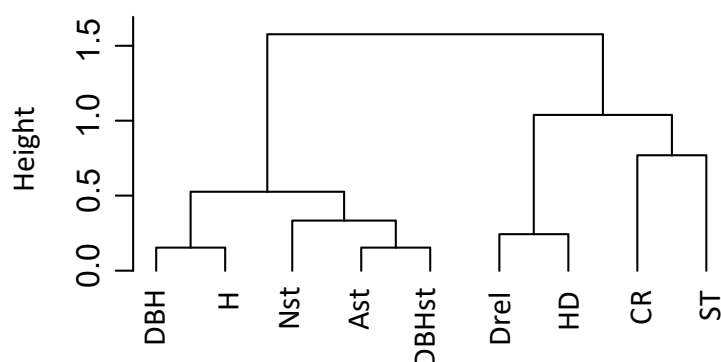


Figure 1. Cluster dendrogram of the stand and individual tree parameters in all stands (pooled recently thinned and other stands). *DBH*—tree diameter at breast height; *H*—tree height; *Nst*—stand density; *Ast*—stand age; *DBHst*—stand mean DBH; *Drel*—tree relative diameter; *HD*—slenderness ratio; *CR*—crown ratio and *ST*—site type.

3. Results

Among the studied stands, the proportion of damaged overstory spruce ranged from 1.8% to 60.9% (mean $22.9 \pm 3.4\%$). Overstory spruce was damaged significantly more (both $p < 0.001$) than that in the understory and advance regeneration (Table 2). Most the damaged overstory spruce was broken, ranging from 72.7% to 100% (mean $98.5\% \pm 1.1\%$) among the stands. Within 13 out of 61 stands, all damaged spruces were broken. A similar proportion ($p > 0.05$) of broken spruce was found in the overstory and understory, and in both stand layers this proportion was significantly larger (both $p < 0.01$) than that for the advance regeneration layer (Table 2). The proportion of damaged overstory spruce trees was similar ($p > 0.05$) on mesic mineral soil and drained peat soil, and for both, the proportion was slightly, but significantly (both $p < 0.05$) higher than among stands on wet mineral soil. Yet, among all damaged spruces, the proportion with broken tops was similar (all $p > 0.05$) among site types (Table 2). In the recently thinned stands, the proportion of overstory spruce with some type of damage was significantly ($p < 0.001$) higher than that in the other stands, yet the proportion of damaged spruce trees with broken top was similar ($p > 0.05$).

We further analyzed the probability of breakage among individual overstory spruce in all stands (pooled recently thinned and other stands). Stand parameters (except the stand height, $p > 0.05$) had a significant effect on the probability of breakage. The proportion of the broken spruce was significantly lower in older stands ($\rho = -0.56$, $p < 0.01$) and in stands with a larger DBH for the overstory spruce ($\rho = -0.50$, $p < 0.001$). The degree of breakage increased with higher stand density ($\rho = 0.48$, $p < 0.001$; Figure 2).

Table 2. Proportion of damaged spruce and proportion of damaged spruce with broken top (mean $\pm$ 95% confidence interval) according to stand layer, site type and applied management in all stands (pooled recently thinned and other stands).

Stand Characteristics		Proportion of Damaged Spruce, %	Proportion of Damaged Spruce with Broken Top, %
Stand layer	overstory	23.5 $\pm$ 1.2	98.5 $\pm$ 0.7
	understory	14.7 $\pm$ 1.7	96.9 $\pm$ 2.2
	advance regeneration	3.2 $\pm$ 1.2	89.3 $\pm$ 12.2
Site type	mesic mineral soil	24.4 $\pm$ 1.7	98.6 $\pm$ 0.9
	wet mineral soil	20.3 $\pm$ 3.1	98.5 $\pm$ 2.1
	drained peat soil	24.5 $\pm$ 2.3	98.5 $\pm$ 1.3
Management	recently thinned	27.8 $\pm$ 1.9	98.5 $\pm$ 1.0
	other stands	20.4 $\pm$ 1.6	98.6 $\pm$ 1.0

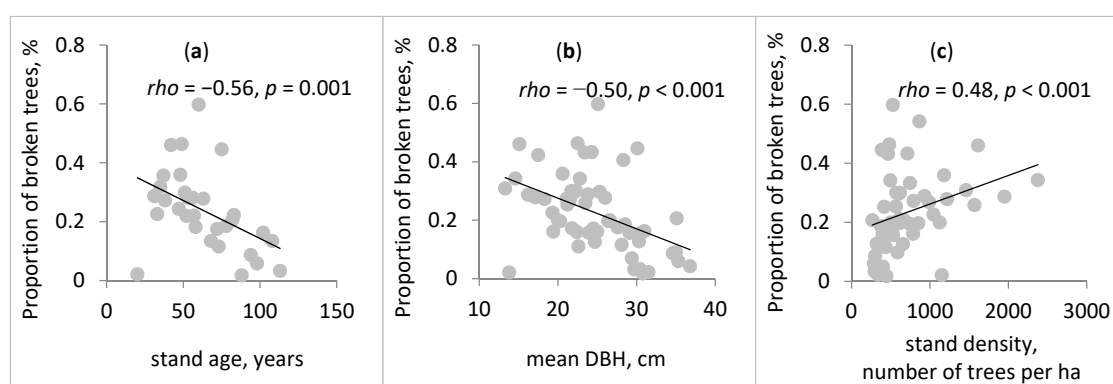


Figure 2. Proportion of broken overstory spruce trees related to (a) stand age; (b) mean diameter at breast height (DBH); and (c) stand density in all stands (pooled recently thinned and other stands).

In addition, the crown ratio, DBH, height, relative diameter and slenderness ratio—all had a significant effect (all $p < 0.001$) on the probability of breakage among overstory spruce trees. Spruce with a crown length of less than 30% had the highest proportion of broken trees (35.4% $\pm$ 7.5%) and were significantly more damaged than trees with a crown length greater than 40% (differences among groups $0.01 < p < 0.001$, Figure 3a). In addition, significantly fewer spruce trees with a crown length greater than 80% of the tree height were broken (11.8% $\pm$ 3.4%, all differences $0.01 < p < 0.001$) than those with lower crown proportions.

A higher proportion of spruce trees with a DBH of 10 to 15 cm and a height of 15 to 17 m were broken (31.5% $\pm$ 3.4% and 32.4% $\pm$ 4.3%, respectively), and damage gradually decreased for trees of larger dimensions (Figure 3b,c). A sharp decrease in the proportion of broken trees was observed for spruce larger than 25 cm. The low proportion of broken trees with a DBH of ≤ 10 cm and a height of ≤ 13 m was largely (59% and 78% of the trees in the corresponding level of diameter and height, respectively) formed by two stands (20- and 31-year-old stands with a mean crown length of 85.8% and 70.8%) having only 7.8% and 18.8%, respectively, of broken trees.

The proportion of broken individual trees was also assessed in relation to the social status within a stand (i.e., in relation to the relative diameter and slenderness ratio). Spruce trees smaller than the stand-wide mean DBH (relative diameter of 0.71 to 1.00) showed the highest proportion of broken tops, ranging from 28.7% $\pm$ 3.1% to 31.9% $\pm$ 3.4% (Figure 3d). That was significantly higher ($0.01 < p < 0.001$) than among the spruce trees with a larger relative diameter. Similarly, the highest proportion of broken trees was 36.3% $\pm$ 3.0% for slenderness ratio 1.01–1.10% and 35.7% $\pm$ 3.9% for slenderness ratio 1.11–1.20 (Figure 3e). That was significantly higher (all $p < 0.001$) than among the trees with lower slenderness ratio. The lower proportions of broken tops among trees with a relative diameter of ≤ 0.7

and slenderness ratio ≥ 1.3 was due to their significantly shorter (for both all $p < 0.001$) heights (0.81 and 0.89 ratios to the stand mean height, respectively) than for all other levels of relative diameter and slenderness ratio.

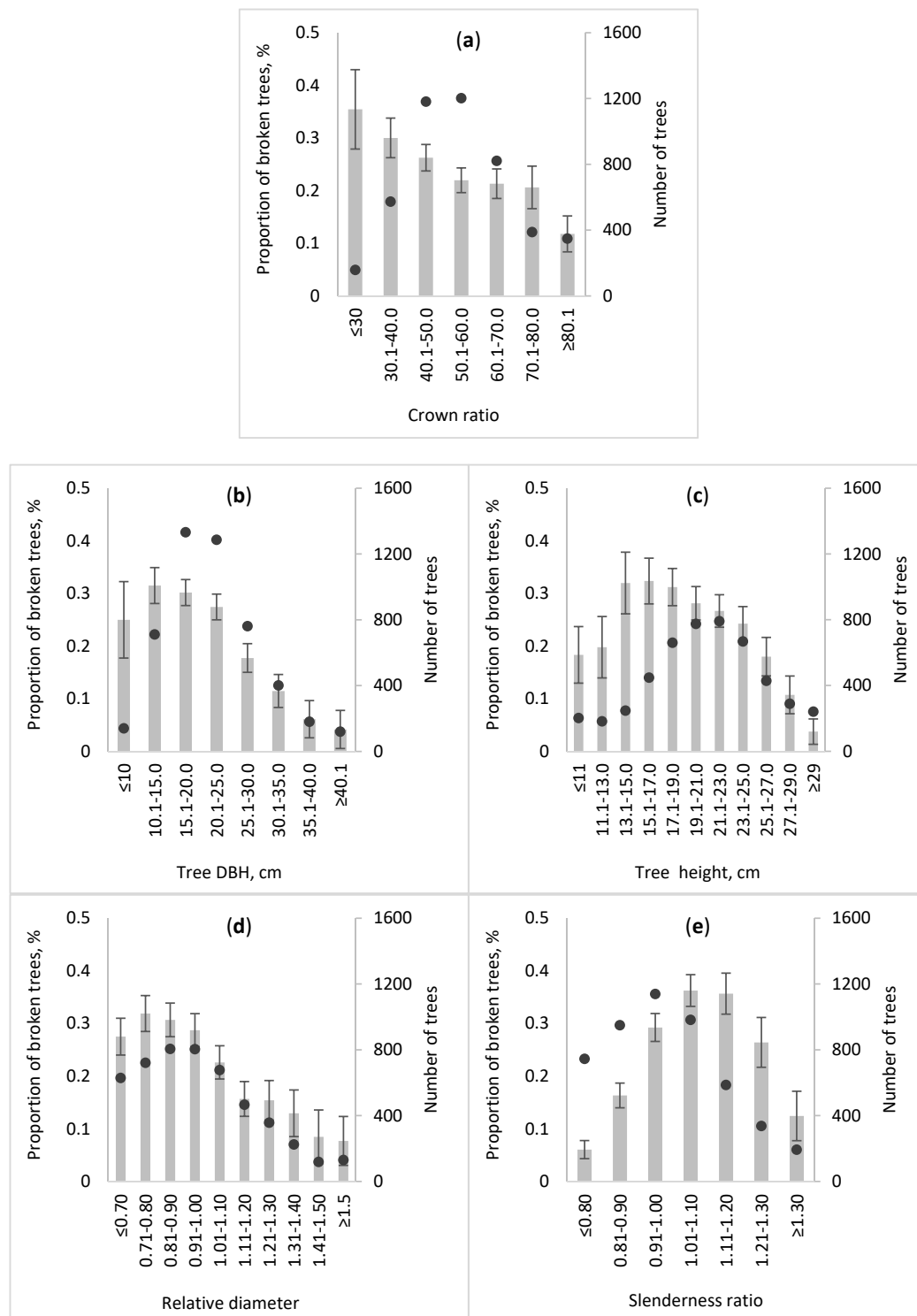


Figure 3. Proportion of broken overstory spruce trees (bars show the mean $\pm$ 95% confidence interval) according to individual tree characteristics: (a) crown ratio, (b) diameter at breast height (DBH), (c) height, (d) relative diameter and (e) slenderness ratio in all stands (pooled recently thinned and other stands). The number of trees (sample size) is denoted as black points.

Regression analyses integrated these separate factors to show how they interacted to determine the susceptibility of individual spruce trees to damage from ice loading. In all stands combined, the probability of individual tree breakage was most accurately predicted using the site type, mean DBH (stand parameters), tree height, relative diameter and crown ratio (individual tree parameters). All factors were significant ($0.036 < p < 0.001$; Table 3). The second-most accurate model did not include tree height and showed all the other significant factors included in the best performing model. The third best model included only DBH and the crown ratio of the individual tree.

Among the recently thinned stands, the best performing model for predicting the probability of individual spruce tree breakage included the site type and stand density (stand parameters) and the tree height, relative diameter and crown ratio (individual tree parameters). All factors were significant ($0.015 < p < 0.001$; Table 4). Hence, four out of five factors for thinned stands are the same as those in the best performing model for all stands. The second-most accurate model for the recently thinned stands included all the same factors except site type. The third best model included four out of five factors compared to the best performing model, but with tree DBH instead of the tree height.

Table 3. Three the most accurate models of the probability of breakage of individual overstory spruce in all stands, listed in an order of accuracy, and the null model.

Model	c			AIC	BIC	Residual Deviance
	Mesic Mineral Soil	Wet Mineral Soil	Drained Peat Soil			
$0.037 \times H^* - 0.090 \times DBHst^{***} - 1.579 \times Drel^{***} + 0.013 \times CR^{***} + c^{**}$	1.067	0.661	0.994	4901.6	4946.8	4888
$-0.063 \times DBHst^{***} - 1.233 \times Drel^{***} + 0.015 \times CR^{***} + c^{**}$	0.801	0.388	0.726	4904	4942.7	4892
$-0.058 \times DBH^{***} + 0.016 \times CR^{***} - 0.685^{***}$	—	—	—	4908.3	4927.6	4902.3
—	—	—	—	5133.9	5140.4	5131.9

Significance level is denoted with asterisks: *— $p < 0.05$; **— $p < 0.01$; ***— $p < 0.001$. Coefficients are denoted as logit values. *H*—tree height; *DBHst*—stand mean diameter; *Drel*—relative diameter; *CR*—crown ratio; *c*—stand type; *DBH*—tree diameter at breast height; AIC—Akaike information criterion; BIC—Bayesian information criterion.

Table 4. Three the most accurate models of the probability of breakage of individual overstory spruce in recently thinned stands, listed in an order of accuracy, and the null model.

Model	c			AIC	BIC	Residual Deviance
	Mesic Mineral Soil	Wet Mineral Soil	Drained Peat Soil			
$0.069 \times H^{***} + 0.001 \times Nst^{***} - 2.086 \times Drel^{***} + 0.012 \times CR^{***} - c^*$	1.619	2.276	1.781	2472.1	2512	2458.1
$0.069 \times H^{***} + 0.001 \times Nst^{***} - 2.058 \times Drel^{***} + 0.014 \times CR^{***} - 1.533^{***}$	—	—	—	2476.5	2504.9	2466.5
$0.051 \times DBH^* + 0.001 \times Nst^{***} - 2.475 \times Drel^{***} + 0.015 \times CR^{***} - c^*$	1.008	1.687	1.187	2478.1	2517.9	2464.1
—	—	—	—	2575.7	2581.4	2573.7

Level of significance denoted with asterisks: *— $p < 0.05$; **— $p < 0.01$; ***— $p < 0.001$. Coefficients denoted as logit values. *H*—tree height; *Nst*—stand density; *Drel*—relative diameter; *CR*—crown ratio; *c*—stand type; *DBH*—tree diameter at breast height; AIC—Akaike information criterion; BIC—Bayesian information criterion.

4. Discussion

Freezing rain and the consequent damage due to ice accumulation is rarely studied in European boreal and hemiboreal forests, yet it may occur as a high-impact hazardous event both for infrastructure [37] and forestry [27]. We observed a large variation in damage levels among the studied stands, ranging from 2% to 61% of trees damaged by ice accumulation. Accordingly, several studies have reported on the heterogeneity of the damage severity among and within stands (e.g., [26,38,39]), which is determined by complex interactions between the intensity of disturbance and the stand and tree parameters.

The ice-accumulation thickness is the major explanatory variable of the damage severity [27,40], with the importance of tree and stand parameters decreasing with the increasing storm intensity [27]. Perhaps for that reason, studies have found diverse responses or ones of different magnitudes between the tree or stand characteristics and damage, although several general trends appear. Other external aggravating factors, such as wind and snow during or after the freezing rain can increase the total damage in forests [41–43]. However, strong wind or accumulating snow were not reported during the freezing rain event at our study stands. Thus, we assume that these did not contribute to the damage that we assessed. However, both ice and snow accumulation form a static load on the tree crowns with a similar mechanical effect; thus, we also refer to studies of damage caused by snow, where appropriate. Most studies also include the effects of wind to some extent.

Among physical site conditions, elevation and slope are the primary characteristics affecting damage severity [27], likely due to influence of these features on wind direction and intensity and crown asymmetry of trees growing on slopes. However, the flat topography of the studied sites suggests a negligible effect of these factors. Furthermore, the soil texture and depth affect the tree susceptibility [41]. We found slight, but significant differences in proportion of damaged spruce trees among soil types, with a higher proportion on mesic mineral and drained peat soils compared to the wet mineral soils. Contrarily, stands on undrained mineral soils were more damaged by snow than stands on organic soils [44], yet no direct relation was suggested to explain these differences. However, unexpectedly (see [41]), no effect on damage type was found regardless of the differences in the soil (root anchorage strength on different soils) among site types.

Damage to individual trees is largely determined by the biomechanics of ice loading and tree parameters [23], with the damage type (uprooting, breakage or bending) related to the wood structural strength and tree stem and root properties [45]. Nearly all damaged trees in our study were broken (mean 99%), as commonly happens with snow loading in middle-aged and mature stands [46]. In the absence of strong wind, ice and snow primarily accumulates on the top of a tree where the vertical force of gravity [41] causes breakage if the bending strength is lower than the root anchorage strength [45].

The tallest, dominant trees were damaged more frequently than trees in overtopped canopy positions, probably because most of the icing is captured by the highest part of the canopy and exterior branches [47]. Ice has a strong attachment to the surface, and is not shed onto trees of a lower canopy position. More damage to overstory trees than to overtopped trees was observed in broadleaf and mixed forests in the leafless state [38,48,49], but could be even more pronounced for evergreen tree species because foliated trees have a greater surface area to hold more ice [41]. Yet, *Abies alba* was more resistant to ice damage than other coniferous (including Norway spruce) and broadleaf species, regardless of the leafless season [27].

Contrary to our findings, a higher probability of damage for understory trees was observed among mixed central European forests [27] and is related to secondary damage caused by falling trees and branches. These differences between studies may also be related to species composition, with the overstory of pure spruce stands catching greater ice load than the overstory of mixed broadleaf coniferous stands. That reduces the amount of ice reaching the understory. Yet, both lower primary damage (the sheltering effect) and the increased secondary damage (from falling debris) may both occur [50], resulting in a similar proportion of damaged trees between stand layers [51].

With our study, the proportion of damaged spruce was significantly lower in the older stands (Figure 2a). Similarly, among other studies with stand ages ranging from 20 to 80 years, the incidence of snow damage was highest for stands at the age of 30 years [44], and those damaged by snow and wind were significantly younger than the undamaged stands [52]. Likewise, a higher snow load was required to cause breakage in older spruce stands [53], likely due to the larger dimension trees. Yet, older trees may also be more susceptible to damage due to the higher occurrence of wood structural defects, as spruce is susceptible to stem cracks [54], bark-stripping [55] and root and butt rot [56].

Generally, resistance to stem breakage is a function of the cube of the stem DBH [41] and a larger stem diameter results in a greater structural rigidity (a higher modulus of rupture) and a higher resistance to ice accumulation before failure [23,32,52,57]. Hence, even, while trees from the upper stand layer in our study were damaged more than ones in lower canopy layers, about 30% of those overstory trees with a DBH from 10 to 15 cm were broken, compared to 3% of trees with a DBH greater than 40 cm. In other studies, after a moderate intensity ice-storm, the probability of damage ranged from about 0.13 to 0.03 for trees with a DBH of 10 to 100 cm, respectively. With ice accumulation >20 mm, the cumulative damage ranged from about 0.75 for trees with a DBH of 10 cm to about 0.35 for trees with a DBH of 100 cm [27]. In unmanaged stands with large trees, about 25% of spruces with a DBH of 15 cm was damaged, while larger trees were damaged about three times less frequently [26]. For snow damage, trees with a DBH of 10 to 60 cm had similar amounts of damage [44], though for snow and wind damage models predicted a slight, nonsignificant increase in probability of breakage with an increasing mean plot DBH [58].

With individual trees in our study, resistance to breakage increased with tree height (Figure 3c), partly due to the intercorrelation with the DBH. Other analyses revealed that both the mean and dominant stand height had a statistically insignificant effect on the proportion of damaged trees [59], but for trees with similar stem taper the resistance increased with tree height [41]. Likewise, for a given diameter or height, trees with a lower slenderness ratio are more stable [41,52,58,60–62]. Overall, tree slenderness is among the main single-tree parameters affecting resistance to loading [41,46,50,60]. Likewise, our analyses revealed increased damage to slenderer and relatively thin trees, with a significantly higher proportion of damaged trees for each succeeding slenderness ratio group up to 1.10 (Figure 3e). This is consistent with findings for several coniferous species, where the slenderness ratio of 0.8 was the threshold for damage occurrence [63].

Another factor that largely determines tree stability is the crown characteristics [46]. Trees with a larger crown are more vigorous due to better growth efficiency [64]. Smaller tree crowns are typically associated with crown asymmetry that increases the risk of damage due to unbalanced ice loading [40,65]. Similarly, we found less frequent damage among trees with a larger crown (Figure 3a), likely because the larger crown depth ensures more evenly distributed weight and lowers the center of gravity of the loading and increases the resistance to breakage [66]. However, a larger crown may have a heavier ice load due to the larger surface area of the canopy area.

Our results showed almost the same factors for the best explanatory models for all stands compared with the recently thinned stands. The site type, tree height, relative diameter, and crown ratio were common for both, with the additional parameters of the stand mean DBH for all stands and the stand density for recently thinned stands (Tables 3 and 4). Stem development and crown morphology are strongly affected by stand density [31,32,67]. Moreover, while our results revealed an increased proportion of broken spruce with a higher stand density (Figure 2c), other findings about how the stand density affects the damage severity are conflicting [23] and should be viewed in context with the tree slenderness ratio (as a measure of individual tree stability) and the initial stand density and effects of past thinning.

Within high-density stands, individual trees with a high slenderness ratio may be less susceptible than a similar tree in more open stands [52,68]. For a level of slenderness, the probability of wind and snow damage decreases with the increasing stand basal area, probably due to mutual support and collective stability, as has also been observed in stands with a basal area greater than about

20 m² ha^{−1} [59]. In very closely spaced stands, more damage may occur when a tree falls into neighboring trees due to intertwined crowns [69]. Moreover, in dense stands, the crowns of the trees tend to be shorter and more asymmetrical than in sparse stands [46] and trees are slenderer [53]. These characteristics may account for the damage in spruce sites where 95% of the snow damage occurred in stands with the first thinning delayed [44].

Overall, thinning reduces competition among trees, increases diameter growth, reduces slenderness [70] and increases the stability of individual trees. Moreover, while stands with a lower basal area are less damaged [39,58], during the first few years, they have increased sensitivity [46,61,71]. Our stands that were thinned during the three years before the ice loading were significantly more damaged than other stands, likely due to lost support from the neighboring trees [71] and the higher wind speed through the more open canopy [46]. Past studies have shown different results regarding the time needed to regain stand stability, but it seems strongly related to the proportion of basal area removed [34]. Heavily thinned spruce stands affected by several storms (the first was three years after thinning) had 10 times greater proportion of damaged basal area (7% and 74%, respectively) than the unthinned stands [34]. In contrast, as soon as two years after thinning, in 22-year-old spruce stands, the damage from snow loading was lower in thinned plots than unthinned plots [72]. Both the stands thinned 6 to 25 years prior to the damage and unmanaged stands have also shown a similar severity of damage [39].

Generally, thinning should strive to increase the stability of the trees to ice loading, similar to recommendations to increase resistance against other more frequently occurring abiotic damage by wind and snow [4]. Different strategies include: a silvicultural regime with no thinning [34], planting at wide spacing and thinning during early stand development [63], removing of high-risk trees [73] and thinning to promote crop trees [71]. However, the implications for financial return should be carefully assessed, while also considering the probability of icing events during a rotation. For instance, using a wide initial spacing and no subsequent thinning may reduce the total revenue before the final felling [34]. Nonetheless, initially sparse spruce stands at the age of 80 years may result in similar production to those with a commonly used higher initial density [31].

5. Conclusions

This study aimed to identify stand- and tree-level parameters affecting the probability of damage from ice accumulation in Norway spruce stands. We found considerable variation in damage severity among the studied stands, with overstory trees being most affected in comparison to those in understory or the advance regeneration. Nearly all damaged overstory trees had broken tops. Stands thinned less than three years before icing event were more susceptible than other stands. At the stand level, the probability of damage was less for older, less dense stands with a greater mean diameter, although the variation of these parameters suggests the need to evaluate other explanatory factors that may provide more accurate estimations. At the individual tree level, all measured parameters had a significant effect on damage occurrence. Among them, tree height, relative diameter and crown ratio were the best explanatory variables for both all stands and recently thinned stands. Overall, management practices that increase stability of individual trees should be promoted to reduce the risk of losses during occasional severe ice loading in Norway spruce stands. Financial implications should be considered when evaluating strategies that may reduce the chance of damage.

Author Contributions: Conceptualization, Å.J. and J.K.; methodology, S.Š., J.K. and J.D.; formal analysis, S.Š.; data curation, A.A., K.B. and E.B.; writing—original draft preparation, S.Š., Å.J. and J.K.; writing—review and editing, J.D.; project administration, Å.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by LVM project number 5.5._002t_101.15.57.

Acknowledgments: Assessment was carried out in LVM project “Forest management risks: prognosis and minimization” (No. 5.5._002t_101.15.57).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Thom, D.; Seidl, R. Natural disturbance impacts on ecosystem services and biodiversity in temperate and boreal forests. *Biol. Rev.* **2016**, *91*, 760–781. [\[CrossRef\]](#)
2. Montagné-Huck, C.; Brunette, M. Economic analysis of natural forest disturbances: A century of research. *J. For. Econ.* **2018**, *32*, 42–71. [\[CrossRef\]](#)
3. Rebane, S.; Jõgiste, K.; Põldveer, E.; Stanturf, J.A.; Metslaid, M. Direct measurements of carbon exchange at forest disturbance sites: A review of results with the eddy covariance method. *Scand. J. For. Res.* **2019**, *34*, 585–597. [\[CrossRef\]](#)
4. Schelhaas, M.J.; Nabuurs, G.J.; Schuck, A. Natural disturbances in the European forests in the 19th and 20th centuries. *Glob. Chang. Biol.* **2003**, *9*, 1620–1633. [\[CrossRef\]](#)
5. Seidl, R.; Schelhaas, M.; Rammer, W.; Verkerk, P.J. Increasing forest disturbances in Europe and their impact on carbon storage. *Nat. Clim. Chang.* **2014**, *4*, 806–810. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Jõgiste, K.; Korjus, H.; Stanturf, J.A.; Frelich, L.E.; Baders, E.; Donis, J.; Jansons, A.; Kangur, A.; Köster, K.; Laarmann, D.; et al. Hemiboreal forest: Natural disturbances and the importance of ecosystem legacies to management. *Ecosphere* **2017**, *8*, e01706. [\[CrossRef\]](#)
7. Baders, E.; Jansons, A.; Matisons, R.; Elferts, D.; Desaine, I. Landscape diversity for reduced risk of insect damage: A case study of Spruce bud Scale in Latvia. *Forests* **2018**, *9*, 545. [\[CrossRef\]](#)
8. Donis, J.; Kitenberga, M.; Šņepsts, G.; Dubrovskis, E.; Jansons, A. Factors affecting windstorm damage at the stand level in hemiboreal forests in Latvia: Case study of 2005 winter storm. *Silva Fenn.* **2018**, *52*, 10009. [\[CrossRef\]](#)
9. Samariks, V.; Krisans, O.; Donis, J.; Silamikele, I.; Katrevics, J.; Jansons, A. Cost–benefit analysis of measures to reduce windstorm impact in pure Norway spruce (*Picea abies* L. Karst.) stands in Latvia. *Forests* **2020**, *11*, 576. [\[CrossRef\]](#)
10. Donis, J.; Saleniece, R.; Krisans, O.; Dubrovskis, E.; Kitenberga, M.; Jansons, A. A financial assessment of windstorm risks for Scots pine stands in hemiboreal forests. *Forests* **2020**, *11*, 566. [\[CrossRef\]](#)
11. Kitenberga, M.; Elferts, D.; Adamovics, A.; Katrevics, J.; Donis, J.; Baders, E.; Jansons, A. Effect of salvage logging and forest type on the post-fire regeneration of Scots pine in hemiboreal forests. *New For.* **2020**, 1–17. [\[CrossRef\]](#)
12. World Meteorological Organisation. International Cloud Atlas. Section 3.2.1.2.2. Available online: <https://cloudatlas.wmo.int/en/supercooled-rain.html> (accessed on 12 June 2020.).
13. Carrière, J.M.; Lainard, C.; Le Bot, C.; Robart, F. A climatological study of surface freezing precipitation in Europe. *Meteorol. Appl.* **2000**, *7*, 229–238. [\[CrossRef\]](#)
14. Bezrukova, N.A.; Jeck, R.K.; Khalili, M.F.; Minina, L.S.; Naumov, A.Y.; Stulov, E.A. Some statistics of freezing precipitation and rime for the territory of the former USSR from ground-based weather observations. *Atmos. Res.* **2006**, *82*, 203–221. [\[CrossRef\]](#)
15. Andrei, S.; Antonescu, B.; Boldeanu, M.; Mărmureanu, L.; Marin, C.A.; Vasilescu, J.; Ene, D. An exceptional case of freezing rain in Bucharest (Romania). *Atmosphere* **2019**, *10*, 673. [\[CrossRef\]](#)
16. Kämäräinen, M.; Hyvärinen, O.; Jylhä, K.; Vajda, A.; Neiglick, S.; Nuottokari, J.; Gregow, H. A method to estimate freezing rain climatology from ERA-Interim reanalysis over Europe. *Nat. Hazards Earth Syst. Sci.* **2017**, *17*, 243. [\[CrossRef\]](#)
17. Seidl, R.; Thom, D.; Kautz, M.; Martin-Benito, D.; Peltoniemi, M.; Vacchiano, G.; Wild, J.; Ascoli, D.; Petr, M.; Honkaniemi, J.; et al. Forest disturbances under climate change. *Nat. Clim. Chang.* **2017**, *7*, 395–402. [\[CrossRef\]](#)
18. Klima, K.; Morgan, M.G. Ice storm frequencies in a warmer climate. *Clim. Chang.* **2015**, *133*, 209–222. [\[CrossRef\]](#)
19. Kämäräinen, M.; Hyvärinen, O.; Vajda, A.; Nikulin, G.; Meijgaard, E.V.; Teichmann, C.; Jacob, D.; Gregow, H.; Jylhä, K. Estimates of present-day and future climatologies of freezing rain in Europe based on CORDEX regional climate models. *J. Geophys. Res. Atmos.* **2018**, *123*. [\[CrossRef\]](#)
20. Sinjur, I.; Vertačnik, G.; Likar, L.; Hladnik, V.; Miklavčič, I.; Gustinčič, M. Žledolom januarja in februarja 2014 v Sloveniji—Prostorska in časovna spremenljivost vremena na območju dinarskih pokrajin. *Gozdarski Vestn.* **2014**, *72*, 299–309.
21. Markosek, J. Severe freezing rain in Slovenia. *Eur. Forecast.* **2015**, *20*, 38–42.
22. Vajda, A. Impacts of severe winter weather events on critical infrastructure. In Proceedings of the RAIN WP2 Workshop on Past Severe Weather Hazards, Berlin, Germany, 27 February 2015.

23. Bragg, D.C.; Shelton, M.G.; Zeide, B. Impacts and management implications of ice storms on forests in the southern United States. *For. Ecol. Manag.* **2003**, *186*, 99–123. [\[CrossRef\]](#)
24. Kraemer, M.J.; Nyland, R.D. *Hardwood Crown Injuries and Rebuilding Following Ice Storms: A Literature Review*; Department of Agriculture, Forest Service, Northern Research Station: Newtown Square, PA, USA, 2010.
25. Šimić Milas, A.; Rupasinghe, P.; Balenović, I.; Groseovski, P. Assessment of forest damage in Croatia using landsat-8 OLI images. *South East Eur. For.* **2015**, *6*, 159–169. [\[CrossRef\]](#)
26. Nagel, T.A.; Firm, D.; Rozenbergar, D.; Kobal, M. Patterns and drivers of ice storm damage in temperate forests of Central Europe. *Eur. J. For. Res.* **2016**, *135*, 519–530. [\[CrossRef\]](#)
27. Klopčič, M.; Poljanec, A.; Dolinar, M.; Kastelec, D.; Bončina, A. Ice-storm damage to trees in mixed Central European forests: Damage patterns, predictors and susceptibility of tree species. *Forestry* **2020**, *93*, 430–443. [\[CrossRef\]](#)
28. De Groot, M.; Ogris, N.; Kobler, A. The effects of a large-scale ice storm event on the drivers of bark beetle outbreaks and associated management practices. *For. Ecol. Manag.* **2018**, *408*, 195–201. [\[CrossRef\]](#)
29. Bāders, E.; Adamovičs, A.; Puriņš, M.; Džeriņa, B. Tree damages by icing in Scots pine (*Pinus sylvestris* L.) stands and factors affecting them. *Res. Rural. Dev.* **2016**, *2*, 6–13.
30. Krisans, O.; Matisons, R.; Rust, S.; Burnevica, N.; Bruna, L.; Elferts, D.; Kalvane, L.; Jansons, A. Presence of root rot reduces stability of Norway spruce (*Picea abies*): Results of static pulling tests in Latvia. *Forests* **2020**, *11*, 416. [\[CrossRef\]](#)
31. Katrevis, J.; Kapostins, R.; Bickovskis, K.; Jansons, A. Influence of initial density on inventory parameters of unthinned Norway spruce stands. In Proceedings of the International Scientific Conference ‘Rural Development’, Vytautas Magnus University, Kaunas, Lithuania, 26–28 September 2019; pp. 273–277.
32. Brüchert, F.; Becker, G.; Speck, T. The mechanics of Norway spruce [*Picea abies* (L.) Karst]: Mechanical properties of standing trees from different thinning regimes. *For. Ecol. Manag.* **2000**, *135*, 45–62. [\[CrossRef\]](#)
33. Valinger, E.; Fridman, J. Factors affecting the probability of windthrow at stand level as a result of Gudrun winter storm in southern Sweden. *For. Ecol. Manag.* **2011**, *262*, 398–403. [\[CrossRef\]](#)
34. Wallentin, C.; Nilsson, U. Storm and snow damage in a Norway spruce thinning experiment in southern Sweden. *Forestry* **2014**, *87*, 229–238. [\[CrossRef\]](#)
35. Bušs, K. *Latvijas PSR Meža Tipoloģijas Pamati*; LRZTIPI: Rīga, Latvia, 1976.
36. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2018.
37. Groenemeijer, P.; Becker, N.; Djidara, M.; Gavin, K.; Hellenberg, T.; Holzer, A.M.; Juga, I.; Jokinen, P.; Jylhä, K.; Lehtonen, I.; et al. Past cases of extreme weather impact on critical infrastructure in Europe. In *RAIN—Risk Analysis of Infrastructure Networks in Response to Extreme Weather*; ESSL: Wessling, Germany, 2015.
38. Jones, J.J.; Pither, J.P.; Debruyne, R.D.; Robertson, R.J. Modeling ice storm damage to a mature, mixed-species hardwood forest in eastern Ontario. *Écoscience* **2001**, *8*, 513–521. [\[CrossRef\]](#)
39. Nielsen, C.; Van Dyke, O.; Pedlar, J. Effects of past management on ice storm damage in hardwood stands in eastern Ontario. *For. Chron.* **2003**, *79*, 70–74. [\[CrossRef\]](#)
40. Proulx, O.J.; Greene, D.F. The relationship between ice thickness and northern hardwood tree damage during ice storms. *Can. J. For. Res.* **2001**, *31*, 1758–1767. [\[CrossRef\]](#)
41. Peltola, H.; Kellomäki, S.; Väisänen, H.; Ikonen, V.P. A mechanistic model for assessing the risk of wind and snow damage to single trees and stands of Scots pine, Norway spruce, and birch. *Can. J. For. Res.* **1999**, *29*, 647–661. [\[CrossRef\]](#)
42. Makkonen, L. Models for the growth of rime, glaze, icicles and wet snow on structures. *Phil. Trans. R. Soc.* **2000**, *358*, 2913–2939. [\[CrossRef\]](#)
43. Houston, T.G.; Changnon, S.A. Freezing rain events: A major weather hazard in the conterminous US. *Nat. Hazards* **2007**, *40*, 485–494. [\[CrossRef\]](#)
44. Jalkanen, A.; Mattila, U. Logistic regression models for wind and snow damage in northern Finland based on the national forest inventory data. *For. Ecol. Manag.* **2000**, *135*, 315–330. [\[CrossRef\]](#)
45. Peltola, H.; Kellomäki, S.; Hassinen, A.; Granander, M. Mechanical stability of Scots pine, Norway spruce and birch: An analysis of tree-pulling experiments in Finland. *For. Ecol. Manag.* **2000**, *135*, 143–153. [\[CrossRef\]](#)
46. Nykänen, M.L.; Peltola, H.; Quine, C.; Kellomäki, S.; Broadgate, M. Factors affecting snow damage of trees with particular reference to European conditions. *Silva Fenn.* **1997**, *31*, 193–213. [\[CrossRef\]](#)

47. Nock, C.A.; Lecigne, B.; Taugourdeau, O.; Greene, D.F.; Dauzat, J.; Delagrangé, S.; Messier, C. Linking ice accretion and crown structure: Towards a model of the effect of freezing rain on tree canopies. *Ann. Bot.* **2016**, *117*, 1163–1173. [\[CrossRef\]](#)
48. Rebertus, A.J.; Shifley, S.R.; Richards, R.H.; Roovers, L.M. Ice storm damage to an old-growth oak-hickory forest in Missouri. *Am. Midl. Nat.* **1997**, *137*, 48–61. [\[CrossRef\]](#)
49. Rhoades, R.W. Ice storm damage in a small valley in southwestern Virginia. *Castanea* **1999**, *64*, 243–251.
50. Priebe, J.E.; Powers, M.D.; Cole, E.C. Species, tree size, and overstory environment affect likelihood of ice storm damage to understory trees in a mature Douglas-fir forest. *For. Ecol. Manag.* **2018**, *409*, 777–788. [\[CrossRef\]](#)
51. Zarnovican, R. Glaze damage in a young yellow birch stand in southern Quebec, Canada. *North. J. Appl. For.* **2001**, *18*, 14–18. [\[CrossRef\]](#)
52. Valinger, E.; Fridman, J. Modelling probability of snow and wind damage in Scots pine stands using tree characteristics. *For. Ecol. Manag.* **1997**, *97*, 215–222. [\[CrossRef\]](#)
53. Päätaalo, M.L. Risk of snow damage in unmanaged and managed stands of Scots pine, Norway spruce and birch. *Scand. J. For. Res.* **2000**, *15*, 530–541. [\[CrossRef\]](#)
54. Zeltniš, P.; Katrevičs, J.; Gailis, A.; Maaten, T.; Jansons, J.; Jansons, Ā. Stem cracks of Norway spruce (*Picea abies* (L.) Karst.) provenances in Western Latvia. *For. Stud.* **2016**, *65*, 57–63. [\[CrossRef\]](#)
55. Krisans, O.; Saleniece, R.; Rust, S.; Elferts, D.; Kapostins, R.; Jansons, A.; Matisons, R. Effect of bark-stripping on mechanical stability of Norway spruce. *Forests* **2020**, *11*, 357. [\[CrossRef\]](#)
56. Arhipova, N.; Gaitnieks, T.; Donis, J.; Stenlid, J.; Vasaitis, R. Butt rot incidence, causal fungi, and related yield loss in *Picea abies* stands of Latvia. *Can. J. For. Res.* **2011**, *41*, 2337–2345. [\[CrossRef\]](#)
57. Petty, J.A.; Worrell, R. Stability of coniferous tree stems in relation to damage by snow. *Forestry* **1981**, *54*, 115–128. [\[CrossRef\]](#)
58. Díaz-Yáñez, O.; Mola-Yudego, B.; González-Olabarria, J.R.; Pukkala, T. How does forest composition and structure affect the stability against wind and snow? *For. Ecol. Manag.* **2017**, *401*, 215–222. [\[CrossRef\]](#)
59. Martín Alcón, S.; González-Olabarria, J.R.; Coll, L. Wind and snow damage in the Pyrenees pine forests: Effect of stand attributes and location. *Silva Fenn.* **2010**, *44*, 399–410. [\[CrossRef\]](#)
60. Päätaalo, M.L.; Peltola, H.; Kellomäki, S. Modelling the risk of snow damage to forests under short-term snow loading. *For. Ecol. Manag.* **1999**, *116*, 51–70. [\[CrossRef\]](#)
61. Zubizarreta-Gerendiain, A.; Pellikka, P.; Garcia-Gonzalo, J.; Ikonen, V.P.; Peltola, H. Factors affecting wind and snow damage of individual trees in a small management unit in Finland: Assessment based on inventoried damage and mechanistic modelling. *Silva Fenn.* **2012**, *46*, 181–196. [\[CrossRef\]](#)
62. Snepsts, G.; Kitenberga, M.; Elferts, D.; Donis, J.; Jansons, A. Stem damage modifies the impact of wind on Norway spruces. *Forests* **2020**, *11*, 463. [\[CrossRef\]](#)
63. Wonn, H.T.; O'Hara, K.L. Height: Diameter ratios and stability relationships for four northern Rocky Mountain tree species. *West. J. Appl. For.* **2001**, *16*, 87–94. [\[CrossRef\]](#)
64. Long, J.N. A practical approach to density management. *For. Chron.* **1985**, *61*, 23–27. [\[CrossRef\]](#)
65. Seischab, F.K.; Bernard, J.M.; Eberle, M.D. Glaze storm damage to western New York forest communities. *Bull. Torrey Bot. Club* **1993**, *120*, 64–72. [\[CrossRef\]](#)
66. Urata, T.; Shibuya, M.; Koizumi, A.; Torita, H.; Cha, J. Both stem and crown mass affect tree resistance to uprooting. *J. For. Res.* **2012**, *17*, 65–71. [\[CrossRef\]](#)
67. Slodicak, M.; Novak, J. Silvicultural measures to increase the mechanical stability of pure secondary Norway spruce stands before conversion. *For. Ecol. Manag.* **2006**, *224*, 252–257. [\[CrossRef\]](#)
68. Smith, W.H. Ice and forest health. *North. J. Appl. For.* **2000**, *17*, 16–19. [\[CrossRef\]](#)
69. Cain, M.D.; Shelton, M.G. Glaze damage in 13-to 18-year-old, natural, even-aged stands of Loblolly pines in Southeastern Arkansas. In *General Technical Report*; US Department of Agriculture, Forest Service, Southern Research Station: Asheville, NC, USA, 2002; pp. 579–583.
70. Mäkinen, H.; Isomäki, A. Thinning intensity and growth of Norway spruce stands in Finland. *Forestry* **2004**, *77*, 349–364. [\[CrossRef\]](#)
71. Belanger, R.P.; Godbee, J.F.; Anderson, R.L.; Paul, J.T. Ice damage in thinned and nonthinned loblolly pine plantations infected with fusiform rust. *South. J. Appl. For.* **1996**, *20*, 136–142. [\[CrossRef\]](#)

72. Štefančík, I. Development of spruce (*Picea abies* [L.] Karst.) target (crop) trees in pole-stage stand with different initial spacing and tending regime. *J. For. Sci.* **2012**, *58*, 456–464.
73. Valinger, E.; Lundqvist, L.; Bondesson, L. Assessing the risk of snow and wind damage from tree physical characteristics. *Forestry* **1993**, *66*, 249–260. [[CrossRef](#)]



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).