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Wind- and snow-induced bending and recovery of birch in young hemiboreal stands

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Abstract. Damage in young birch stands after an extensive snowing event was assessed in hemiboreal birch stands at the age of 1 to 30 years. Tree diameter, height, and stem bending were measured, stand age and time of thinning adopted from inventory data, and proximity from a sample plot to nearest adjacent mature stand measured. Stem bending was re-measured after one growing season to assess tree recovery potential. Stem damage was found for 31.0% of birch trees, with 93.2% of them bent. Tree stability was linked to its social position within the stand and taper. The proportion of undamaged trees increased from 54.5% to 80.9% for trees with relative diameter from <0.4 to >1.6, and from 69.8% to 81.7% for trees with height-to-diameter ratio >1.4 and <1.0, respectively. Stands at the age of 11 to 20 years were damaged most severely, with 19.2% of trees bent at an angle 46 to 90°. The proximity of mature adjacent stand had a significant negative effect on the proportion of damaged trees in a distance of 2.1 to 2.5 magnitudes of the height of the adjacent stand. After one growing season, 31.0% of trees had less intense bending and 8.4% had more intense bending as compared with the initial assessment. Recovery to a vertical state was more successful for smaller trees and trees initially bent at a smaller angle. The results indicate the importance of a stable stem form and spatial planning of heterogeneity in heights of adjacent stands to avoid damage at a young age.

Key words: arched stem, freezing-rain, recent thinning, slenderness ratio.

INTRODUCTION

Natural disturbances serve important ecological functions by affecting forest structure and the dynamics of forest stands (Thom & Seidl, 2016), but they also strongly, and almost always negatively, affect economic returns for landowners (Montagné-Huck & Brunette, 2018), and carbon sequestration (Klesse et al., 2016). In European forests, the main focus has been put on studies of wind, insects, and fire caused damages (Schelhaas et al., 2003; Seidl et al., 2014), whereas the impact of extreme precipitation events is relatively rarely studied. Snow is an important ecological component that insulates vascular plants from low-temperature injuries, thus contributing to growth and vitality (Blume-Werry et al., 2016). But snow can also have a destructive effect on trees when its loading is excessively heavy. During recent years, damages from snow loading are found in 7% of the forest land in Finland (Korhonen et al., 2017), whereas, in European forests, the snow has caused damages to about one million cubic meters annually during the period 1950–2000 (Schelhaas et al., 2003).

The occurrence of damaging snow in Northern Europe is projected to change in the future, but studies have revealed controversial trends. The frequency of damaging snow accumulation across Finland in 2021–2050 was predicted to decrease by 23% in comparison to the period of 1961–1990, and by 56% in comparison to 2070–2099 (Kilpeläinen et al., 2010). In the most affected regions, the number of risk days was predicted to decrease from over 30 days to eight days per year at the end of the century (Kilpeläinen et al., 2010). The more recent study, in contrast, has projected an increase in annual maximum loads of wet and frozen snow in eastern and northern Finland as much as up to 60% for a period of 2070–2099 under the high-emission RCP8.5 scenario as compared to 1980–2009 (Lehtonen et al., 2016). Besides the factors related to meteorological factors, damage severity is affected by the response of the trees linked to the individual tree and stand parameters, the site physical conditions, and the past silvicultural treatments (e.g. Jalkanen & Mattila, 2000; Hlásny et al., 2011; Díaz-Yáñez et al., 2017, 2019). Thus, even under the present frequency and intensity of the snow accumulation, the damage might rise as forests are becoming more vulnerable due to an increase in the total growing stock and age (Schelhaas et al., 2003; Seidl et al., 2011).

Based on an analysis of snow damage in Sothern Finland, a snow load of at least 40 mm water equivalent over a five-day period is necessary to break individual large stems (Solantie, 1994). However, the nature of damaging events is complex. If the temperature is near the freezing point, snow loading might be accompanied by other precipitation, such as freezing rain or rime, and wind. In the field, the effect of a certain factor is problematic to distinguish. Wet snow and freezing rain may interchange depending on temperature fluctuations and the effect of these types of precipitation is altered by a wind that has complex spatial and temporal dynamics within the forest canopy (Kamimura *et al.*, 2019). The water content of snow depends on temperature, and while dry snow is easy to shed, wet snow is more likely to accumulate (Nykänen *et al.*, 1997), whereas freezing rain forms an adherent glaze on branches. The increasing wind speed typically enhances the accumulation of snow until wind speed exceeds 9 m s^{-1} when removal of unfrozen snow starts to dominate (Solantie, 1994; Nykänen et al., 1997). In the case of wet, attached snow or glaze, however, a strong wind is likely to facilitate damages. Therefore, studies typically assess the combined effect of wind, snow, and freezing rain (Valinger et al., 1993; Valinger & Pettersson, 1996; Peltola et al., 1997; Peltola et al., 1999; Valinger & Fridman, 1999; Jalkanen & Mattila, 2000; Päätalo, 2000; Zhu et al., 2006; Martín-Alcón et al., 2010; Zubizarreta-Gerendiain et al., 2012; Díaz-Yáñez et al., 2017, 2019; Duperat et al., 2020).

A recent study based on the Norwegian National Forest Inventory has shown that snow is the most frequent damaging agent in birch stands, especially at an intermediate and mature age (Díaz-Yáñez et al., 2016). As compared to coniferous species, deciduous trees are considered to be less susceptible to snow damage (Peltola et al., 1997; Jalkanen & Mattila, 2000; Päätalo, 2000) due to the smaller crown area during the winter when the snow damage mostly occurs (Lehtonen et al., 2016). However, these studies have accounted only for stem and root failure to resist snow loading. Stem bending is the least studied among the snow damage types, presumably because it is more frequent in young stands (Martiník & Mauer, 2012) and does not cause tree death. However, stem bending might be irreversible (Beach et al., 2010) and cause internal wood defects both from initial disturbance (Fredericksen et al., 1994; Jakubowski & Pazdrowski, 2006) and the formation of reactive wood for trees that continue to grow leaning (Nishikubo et al., 2007; Donaldson & Singh, 2016). The faith of the bent trees is rarely quantified, however, this would provide valuable information to support decision making for landowners. If a large proportion of trees is permanently bent, starting over might be considered.

The extensive snowing and freezing rain events cannot be prevented, however, stand resistance and resilience can be increased through silvicultural measures that control the stability of trees. Acknowledging these factors, and implementing them into forest management might mitigate the potential impact of freezing rain and snow loading on trees. This study aimed to 1) characterize stem damage types caused by freezing rain and snow-accumulation in young birch stands, 2) assess factors affecting damage severity concerning individual tree and stand parameters, and 3) assess tree recovery potential.

MATERIALS AND METHODS

In the last ten-day period of December 2010, according to the data from the Latvian Environment, Geology and Meteorology Centre, the upper layer of the air mass passing through Latvia was warm and resulted in snowing along with drizzle, rain, and freezing-rain. The amount of precipitation exceeded the norm (30-year-average) by 2.7 times, mainly in a form of wet snow.

The snow damage was assessed in young birch-dominated stands in the spring of 2011 in the south-eastern part of Latvia, i.e. the region that was most severely affected by extensive snow loading. One hundred stands (total area 215 ha) with birch (*Betula pendula* and *Betula pubescens*) accounting for more than 30% of the number of trees (if the height of the dominant species <12 m) or growing stock (if the height of the dominant species ≥12 m) at the age from 1 to 30 years were selected. In each stand, 10, 15, or 20 sample plots were established for a stand size of 0.5 to 1 ha, 1.1 to 2 ha, or 2.1 to 10 ha, respectively. Plot spatial distribution (coordinates) within the stand was generated using the Repeating Shapes tool (v. 1.5.152) for ArcGIS (Jenness, 2012). The size of a sample plot was 25, 50, or 75 m^2 for stands at the age of <10, 11 to 20, or 21 to 30 years, respectively. In total, 1477 sample plots were established, and 14,617 trees (9525 birch trees) were measured. The total area of the sample plots was 8.1 ha.

Diameter at 1.3 m at the breast height (DBH) was measured and species noted for all trees that were at least half of the height of the dominant canopy. Height (H) was measured for four trees per sample plot. The height of the straight trees was measured with an accuracy of 0.1 m if H < 3.0 m or 0.5 m if a tree was higher. Height (stem length) of the bent trees was calculated assuming that the length of the stem is the length of the arc between the tree top and stem base. The arc length was calculated based on the Huygens formula, considering a) height of the treetop above the ground level at the stem base, b) horizontal distance between the stem base and treetop vertical projection, and c) height of the stem in the half of the distance of assumption b.

For each sample plot, the distance from the centre to the nearest adjacent stand and the height of the dominant canopy of this stand were measured. Stem slenderness coefficient (ratio between tree height (m) and DBH (cm)), and relative diameter (ratio between DBH of an individual tree and the stand mean DBH) was calculated to characterize a tree's social position within the stand. The measured data were used to calculate stand density (number of trees per ha) and stand composition. Stand age and timing of tree removal during the previous years (2010 to 2009, 2008 to 2004, and before 2004 or none) were obtained from the stand inventory data.

The stem damage type—bent, broken, or uprooted—was noted. The stem bending was measured as a deviation from the vertical axis from the tree stem base to the top using a protractor and ruler. The damage was graded (Table 1) according to type and intensity. Trees that were bent up to 15° (Grade 0) were regarded as undamaged.

Table 1. Grading of the stem damage

Damage grade	Damage type	Damage intensity, degrees
Grade 0	undamaged	–
Grade 1	bent	16–30
Grade 2	bent	31–45
Grade 3	bent	46–60
Grade 4	bent	>60
Grade 5	Broken/uprooted	–

a deviation from the vertical axis from the tree stump to top.

Re-measurements in 20 randomly selected stands were done after one growing season in autumn 2011. In each stand, the damage of all previously measured birch trees (in total 1622 trees) was assessed using the same grading (Table 1).

We used a chi-squared test to assess the effect of relative diameter, slenderness coefficient, and stand age on the number of damaged trees among the damage grades and the effect of stand age and timing of thinning on the number of stands among the stand state categories. The effect of proximity of an adjacent mature stand was assessed by one-way analysis of variance. The effect of tree height on the number of trees among the categories of change in the bending degree (increased, stable, decreased) was assessed by chi-squared test.

RESULTS AND DISCUSSION

Initial assessment

The snow-induced damages, i.e. stem deviation larger than 15° from the vertical axis, stem breakage, or uprooting, were observed for 31.0% of the 9525 assessed birch trees. Stem bending was the prevailing damage type, accounting for 93.2% of all damaged birch trees. Among the damaged trees, 5.6% had broken stems, and 1.2% was uprooted. Studies have shown that birch is more prone to bending than other economically important hemiboreal tree species (Martiník & Mauer, 2012). The level of snow-induced bending observed in birch stands at the age of four to 20 years in central Europe was even higher than in our study, with 58% to 89% of all birches bent (Martiník & Mauer, 2012).

The tree social position within the stand significantly (P < 0.001) affected the damage intensity. Trees of a large relative diameter had a smaller proportion of more severely bent trees than relatively thicker trees but increased the proportion of broken and uprooted trees (Fig. 1a). The proportion of undamaged trees increased from 54.5% among trees with relative diameter <0.4 to 80.9% for trees with relative diameter <1.6. The proportion of most severely bent trees had the opposite trend: from 5.9% for the relatively largest trees to 16.9% for the relatively smallest trees. A similar pattern was reported from stands damaged by freezing rain (Klopčič et al., 2020), and might be explained by secondary damage (domino effect) from the bent neighbouring trees

(Rhoads et al., 2002; Bragg et al., 2004). Several other studies, however, have indicated less damage from ice accumulation to trees of lower social strata due to the sheltering effect (Belanger et al., 1996; Rebertus et al., 1997; Rhoades, 1999; Zarnovican, 2001; Šēnhofa et al., 2020).

A height-to-diameter ratio was significantly ($P < 0.001$) linked to damage grade. Trees with high slenderness ratio had a higher proportion of damaged trees and a higher proportion of more severely bent trees than trees with low slenderness ratio (Fig. 1b). The proportion of undamaged trees was from 69.8% for trees with a slenderness ratio >1.4 to 81.7% for trees with a slenderness ratio <1.0. The proportion of trees bend at an angle of 46 to 90° had an opposite trend, and increased from 8.3% to 16.0% for trees with a slenderness ratio <1.0 and >1.4, respectively. Our observed link between damage occurrence and stem taper is typical for damage from snow and ice accumulation (Nykänen et al., 1997; Peltola et al., 1997). The study that analysed the bending of birch, however, found no differences in slenderness ratio between intact and damaged trees (Martiník & Mauer, 2012). Differences with our results might be related to stand density, as their analysed stands had an extremely high number of trees (18,400 to 50,600 trees ha^{-1}). In such tightly spaced stands both damaged and intact trees had high slenderness ratios (mean values about 150 to 170) thus diminishing the effect of stable stem taper.

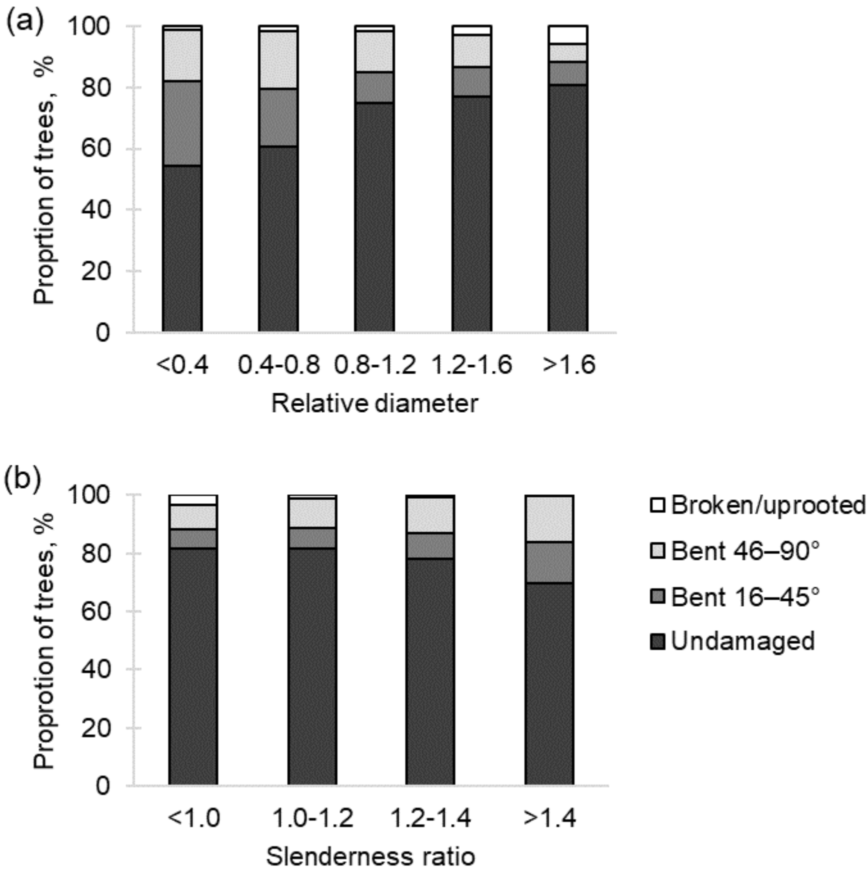

Figure 1. The proportion of trees among the damage grades according to relative diameter (D_{tree}/D_{stand}) and slenderness ratio (HD^{-1}).

Stand age significantly (P < 0.001) affected tree distribution among the damage grades (Fig. 2). Stands up to the age of 10 years were least damaged, with 84.3% of trees undamaged. The medium-aged stands (11 to 20 years) were damaged most severely: the proportion of undamaged trees was the lowest (63.5%) and the proportion of trees bent at an angle 60 to 90° was the largest (19.2%) among the groups of stand age. Stands at the age of 21 to 30 years were damaged slightly less than the medium-aged stands.

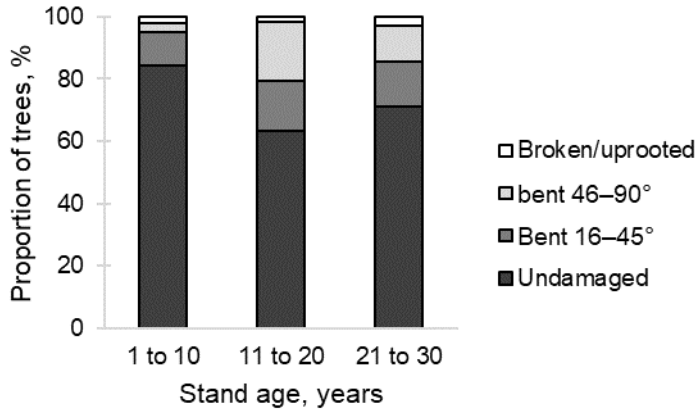

Figure 2. Distribution of trees among the damage grades according to stand age.

The proportion of damaged trees per stand affected its status (undamaged, damaged, or destroyed) after the disturbance. Stand age was a significant factor (*P* = 0.01) affecting its status. Stands at the age of 11 to 20 years had suffered the most, with 49.1% of them damaged and 18.9% destroyed (Fig. 3a). An age-related trend for the proportion of damaged trees was also showed in a severely bent birch stand in central Europe (Martiník & Mauer, 2012). Stand younger than six years were least damaged, whereas in stands at the age of seven to 10 years almost every (91% to 97%) birch was bent, followed by a gradual decrease of the proportion of damaged birches in older stands (Martiník & Mauer, 2012). A similar trend but biased to a larger stand age was observed in a deciduous forest after freezing rain (Rhoads et al., 2002). Stands at the age of 14 years had only a few bent trees along the openings, while adjacent 24- to 28-year-old stands had damaged 36% of stems, with 78% of damaged trees severely bent.

Less damage to trees at a younger age is likely due to smaller tree dimensions, as smaller tree crowns can accumulate a smaller amount of snow. Young trees are also more flexible to resist bending due to smaller tree diameters (Brüchert et al., 2000). Indeed, bending of maple and aspen was almost exclusively found for stems smaller than 18 cm, whereas trees of a larger diameter had a substantial crown loss (Proulx & Greene, 2001). Higher susceptibility to bending for younger trees as opposed to stem breakage in middle-aged and mature stands is also observed for ice accumulation in coniferous stands (Bragg et al., 2004; Bāders et al., 2016).

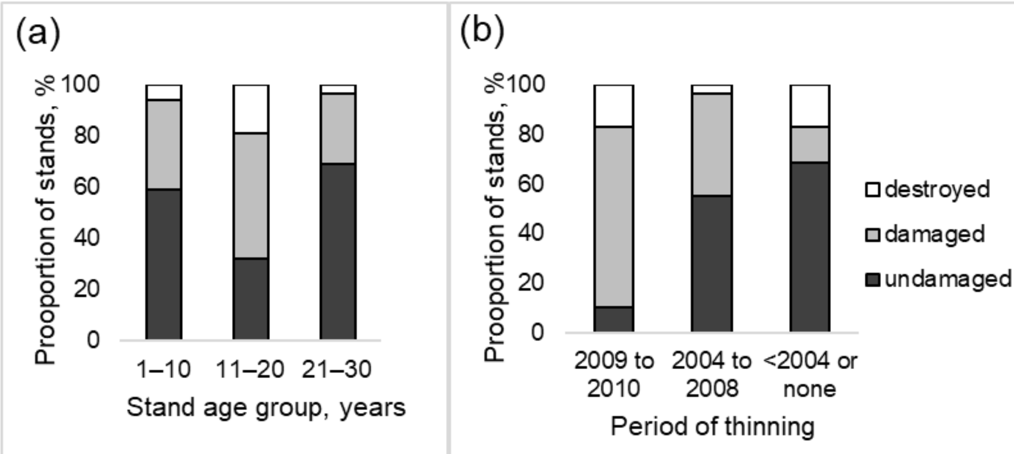

Figure 3. Stand status (undamaged, damaged, or destroyed) according to (a) stand age, and (b) year of thinning.

A higher stand density has been linked to an increased proportion of damaged trees (Valinger & Pettersson, 1996; Martiník & Mauer, 2012) due to consequent changes in a stem taper and crown shape. Pre-commercial thinning is an efficient measure to promote the growth of diameter and reduce slenderness for birch (Rytter & Werner, 2007; Rytter, 2013) thus increasing the stability of individual trees. However, the timing of previous tree removal significantly ($P < 0.001$) affected stand susceptibility as shown by an increased proportion of damaged trees in recently thinned stands (Fig. 3b). Among the stands that were thinned during the previous two years, only 10.3% were undamaged, whereas, among stands that were thinned three to seven or more than eight years before the disturbance, the proportion of undamaged stands was 55.2% and 68.3%, respectively. Temporally increased susceptibility might also contribute to explain the high proportion of severely damaged stands at the age of 11 to 20 years, as stands are usually thinned at this age.

If the reduction of competition is delayed, stem slenderness for densely growing trees increases significantly, and even after competition release cannot recover to the level of the timely thinned trees (Rytter, 2013). Instead, open stands with highly tapering individuals that have lost support from the neighbouring trees are formed (Belanger et al., 1996). Trees in an open stand might suffer more damage as more snow and ice could accumulate on an individual tree (Belanger et al., 1996), and increased wind speed within the canopy might facilitate damage. Our results agree with the study of snow and ice accumulation in a thinning experiment in 28-year-old *Betula alleghaniensis* stand that has shown an increased proportion of severely bent trees in relation to thinning intensity (Zarnovican, 2001). In pine and spruce thinning and fertilization experiment, Valinger et al. (1994) have found no statistically significant differences in the proportion of leaning and uprooted trees after four to eight years after thinning, although in all treatments it was by 60% to 100% higher than in the control plots. Authors have claimed that leaning and uprooted trees are wind-induced damage and stem breakage was snow-induced damage, whereas in our study bending was primarily caused by snow and ice loading, accompanied by wind. However, their studied stands were notably older (34 to 58 years at the experiment establishment) in comparison to our stands. In a study of ice accumulation caused damage in thinned and unthinned loblolly pine stands at age of 19 to 22 years, bending was found for three to seven percent of trees regardless of applied treatment (Belanger et al., 1996).

Stands with mean tree height within the range of 4 to 16 m had a large variation in the proportion of damaged trees, from nearly all trees damaged to any damaged trees (Fig. 4). Stands with smaller and higher mean height were damaged less severely, with at least half of the trees undamaged. Our results agree well with the previous observations (eight to 15 m) in severely damaged birch stands (Martiník & Mauer, 2012).

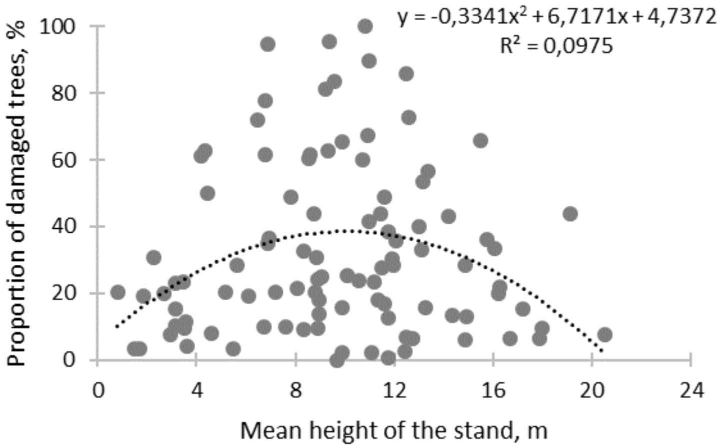

Figure 4. The proportion of damaged trees in relation to mean stand height.

Proximity to the nearest adjacent stand significantly affected the proportion of bent trees, with a larger proportion of damaged trees closer to the edge of the adjacent mature stand (Fig. 5). This proportion decreased from 43.2 ± 2.4% (mean ± confidence interval) in plots that were closer than half of the adjacent stand height, to 19.3 ± 3.7% in plots that were at the distance of 2.1 to 2.5 magnitudes of a height of the adjacent stand.

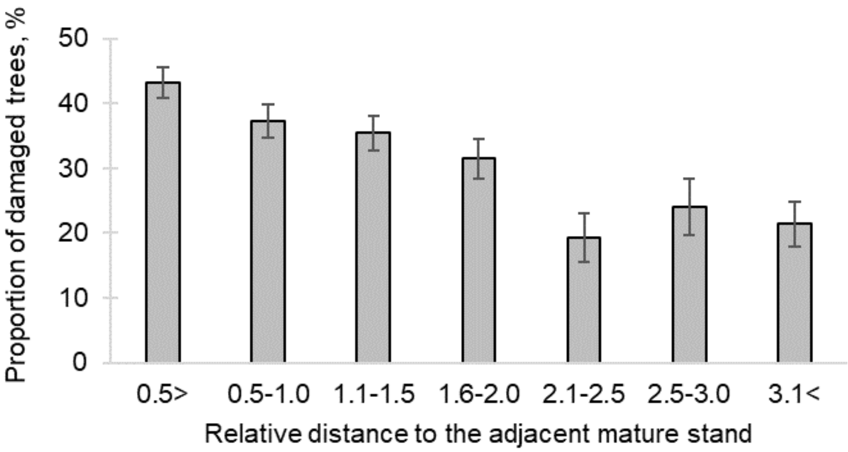

Figure 5. The proportion of damaged trees and their confidence interval in relation to the relative distance (relative to the height of the mature stand) from the adjacent mature stand.

Our observed distance where the effect of proximity of a mature adjacent stand slows down coincides with results of studies that have characterized wind profile in a forest. When wind flows from the direction of a lower canopy (young stand) to a higher forest edge (mature stand), wind facilitated damage is expected to increase closer to the mature stand. The open area of the lower canopy promotes an increase in a wind drag (Venäläinen et al., 2004; Heinonen et al., 2009; Belcher et al., 2012), and is followed by a turbulent flow at the edge of the downwind mature stand (Dupont & Brunet, 2008; Belcher et al., 2012). If the wind comes from a mature upwind stand, it provides lee to the downwind young stand (Heinonen et al., 2009; Zeng et al., 2009) in a distance of one to two heights of the upwind stand canopy (Peltola et al., 1999; Belcher et al., 2012). Additionally, wind could also cause shedding snow in a windward direction from a higher to the lower canopy, thus increasing loading to young trees (Solantie, 1994; Nykänen et al., 1997).

Re-measuring

After one growing season, 60.7% of birch trees had the same damage intensity (the difference between measurements smaller or equal to ±5°), 8.3% had more intense bending, and 31.0% of trees had less intense bending as compared with the initial assessment. Among the re-measured trees, 45.9% were initially classified as undamaged, and this number increased to 56.7% after one growing season. Tree fate (increased, decreased, or stable degree of bending) was significantly affected ($P < 0.001$) by its height. The largest changes in damage intensity were obtained for trees smaller than 6 m, among which 38.4% of trees reduced the degree of bending. The damage intensity was most stable in the largest trees: 75.3% of trees had not changed the position more than five degrees, and 19.4% had reduced degree of bending (Fig. 6).

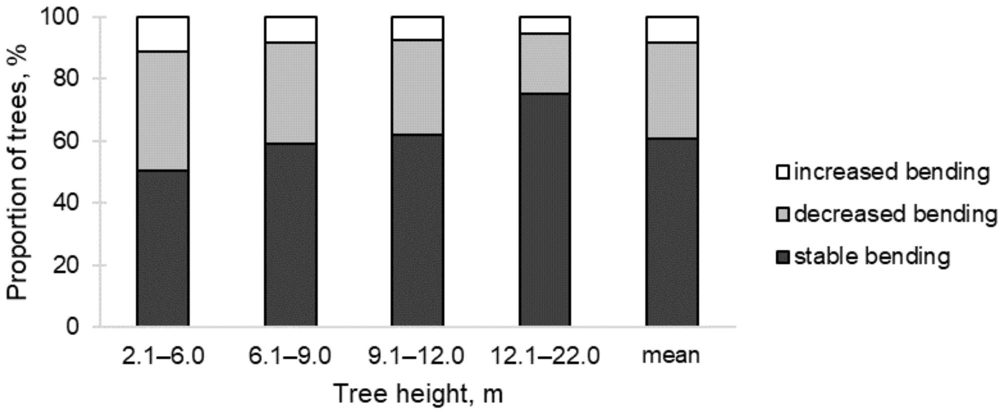

Figure 6. The proportion of trees that have increased (increase >5°), stable (change smaller or equal to ±5°), or decreased (decrease >5°) degree of bending after one growing season.

Among the trees that initially were classified as undamaged (deviation <15°), 97.8% were re-assessed as undamaged. Trees with initial stem deviation 16–30° tended to unbend: among such trees, 82.8% of the re-measured trees had stem deviation smaller than 15°. For trees with initial stem deviation 31–45°, about half of trees (49.2%) with height up to 9 m were re-assessed as undamaged (deviation <15°), whereas for taller trees only four out of 30 individuals were unbent. For the most severely damaged trees (initial deviation ≥61°), the majority (86.8%) were re-assessed at the same damage intensity, and only 0.34% of trees were able to unbend to stem deviation smaller than 15° (Fig. 7).

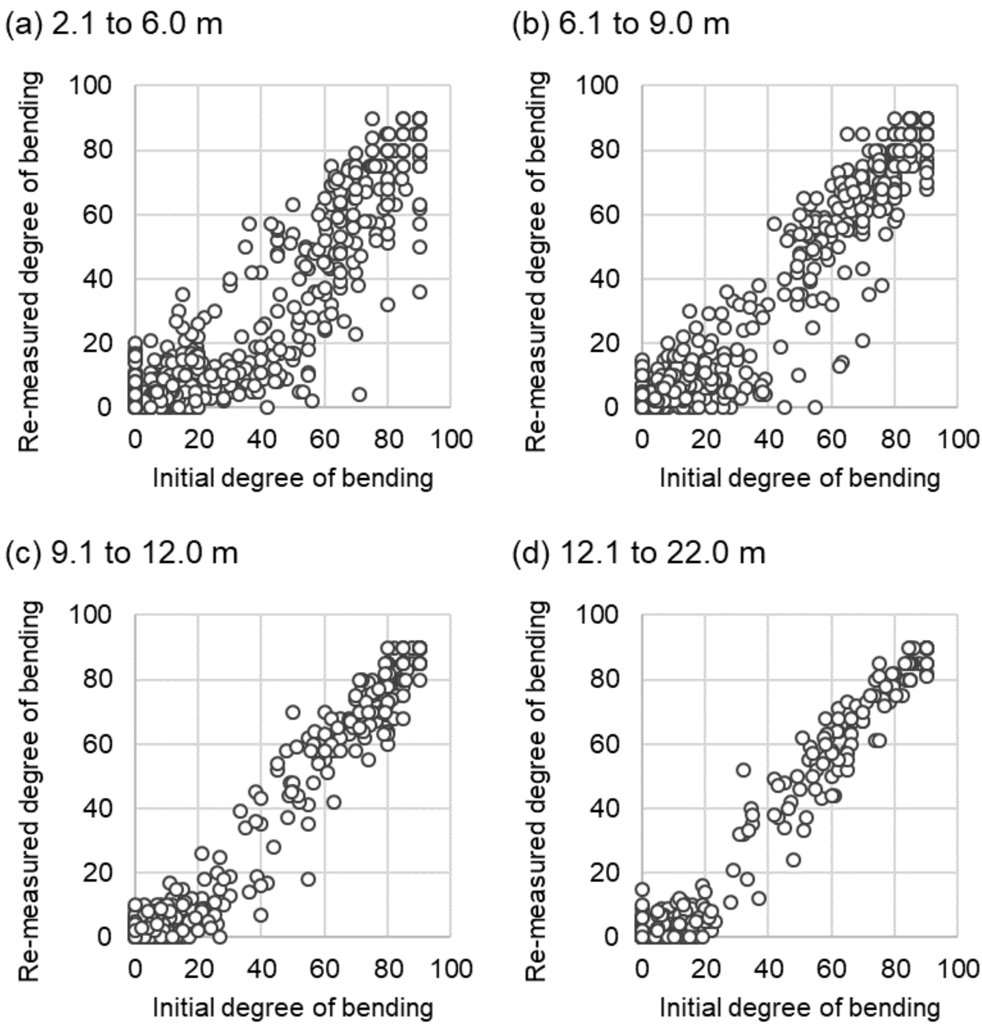

Figure 7. Damage intensity at the re-measuring in autumn in relation to initial measuring in spring for trees with height (a) 2.1 to 6.0 m, (b) 6.1 to 9.0 m, (c) 9.1 to 12.0 m, and (d) 12.1 to 22.0 m.

Our results are in accordance with the observation of Greene et al. (2007) that have noticed rapid recovery of small trees after an ice loading but decreased capability of recovery as tree height increased but less successful recovery for larger stems. Trees that are capable to recover vertical growth of the top may initially have crooks at the stem base, although, for trees damaged at the seedling stage (one to two meters height) no external sights were visible 10 years later for pines (Oliver, 1970). If a tree remains bent over a growing season its recovery to a vertical state is less likely. An increase in living crown hinders unbending, as it applies additional force due to gravity (Peltola et al., 1999).

CONCLUSIONS

The susceptibility to wind- and snow-induced bending is linked to individual tree parameters, the timing of thinning, and proximity to the mature adjacent stand. Damage might be diminished through silvicultural measures that increase the stability of individual trees at a young age with particular importance of tree stability near the mature adjacent stand. Stands at an older age were damaged less than younger stands, however, recovery of these stands might be less successful as a larger proportion of higher trees tend to remain arched.

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