*forests*

MDPI

*Brief Report*

# Regularly Planted Rather Than Natural Understory of Norway Spruce (*Picea abies* H. Karst.) Contributes to the Individual Stability of Canopy Silver Birch (*Betula pendula* Roth.)

**Oskars Krišāns [1], Roberts Matisons [1], Jānis Vuguls [1], Endijs Bāders [1], Steffen Rust [2], Didzis Elferts [1,3], Renāte Saleniece [1] and Āris Jansons [1,*]**

[1] Latvian State Forest Research Institute 'Silava', 111 Rigas Str., LV-2169 Salaspils, Latvia; oskars.krisans@silava.lv (O.K.); roberts.matisons@silava.lv (R.M.); janis.vuguls@silava.lv (J.V.); endijs.baders@silava.lv (E.B.); didzis.elferts@lu.lv (D.E.); renate.saleniece@silava.lv (R.S.)

[2] Faculty of Resource Management, University of Applied Sciences and Arts, Büsgenweg 1a, 37077 Göttingen, Germany; steffen.rust@hawk.de

[3] Faculty of Biology, University of Latvia, 1 Jelgavas Str., LV-1004 Riga, Latvia

* Correspondence: aris.jansons@silava.lv; Tel.: +371-2-910-9529

**Abstract:** Forest plantations, particularly high-density planted stands, are considered to be more prone to wind damage compared to naturally regenerated stands. The wind resistance (mechanical stability) of plantations can, however, be improved by close-to-natural management, for example, combining pioneer and shade-tolerant species. Presumably, the stability of such stands would be enhanced by the reduced competition of canopy trees and stronger root contacts provided by understory trees, which depend on spatial distribution. In the hemiboreal forest zone, silver birch (*Betula pendula* Roth.) and Norway spruce (*Picea abies* (L.) H.Karst.) form such a combination naturally. In this study, the static tree-pulling tests were performed to estimate the mechanical stability of canopy silver birch growing with random Norway spruce understory in naturally regenerated (post-clear-cut) and regularly planted bi-species mixed stands. The regular mixing of the high-density bi-species stand significantly improved the loading resistance of canopy silver birch compared to the naturally regenerated stands of similar composition and age. Such an effect might be related to the stratification of the canopy space between pioneer birch and shade-tolerant spruce, which improved the individual stability of the canopy trees. Further, a regular rooting network of the planted stands likely contributed to the stability by reducing weak spots. Accordingly, the wind resistance of trees in regularly planted bi-species stands might be improved, avoiding additional management.

**Keywords:** static tree-pulling tests; wind resistance; wind damage; mixed forest; silver birch; *Betula pendula*



**Citation:** Krišāns, O.; Matisons, R.; Vuguls, J.; Bāders, E.; Rust, S.; Elferts, D.; Saleniece, R.; Jansons, Ā. Regularly Planted Rather Than Natural Understory of Norway Spruce (*Picea abies* H. Karst.) Contributes to the Individual Stability of Canopy Silver Birch (*Betula pendula* Roth.). *Forests* **2022**, *13*, 942. https://doi.org/10.3390/f13060942

Academic Editor: Thomas J. Dean

Received: 13 May 2022
Accepted: 13 June 2022
Published: 16 June 2022



## 1. Introduction

In European forests, wind is the major natural disturbance, causing more than half the damage to growing stock [1], thus resulting in considerable socio-economic and ecological impacts [2]. Under the changing climate, wind damage to growing stock is steadily increasing with the intensification of storms [3–5], highlighting the necessity for climate-smart management to sustain forest productivity [6–9]. Under such an approach, alterations or diversification in species composition and stand structure are considered among the most effective means [6–9]. Forest stands with structures that tend to be more similar to natural ones are presumed to be more resilient to wind damage [10,11], as higher structural heterogeneity of the canopy reduces the amplification of mechanical loading of stems, thus enhancing collective stability [12]. Higher frequency of root contacts, as well as the diversity of rooting strategies of trees, might also contribute to collective stability [13]. However, the irregularities in tree distribution, both in terms of position and vertical stratification of canopies, might reduce the loading resistance of individual trees, causing weak points in the chain of collective stability [13]. Accordingly, the information on stand and tree characteristics affecting the mechanical stability of mixed stands is still incomplete [14,15], as most of the evidence has been obtained from windthrow surveys, in which the control of environmental and management effects is uncertain [14].

A controlled evaluation of tree loading resistance can be sufficiently performed by static tree-pulling tests, which are widely applied for the examination of the strength of soil-root anchorage and stem stiffness [16,17]. Individual-tree loading resistance can be quantified as the maximum basal bending moment [16,17] and used in characterizing wind resistance [18]. Accordingly, such tests facilitate the evaluation of tree loading resistance according to different forest management strategies, thus contributing to climate-smart management [19]. Plantation forests, particularly the high-density ones, are considered to be more prone to wind damage compared to naturally regenerated stands [19]. Nevertheless, there is evidence that wind resilience can be substantially increased by appropriate management—by mimicking natural structures and compositions [8]. One such approach is the combining of faster-growing pioneers as canopy trees with a shade-tolerant tree understory (advanced growth) [20]. In such a combination, the understory trees can amplify root contacts, thus facilitating the collective soil-root anchorage of a stand [21]. At the same time, canopy trees are subjected to higher wind loads [19], stimulating their individual stability [22]. In the hemiboreal forest zone in the Eastern Baltic region, shade-tolerant Norway spruce (*Picea abies* (L.) H.Karst.) commonly naturally regenerates with pioneer silver birch (*Betula pendula* Roth.), forming mixed stands [23,24].

The aim of this study was to compare the loading resistance of canopy silver birch growing in naturally regenerated and evenly planted stands with randomly and regularly distributed Norway spruce understory, respectively. We hypothesise that the individual loading resistance of canopy silver birch would be increased in the interplanted bi-species (and thus more spatially homogeneous) stands with regular understory.

## 2. Materials and Methods

### *2.1. Study Site and Sample Trees*

The study was carried out in the hemiboreal forest zone in Latvia, where birch is present in 28% of the forests, which cover ca. 51% of the country [25,26]. Most birch stands have regenerated naturally. However, commercial plantations are common; ca. 67% of birch stands have a Norway spruce understory [26]. A total of five stands (two experimental trial plantations and three naturally regenerated stands) of silver birch in three nearby localities in the central part of Latvia were studied (N 56°42′ E 23°50′; N 56°27′ E 22°54′; N 56°40′ E 25°55′). Considering that monocultures historically have been the main type of plantation within the region due to increased productivity at a young age [27], only two experimental plantations of regular birch–spruce mixture has been established in Latvia.

All of the studied stands were growing under lowland conditions (<150 m a.s.l.) with flat terrain on freely draining mesotrophic fine sandy soils with similar fertility and gravimetric water content (Table 1). The climate at the studied stands can be described as humid continental [28], with the mean annual air temperature of 6.8 °C and the annual sum of precipitation of 684.6 mm [29]. The wind climate is predetermined by the dominant westerlies winds from the North Atlantic [30], with the mean annual wind speed higher in coastal parts, reaching 4.1 m $s^{-1}$, while inland, it is 2.6 m $s^{-1}$ [29]. The mean maximum wind speed at the elevation of 10 m was similar among the localities, ranging between 16.72 and 19.67 m $s^{-1}$ [31].

**Table 1.** Stands' species composition (proportion from the total basal area), the number (Tree n), mean (± 95% confidence interval) diameter at breast height (DBH), height (H), height–diameter ratio (H/DBH), stem–wood volume ($V_{stem}$), soil–root plate volume ($V_{roots}$) of the sampled trees, as well as the local (at 12.61 m distance from the sampled tree) stand basal area (G), soil gravimetric water content ($\theta_g$) and soil density ($\rho_{Soil}$). Tree species are abbreviated as follows: B—silver birch (*Betula pendula* Roth.), S—Norway spruce (*Picea abies* (L.) H.Karst.), A—common aspen (*Populus tremula* L.); P—Scots pine (*Pinus sylvestris* L.), O—common oak (*Quercus robur* L.), OT—other species (mostly *Padus avium* Mill., *Sorbus aucuparia* L., *Salix caprea* L., *Acer platanoides* L., *Alnus glutinosa* (L.) Gaertn., *Alnus incana* (L.) Moench.).

| Site No. | Species Composition (%) | Tree n | DBH (cm) | H (m) | H/DBH | $V_{stem}$ ($m^3$) | $V_{roots}$ ($m^3$) | G ($m^2$ $ha^{-1}$) | $\theta_g$ (%) | $\rho_{Soil}$ (kg $m^{-3}$) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Planted** | | | | | | | | | | |
| 1 | B (64.8) S (34.6) OT (0.6) | 7 | 27.0 ± 3.7 | 29.2 ± 1.1 | 1.10 ± 0.10 | 0.78 ± 0.27 | 1.05 ± 0.30 | 43.3 ± 2.9 | 10.5 ± 1.6 | 1290 ± 43 |
| 2 | B (50.3) S (49.6) OT (0.1) | 7 | 26.5 ± 3.2 | 29.8 ± 1.7 | 1.14 ± 0.11 | 0.76 ± 0.21 | 0.89 ± 0.46 | 49.2 ± 12.1 | 8.8 ± 3.4 | 1275 ± 53 |
| **Naturally Regenerated** | | | | | | | | | | |
| 3 | B (70.2) S (26.8) OT (3.0) | 9 | 25.3 ± 1.7 | 28.8 ± 1.2 | 1.15 ± 0.08 | 0.66 ± 0.09 | 0.94 ± 0.35 | 38.7 ± 3.1 | 7.2 ± 1.4 | 1213 ± 37 |
| 4 | B (65.4) S (34.1) OT (0.5) | 4 | 21.7 ± 2.8 | 22.9 ± 1.9 | 1.06 ± 0.09 | 0.39 ± 0.13 | 1.23 ± 0.58 | 41.1 ± 9.8 | 13.6 | 1306 |
| 5 | B (72.5) S (3.6) P (6.4) O (4.5) A (4.5) OT (8.5) | 8 | 34.0 ± 3.1 | 33.0 ± 1.2 | 0.99 ± 0.10 | 1.36 ± 0.26 | 1.99 ± 0.48 | 33.4 ± 2.6 | 9.2 ± 0.9 | 1260 ± 43 |

Both experimental stands were 45 years old, and they were established to test the productivity and potential of an even mixture of birch and spruce, in which trees were planted in a regular grid (1 × 2 m). The grid was filled with a similar number of three-year-old birch and spruce seedlings, which were regularly mixed (chessboard principle interplanting). Until the sampling, no thinning operations have been performed; therefore, the changes in tree spatial distribution and species composition (proportion from the total basal area) have occurred under natural competition. As a result, the faster-growing pioneer birch has overgrown spruce, forming the upper canopy layer, mostly leaving spruce in the understory (reaching ≤ 75% of canopy height). Some spruces have reached the canopy. Nearby naturally regenerated stands of silver birch (area > 0.7 ha) with a Norway spruce understory (advanced growth) growing under similar conditions were selected for comparison. The age of naturally regenerated stands was 51 ± 15 years. The naturally regenerated stands were managed conventionally (presuming a 70-year rotation cycle with pre-commercial thinning and one to two thinnings), implying they have undergone precommercial thinning; following thinning has not been performed.

In total, 35 canopy birch trees without visual signs of mechanical damage or fungal infestation were sampled—14 in the experimental interplanted stands and 21 in the nearby naturally regenerated stands (Table 1). Sample trees were selected in accordance with the stem diameter distribution of stands. Trees growing on the edges of openings were avoided to minimise the edge effect on the loading resistance.

### 2.2. Static Tree-Pulling Tests

Static tree-pulling tests were performed during February–September 2020 according to Krišāns et al. [32]. In brief, sample trees were detopped to prevent the effect of wind and tree weight on the measurements and pulled destructively until reaching a failure (exclusively by uprooting in this study). The detopping was performed 1 m above the half-height of the tree where the pulling line was anchored (Supplementary Material, Figure S1). The pulling line was formed by a pulley block system of two opposite Roll Double pulleys (Edelrid, Germany) and a 12 mm polyester rope. The base anchor was located at a distance of 30–40 m (Supplementary Material, Figure S1). A portable 2-stroke motor winch (1800 Capstan Cable Winch, Nordforest, Germany) was used for pulling (Supplementary Material, Figure S2).

During the pulling, stem stability variables were measured simultaneously using the TreeQinetic System (Argus Electronic GmbH, Rostock, Germany). The pulling force and the angle of the pulling line were recorded by a dynamometer placed above the pulley block system. Stem tilting was recorded by inclinometers at the stem base and at 5 m height. On the compression side (facing the pulling line), deformation of the stem was measured using a strain gauge (Elastometer) at the height of 1 m (Supplementary Material, Figure S1).

### 2.3. Data Processing and Analysis

To characterize the spatial structure of the studied stands in terms of tree position, the average nearest neighbor statistic [33] was calculated based on the Euclidean distance matrix. The positions of canopy (overstory) trees were obtained from a ground survey and areal recognition images (centroid of crown projection). The statistic was calculated as the ratio of the observed mean distance (within a stand) and hypothetical mean distance between randomly distributed objects with the same density and generalized by the Z-test [33]. The analysis was performed in ArcGIS 10.2 using the spatial statistics package (ESRI, Redlands, CA, USA). The mean distance between trees within the studied stands and basal area according to stand type were compared by a simple *t*-test.

To estimate the loading resistance of trees, basal bending moment (BBM, in kNm) was estimated based on the pulling force and the angle of the pulling line as follows:

$$BBM = F \times h_{anchor} \times cos(median(\alpha_{line})) \quad (1)$$

where $F$ is the pulling force, $h_{anchor}$ is the height of the upper anchoring point (half of the tree height) and $\alpha_{line}$ is the angle of the pulling line. Stem curvature ($N_{\Delta}$, °) was expressed as the difference between tilt measurements at the stem base and the height of 5 m:

$$N_{\Delta} = N_{5m} - N_{base} \tag{2}$$

Primary (PF) and secondary (SF) failures were estimated as the stability proxies based on the proportionality of BBM and $N_{\Delta}$ [34–36]. The PF was evaluated graphically as BBM when the proportionality (linear dependence of elastic deformation) between BBM and $N_{\Delta}$ disappeared. The PF is recognized as internal wood damage occurring under the compression of wood, which is not visually evident during the pulling test [34–36]. The maximum BBM at the failure (either as uprooting or stem breakage) was considered as the point of SF.

Stem stiffness of the sample trees was characterized by the modulus of elasticity (MOE), which was calculated as follows:

$$MOE = \frac{BBM \cdot y}{I \cdot e} \tag{3}$$

where $BBM$ is calculated for the height of strain gauge, $y$ is the distance between the central axes of the strain gauge and stem, $I$ is the second moment of area of the stem cross-section and $e$ is the strain measured by the strain gauge.

The volume of the soil-root plate was approximated using the volume equation of an elliptical paraboloid as follows:

$$V = \left(\frac{1}{2}\right) \cdot \pi \cdot a \cdot b \cdot h \tag{4}$$

where $a$ and $b$ are the longest and shortest radii of the root plate, respectively, and $h$ is the depth of the soil-root plate.

Linear mixed-effects models (analysis of covariance) were used to evaluate the differences in $BBM_{PF}$, $BBM_{SF}$, MOE and the volume of the soil-root plate between the stand types (interplanted and naturally regenerated), accounting for tree size and location. The model in general form was:

$$y_{ijk} = dim_{ij} + st_k + dim_{ij} \times st_k + (site_j) + \varepsilon_{ij} \tag{5}$$

where $dim_{ij}$ is the tree size covariate, $st_k$ is the fixed effect of stand type and $dim_{ij} \times st_k$ is the interaction between the covariate and stand type. To account for the uneven distribution of sampled trees between tested groups, pseudoreplication and local specifics, the growing site was included as the random effect ($site_j$). Stemwood volume ($V_{stem}$) was included as a covariate to account for differences in tree size [37]. The $V_{stem}$ was calculated according to a local equation as follows:

$$V_{stem} = 0.0000909 \times H^{0.71677} \times DBH^{0.16692 \times 0.4343 \times ln(H) + 1.7570} \tag{6}$$

where $DBH$ is the stem diameter at breast height in cm and $H$ is tree height in m.

The model was fit by the maximum likelihood approach. The significance of fixed effects was estimated by Wald $\chi^2$ (model ANOVA). Data analysis was performed in R (v. 4.1.2.) [38] using the packages "lme4" [39], "lmerTest" [40] and "MuMIn" [41].

## 3. Results and Discussion

Higher lateral loading resistance of stems was estimated for birches growing in the interplanted than in naturally regenerated stands, as indicated by the significant interaction between $V_{stem}$ and stand type, implying a steeper slope of BBM at both PF and SF (Figure 1, Tables 2 and 3). These slopes indicated increasing differences between the groups as trees grow, implying the relevance of studied management, as the risk of wind damage is proportional to tree size [11,15]. The individual effect of stand type, which in the current analysis primarily represents the mean dimensions of sampled trees, was not significant, as comparable stands in terms of productivity were selected for sampling. Similarly to earlier static tree-pulling studies on birch [18,32,37], $V_{stem}$ was a significant proxy of tree size when assessing both the $BBM_{PF}$ and $BBM_{SF}$ (Table 3), as it is an integral tree dimension. The differences in loading resistance were size-independent, as indicated by the significant interaction between stand type and $V_{stem}$ (Table 3) for $BBM_{PF}$ ($p < 0.01$) and $BBM_{SF}$ ($p < 0.05$) (Table 3). Accordingly, the differences in regression slopes (Figure 1) showed 20% and 21% increases in the loading resistance of trees growing in the planted stands with regular understory to PF and SF, respectively (Table 2). The mechanical stability of birches in the interplanted stands exceeded that in stands on deep peat, waterlogged and freely draining mineral soils; it also was higher compared to solitary trees in greeneries [18,32,37]. Still, such differences might be partially related to site productivity, and hence stand density, which affects collective stability [12]. The occurrence of PF implies internal damages to wood fibers [34,35], which can reduce tree vitality [42,43]. Furthermore, the recovery period after such damage might be long, suggesting an accumulation of internal damages [36], thus increasing the risk of fatal failure in the long term. In the studied stand types, birch apparently differed by the trade-offs of individual and, particularly, collective stability, which is essential in high-density stands [13].

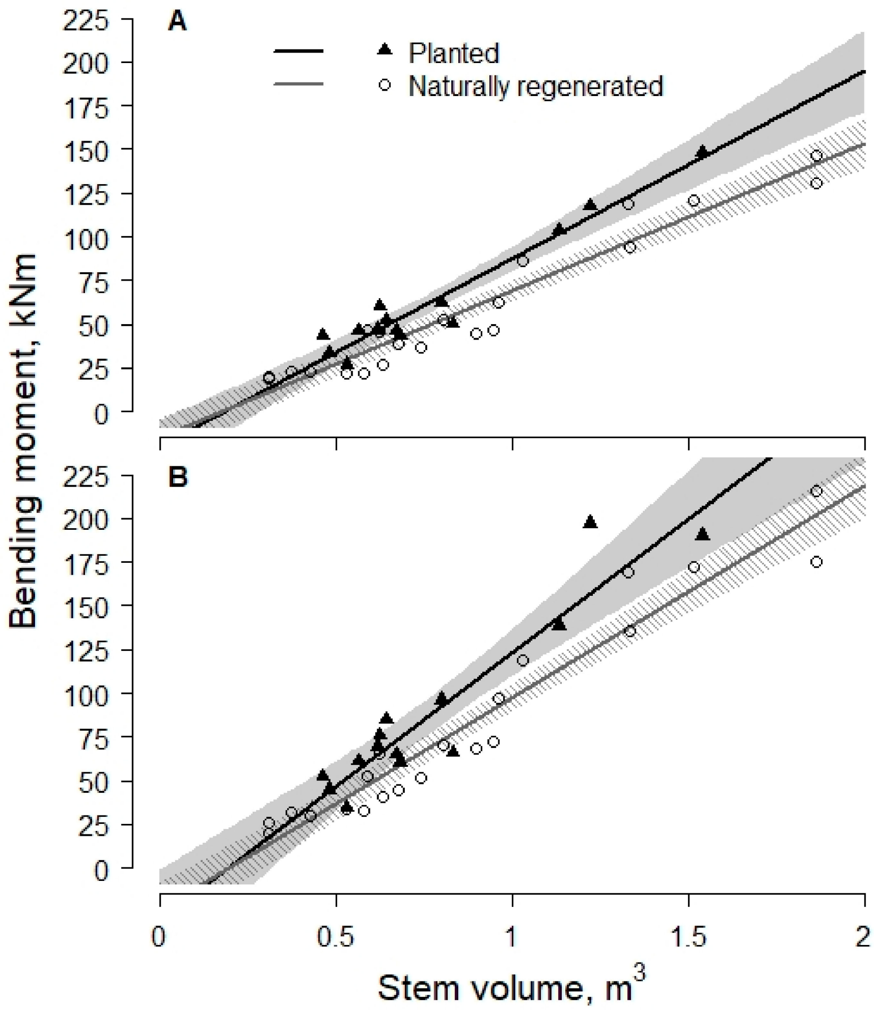


**Figure 1.** Basal bending moment of silver birch at the (**A**) primary failure and the (**B**) secondary failure. The shaded area indicates 95% confidence interval.

**Table 2.** Mean (±95% confidence interval) relationship between basal bending moment and stem-wood volume (in $m^3$) of silver birch at primary ($BBM_{PF}$) and secondary failures ($BBM_{SF}$), the modulus of elasticity (MOE) and the number of trees with stem breakage in each sampled site.

| Site No. | $BBM_{PF}$ ($kNm \cdot m^{-3}$) | $BBM_{SF}$ ($kNm \cdot m^{-3}$) | MOE (GPa) |
|---|---|---|---|
| **Planted** | | | |
| 1 | 74.5 ± 12.7 | 100.0 ± 16.8 | 16.2 ± 3.5 |
| 2 | 83.6 ± 8.5 | 119.9 ± 16.8 | 19.0 ± 2.7 |
| **Naturally Regenerated** | | | |
| 3 | 52.7 ± 7.5 | 73.7 ± 9.7 | 12.0 ± 1.6 |
| 4 | 67.2 ± 8.3 | 81.4 ± 10.8 | 9.7 ± 1.6 |
| 5 | 73.4 ± 8.7 | 105.6 ± 11.0 | 16.1 ± 2.4 |

**Table 3.** Statistics of the linear mixed-effects models characterizing basal bending moment of silver birch at the primary ($BBM_{PF}$) and secondary ($BBM_{SF}$) failures, modulus of elasticity (MOE), and soil-root plate volume ($V_{roots}$) under static loading.

| | $BBM_{PF}$ | | $BBM_{SF}$ | | MOE | | $V_{roots}$ | |
|---|---|---|---|---|---|---|---|---|
| **Predictors** | $\chi^2$ | ***p*-Value** | $\chi^2$ | ***p*-Value** | $\chi^2$ | ***p*-Value** | $\chi^2$ | ***p*-Value** |
| (Intercept) | 3.34 | 0.07 | 2.96 | 0.09 | 27.26 | <0.001 | 3.66 | 0.06 |
| $V_{stem}$ | 157.69 | <0.001 | 128.78 | <0.001 | 8.24 | <0.01 | 6.45 | <0.05 |
| Stand type | 0.53 | 0.47 | 0.51 | 0.48 | 8.84 | <0.01 | 3.23 | 0.07 |
| $V_{stem}$ by stand type | 5.39 | <0.01 | 4.98 | <0.05 | 2.55 | 0.11 | 2.07 | 0.15 |
| **Random Effects** | | | | | | | | |
| $\sigma^2$ | 95.77 | | 224.21 | | 12.45 | | 0.27 | |
| $\tau_{00}$ | 30.03 | | 79.48 | | 0.10 | | 0.08 | |
| ICC | 0.24 | | 0.26 | | 0.01 | | 0.23 | |
| $n_{site}$ | 5 | | 5 | | 5 | | 4 | |
| Observations | 35 | | 35 | | 34 | | 27 | |
| Marginal $R^2$ | 0.91 | | 0.90 | | 0.40 | | 0.44 | |
| Conditional $R^2$ | 0.93 | | 0.92 | | 0.41 | | 0.57 | |

The planted stands had significantly lower ($p < 0.001$) spacing compared to naturally regenerated stands (1.7 and 4.0 m, respectively; Table 4), as well as significantly higher ($p < 0.01$) stand basal area (Table 2), indicating a higher competition, which stimulates height growth while restricting soil-root plate size [44]. The spatial distribution of canopy trees in the stands, however, was similar (dispersed or random) irrespectively to stand type, implying that comparable processes have been shaping their structure [45]. Concomitantly, the volume of soil-root plate ($p = 0.07$) and tree height ($p = 0.86$) were similar (Tables 1 and 3), presumably indicating similar individual stability [46]. However, a regular mixture of species with different growth strategies effectively stratified the canopy in the planted stands [47], as the relatively faster-growing birch overtook the canopy, leaving more space for spruce in the understory [24]. Hence, the crowns of birch had more space, which corresponded to four times lower partial stand density (Table 4), thus stimulating individual stability [47]. The presence of a regular understory presumably provided a more homogeneous root network, thus reinforcing the soil with roots of the spruce understory [48], which is particular considering the prevailing uprooting. Spruce is also known for forming inter and intraspecific root grafts [49,50], which contribute to both collective and individual stability [13,21].

**Table 4.** Mean distance between trees within each stand and statistics of the average nearest neighbor statistic method characterizing the spatial distribution pattern within each tested stand.

| Site No. | Distance (m) | *z*-Score | *p*-Value | Spatial Distribution |
|---|---|---|---|---|
| **Planted** | | | | |
| 1 | 1.6 | 0.519 | 0.603 | Random |
| 2 | 1.7 | 5.647 | <0.001 | Dispersed |
| **Naturally** | | | | |
| 3 | 3.9 | 5.977 | <0.001 | Dispersed |
| 4 | 3.7 | 1.352 | 0.176 | Random |
| 5 | 4.5 | 9.122 | <0.001 | Dispersed |

The slenderness of trees (height–diameter ratio; Table 1), which is considered a characteristic related to susceptibility to wind damage [43], was similarly ($p = 0.29$) high in the studied stands, which might increase the risk of stem breakage rather than uprooting under dynamic stresses of an actual wind loading [51]. However, during the pulling tests, all sampled trees uprooted, which is in accordance with earlier static tree-pulling studies of birch, which showed stem breakage to be less frequent on freely draining mineral soils [18,37]. This implies that stem stiffness exceeded the strength of soil-root anchorage [43] despite a low taper. Further, it might be speculated that improved soil-root anchorage in the planted stands likely allowed trees to reallocate more assimilates to stem growth [52], thus enhancing stem resistance against elastic deformation [53]. This is suggested by significantly higher ($p < 0.05$) values of MOE (Tables 2 and 3), which, however, is affected by stand density and productivity [53–55]. Nevertheless, stem stiffness of birch in planted stands might be increased by the competition, which affects the stiffness and strength of wood without apparent changes in wood density [56]. Under such competition, the radial growth might also be interfered for understory spruce trees, resulting in higher wood density [57,58] and thus higher individual stability [59]. The effect of growth rate on the differences in stemwood stiffness [60–62] is unlikely due to the similar age and dimensions of the studied trees and stands (Table 1).

Summarizing, the studied high-density interplanting of silver birch–Norway spruce bi-culture shows the potential to increase wind stability of commercial stands by mimicking species composition following the course of natural regeneration [2,24]. Although the future commercial potential for spruce within the region is declining [63,64], its understory might still provide a valuable contribution to wind resistance and resilience of mixed commercial stands. Under sheltering in the understory, reduced transpiration [65] and wind loading [43] might also minimize the negative carry-over effects of disturbances and their interactions on spruce [42,43,66]. Furthermore, the slow-growing understory spruce is presumed to be less susceptible to pathogens [67], while species mixture also creates natural barriers to the spread of pathogens and pests [68,69]. The increase in loading resistance and comparable dimensions of trees also suggest that in interplanted (regularly mixed) birch-spruce stands thinning might be postponed, thus reducing damages and management costs [70,71].

## 4. Conclusions

The application of close-to-natural species composition in combination with regular interplanting indicated positive effects of tree species interaction on wind resilience of mixed stands (tree plantations). The hypothesis of the study was approved as the loading resistance of silver birch grown in regularly planted stands accompanied by a regular understory of Norway spruce was higher compared to naturally regenerated stands of similar composition yet with random understory. This highlights the opportunities provided by structural diversity and productive relationships for the reduction of wind damages under the intensifying storms coupled with increasing precipitation within the region. Therefore, the management of plantation forests in accordance with natural species composition could boost the wind stability, exceeding that of naturally regenerated forests, and counteract the growing risks in the future. This also implies that bi-species interplantations might be managed without thinnings, thus reducing the risk of mechanical damage to the trees before the final harvest.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f13060942/s1, Figure S1: A scheme of the destructive static pulling test setup, Figure S2: A scheme of the placement of motor-winch in the static pulling test setup.

**Author Contributions:** Conceptualization, J.V. and O.K.; methodology, J.V., O.K., S.R. and E.B.; formal analysis, D.E. and R.M.; data curation, E.B. and R.S.; writing—original draft preparation, O.K., R.M. and J.V.; writing—review and editing, R.S., S.R. and Ā.J.; supervision, Ā.J.; project administration, Ā.J. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the ERDF project "Birch and aspen stand management decision support tool for reduction of wind damages" (No. 1.1.1.1/18/A/134).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** We acknowledge the contribution of Jānis Donis with scientific discussions as well as effort by Andris Seipulis, Ilvars Ieviņš and Rolands Kāpostiņš in the field work.

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

## References

1. 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]
2. Hanewinkel, M.; Cullmann, D.A.; Schelhaas, M.J.; Nabuurs, G.J.; Zimmermann, N.E. Climate change may cause severe loss in the economic value of European forest land. *Nat. Clim. Chang.* **2013**, *3*, 203–207. [CrossRef]
3. Forzieri, G.; Girardello, M.; Ceccherini, G.; Spinoni, J.; Feyen, L.; Hartmann, H.; Beck, P.S.A.; Camps-Valls, G.; Chirici, G.; Mauri, A.; et al. Emergent vulnerability to climate-driven disturbances in European forests. *Nat. Commun.* **2021**, *12*, 1081. [CrossRef] [PubMed]
4. Oouchi, K.; Yoshimura, J.; Yoshimura, H.; Mizuta, R.; Kusunoki, S.; Noda, A. Tropical cyclone climatology in a global-warming climate as simulated in a 20 km-mesh global atmospheric model: Frequency and wind intensity analyses. *J. Meteorol. Soc. Jpn. Ser. II* **2006**, *84*, 259–276. [CrossRef]
5. Della-Marta, P.M.; Mathis, H.; Frei, C.; Lininger, M.A.; Kleinn, J.; Appenzeller, C. The return period of wind storms over Europe. *Int. J. Climatol.* **2009**, *29*, 437–459. [CrossRef]
6. Griess, V.C.; Knoke, T. Growth performance, windthrow, and insects: Meta-analyses of parameters influencing performance of mixed-species stands in boreal and northern temperate biomes. *Can. J. For. Res.* **2011**, *41*, 1141–1159. [CrossRef]
7. 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]
8. Jactel, H.; Bauhus, J.; Boberg, J.; Bonal, D.; Castagneyrol, B.; Gardiner, B.; Gonzalez-Olabarria, J.R.; Koricheva, J.; Meurisse, N.; Brockerhoff, E.G. Tree diversity drives forest stand resistance to natural disturbances. *Curr. For. Rep.* **2017**, *3*, 223–243. [CrossRef]
9. Brockerhoff, E.G.; Barbaro, L.; Castagneyrol, B.; Forrester, D.I.; Gardiner, B.; González-Olabarria, J.R.; Lyver, P.O.B.; Meurisse, N.; Oxbrough, A.; Taki, H.; et al. Forest biodiversity, ecosystem functioning and the provision of ecosystem services. *Biodivers. Conserv.* **2017**, *26*, 3005–3035. [CrossRef]
10. Mason, W.L. Are irregular stands more windfirm? *For. Int. J. For. Res.* **2002**, *75*, 347–355. [CrossRef]
11. Pukkala, T.; Laiho, O.; Lähde, E. Continuous cover management reduces wind damage. *For. Ecol. Manag.* **2016**, *372*, 120–127. [CrossRef]
12. Seidl, R.; Rammer, W.; Blennow, K. Simulating wind disturbance impacts on forest landscapes: Tree-level heterogeneity matters. *Environ. Model. Softw.* **2014**, *51*, 1–11. [CrossRef]
13. 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]
14. Bauhus, J.; Forrester, D.I.; Gardiner, B.; Jactel, H.; Vallejo, R.; Pretzsch, H. Ecological stability of mixed-species forests. In *Mixed Species Forests*; Springer: Berlin, Germany, 2017; pp. 337–382. [CrossRef]
15. Gardiner, B.; Blennow, K.; Carnus, J.-M.; Fleischer, P.; Ingemarson, F.; Landmann, G.; Lindner, M.; Marzano, M.; Nicoll, B.; Orazio, C.; et al. *Destructive Storms in European Forests: Past and Forthcoming Impacts*; European Forests Institute: Joensuu, Finland, 2010.

16. Nicoll, B.C.; Ray, D. Adaptive growth of tree root systems in response to wind action and site conditions. *Tree Physiol.* **1996**, *16*, 891–898. [CrossRef]
17. 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]
18. Krišāns, O.; Matisons, R.; Kitenberga, M.; Donis, J.; Rust, S.; Elferts, D.; Jansons, Ā. Wind resistance of Eastern Baltic silver birch (*Betula pendula* roth.) suggests its suitability for periodically waterlogged sites. *Forests* **2021**, *12*, 21. [CrossRef]
19. Gardiner, B. Wind damage to forests and trees: A review with an emphasis on planted and managed forests. *J. For. Res.* **2021**, *26*, 248–266. [CrossRef]
20. Dhôte, J.-F. Implication of forest diversity in resistance to strong winds. In *Forest Diversity and Function*; Springer: Berlin/Heidelberg, Germany, 2005; pp. 291–307. [CrossRef]
21. Bergeron, C.; Ruel, J.C.; Élie, J.G.; Mitchell, S.J. Root anchorage and stem strength of black spruce (*Picea mariana*) trees in regular and irregular stands. *For. Int. J. For. Res.* **2009**, *82*, 29–41. [CrossRef]
22. Li, Z.G.; Gong, M. Mechanical stimulation-induced cross-adaptation in plants: An overview. *J. Plant Biol.* **2011**, *54*, 358–364. [CrossRef]
23. Hynynen, J.; Niemistö, P.; Viherä-Aarnio, A.; Brunner, A.; Hein, S.; Velling, P. Silviculture of birch (*Betula pendula* Roth and *Betula pubescens* Ehrh.) in Northern Europe. *Forestry* **2010**, *83*, 103–119. [CrossRef]
24. Baders, E.; Senhofa, S.; Purina, L.; Jansons, A. Baltic forestry natural succession of Norway spruce stands in hemiboreal forests: Case study in Slitere National Park, Latvia. *Balt. For.* **2017**, *23*, 522–528.
25. Bāders, E.; Lūkins, M.; Zariņš, J.; Krišāns, O.; Jansons, Ā.; Jansons, J. Recent land cover changes in Latvia. *Res. Rural Dev.* **2018**, *1*, 34–39. [CrossRef]
26. Latvian State Forest Research Institute "Silava". National Forest Inventory of Latvia. Available online: http://www.silava.lv/petijumi/nacionlais-mea-monitorings.aspx (accessed on 7 February 2022).
27. Gailis, A.; Karklina, A.; Purvinš, A.; Matisons, R.; Zeltinš, P.; Jansons, A. Effect of breeding on income at first commercial thinning in silver birch plantations. *Forests* **2020**, *11*, 327. [CrossRef]
28. Belda, M.; Holtanová, E.; Halenka, T.; Kalvová, J. Climate classification revisited: From Köppen to Trewartha. *Clim. Res.* **2014**, *59*, 1–13. [CrossRef]
29. LEGMC Latvian Environment, Geology and Meteorology Centre. *Climate in Latvia*. 2020. Available online: https://klimats.meteo.lv/klimats/latvijas_klimats/ (accessed on 21 March 2022).
30. Jaagus, J.; Briede, A.; Rimkus, E.; Remm, K. Precipitation pattern in the Baltic countries under the influence of large-scale atmospheric circulation and local. *Int. J. Climatol.* **2010**, *30*, 705–720. [CrossRef]
31. Karagali, I.; Hahmann, A.N.; Badger, M.; Hasager, C.; Mann, J. New European wind atlas offshore. *J. Phys. Conf. Ser.* **2018**, *1037*, 052007. [CrossRef]
32. Krišāns, O.; Čakša, L.; Matisons, R.; Rust, S.; Elferts, D.; Seipulis, A.; Jansons, Ā. A static pulling test is a suitable method for comparison of the loading resistance of silver birch (*Betula pendula* roth.) between urban and peri-urban forests. *Forests* **2022**, *13*, 127. [CrossRef]
33. Hui, G.; Zhang, G.; Zhao, Z.; Yang, A. Methods of forest structure research: A review. *Curr. For. Rep.* **2019**, *5*, 142–154. [CrossRef]
34. Detter, A.; Richter, K.; Rust, C.; Rust, S. Aktuelle Untersuchungen zum Primärversagen von grünem Holz-Current studies on primary failure in green wood. In Proceedings of the Conference Deutsche Baumpflegetage, Augsburg, Germany, 5–7 May 2015; pp. 156–167.
35. Detter, A.; Rust, S.; Rust, C.; Maybaum, G. Determining strength limits for standing tree stems from bending tests. In Proceedings of the 18th International Nondestructive Testing and Evaluation of Wood Symposium, Madison, WI, USA, 24–27 September 2013; Ross, R.J., Wang, X., Eds.; U.S. Department of Agriculture, ForestService, Forest Products Laboratory: Madison, WI, USA, 2013; p. 226.
36. Detter, A.; Van Wassenaer, P.; Rust, S. Stability recovery in London Plane trees eight years after primary anchorage failure. *Arboric. Urban For.* **2019**, *45*, 279–288. [CrossRef]
37. Krišāns, O.; Matisons, R.; Vuguls, J.; Rust, S.; Elferts, D.; Seipulis, A.; Saleniece, R.; Jansons, Ā. Silver birch (*Betula pendula* Roth.) on dry mineral rather than on deep peat soils is more dependent on frozen conditions in terms of wind damage in the Eastern Baltic region. *Plants* **2022**, *11*, 1174. [CrossRef]
38. Core Team, R. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2020.
39. Bates, D.; Maechler, M.; Bolker, B.; Walker, S. Fitting linear mixed-effects models using lme4. *J. Stat. Softw.* **2015**, *67*, 1–48. [CrossRef]
40. Kuznetsova, A.; Brockhoff, P.B.; Christensen, R.H.B. lmerTest package: Tests in linear mixed effects models. *J. Stat. Softw.* **2017**, *82*, 1–26. [CrossRef]
41. Bartoń, K. MuMIn: Multi-Model Inference. Available online: http://cran.rproject.org/package=MuMIn (accessed on 19 March 2022).
42. Csilléry, K.; Kunstler, G.; Courbaud, B.; Allard, D.; Lassègues, P.; Haslinger, K.; Gardiner, B. Coupled effects of wind-storms and drought on tree mortality across 115 forest stands from the Western Alps and the Jura mountains. *Glob. Chang. Biol.* **2017**, *23*, 5092–5107. [CrossRef] [PubMed]

43. Gardiner, B.; Berry, P.; Moulia, B. Review: Wind impacts on plant growth, mechanics and damage. *Plant Sci.* **2016**, *245*, 94–118. [CrossRef] [PubMed]
44. Peet, R.K.; Christensen, N.L. Competition and tree death. *Bioscience* **1987**, *37*, 586–595. [CrossRef]
45. Forrester, D.I. Linking forest growth with stand structure: Tree size inequality, tree growth or resource partitioning and the asymmetry of competition. *For. Ecol. Manag.* **2019**, *447*, 139–157. [CrossRef]
46. Samariks, V.; Īstenais, N.; Seipulis, A.; Miezīte, O.; Krišāns, O.; Jansons, Ā. Root-soil plate characteristics of silver birch on wet and dry mineral soils in Latvia. *Forests* **2021**, *12*, 20. [CrossRef]
47. Shanin, V.; Grabarnik, P.; Shashkov, M.; Ivanova, N.; Bykhovets, S.; Frolov, P.; Stamenov, M. Crown asymmetry and niche segregation as an adaptation of trees to competition for light: Conclusions from simulation experiments in mixed boreal stands. *Math. Comput. For. Nat. Resour. Sci.* **2020**, *12*, 26–49.
48. Flepp, G.; Robyr, R.; Scotti, R.; Giadrossich, F.; Conedera, M.; Vacchiano, G.; Fischer, C.; Ammann, P.; May, D.; Schwarz, M. Temporal dynamics of root reinforcement in European spruce forests. *Forests* **2021**, *12*, 815. [CrossRef]
49. Külla, T.; Lõhmus, K. Influence of cultivation method on root grafting in Norway spruce (*Picea abies* (L.) Karst.). In *The Supporting Roots of Trees and Woody Plants: Form, Function and Physiology*; Stokes, A., Ed.; Springer: Dordrecht, The Netherlands, 2000; pp. 109–118, ISBN 978-94-017-3469-1.
50. Graham, B.F.; Bormann, F.H. Natural root grafts. *Bot. Rev.* **1966**, *32*, 255–292. [CrossRef]
51. Quine, C.P.; Gardiner, B.A.; Moore, J. Wind disturbance in forests: The process of wind created gaps, tree overturning, and stem breakage. In *Plant Disturbance Ecology: The Process and the Response*; Johnson, E.A., Miyanishi, K., Eds.; Academic Press: Cambridge, MA, USA, 2021; pp. 117–184, ISBN 9780128188132.
52. Skomarkova, M.V.; Vaganov, E.A.; Mund, M.; Knohl, A.; Linke, P.; Boerner, A.; Schulze, E.D. Inter-annual and seasonal variability of radial growth, wood density and carbon isotope ratios in tree rings of beech (*Fagus sylvatica*) growing in Germany and Italy. *Trees* **2006**, *20*, 571–586. [CrossRef]
53. Voelker, S.L.; Lachenbruch, B.; Meinzer, F.C.; Strauss, S.H. Reduced wood stiffness and strength, and altered stem form, in young antisense 4CL transgenic poplars with reduced lignin contents. *New Phytol.* **2011**, *189*, 1096–1109. [CrossRef]
54. Waghorn, M.J.; Mason, E.G.; Watt, M.S. Influence of initial stand density and genotype on longitudinal variation in modulus of elasticity for 17-year-old Pinus radiata. *For. Ecol. Manag.* **2007**, *1–3*, 67–72. [CrossRef]
55. Šilinskas, B.; Varnagiryte-Kabašinskiene, I.; Aleinikovas, M.; Beniušiene, L.; Aleinikoviene, J.; Škema, M. Scots pine and Norway spruce wood properties at sites with different stand densities. *Forests* **2020**, *11*, 587. [CrossRef]
56. Christensen-Dalsgaard, K.K.; Ennos, A.R. Effects of drought acclimation on the mechanical properties of Ochroma pyramidale, *Betula pendula* and Acacia karroo tree seedling stems. *Forestry* **2012**, *85*, 215–223. [CrossRef]
57. Koponen, T.; Karppinen, T.; Hæggström, E.; Saranpää, P.; Serimaa, R. The stiffness modulus in Norway spruce as a function of year ring. *Holzforschung* **2005**, *59*, 451–455. [CrossRef]
58. Pollet, C.; Henin, J.M.; Hébert, J.; Jourez, B. Effect of growth rate on the physical and mechanical properties of Douglas-fir in western Europe. *Can. J. For. Res.* **2017**, *47*, 1056–1065. [CrossRef]
59. 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]
60. Luostarinen, K.; Möttönen, V. Radial variation in the anatomy of *Betula pendula* wood from different growing sites. *Balt. For.* **2010**, *16*, 209–216.
61. Dunham, R.A.; Cameron, A.D.; Petty, J.A. The effect of growth rate on the strength properties of sawn beams of silver birch (*Betula pendula* Roth). *Scand. J. For. Res.* **1999**, *14*, 18–26. [CrossRef]
62. Lachowicz, H.; Sajdak, M.; Paschalis-Jakubowicz, P.; Cichy, W.; Wojtan, R.; Witczak, M. The influence of location, tree age and forest habitat type on basic fuel properties of the wood of the silver birch (*Betula pendula* Roth.) in Poland. *BioEnergy Res.* **2018**, *11*, 638–651. [CrossRef]
63. Yousefpour, R.; Hanewinkel, M.; Le Moguédec, G. Evaluating the suitability of management strategies of pure Norway spruce forests in the Black Forest area of Southwest Germany for adaptation to or mitigation of climate change. *Environ. Manag.* **2010**, *45*, 387–402. [CrossRef]
64. Čermák, P.; Kolář, T.; Žid, T.; Trnka, M.; Rybníček, M. Norway spruce responses to drought forcing in areas affected by forest decline. *For. Syst.* **2019**, *28*, 13. [CrossRef]
65. Krišāns, O.; Puriņa, L.; Mesters, D.; Kāpostiņš, R.; Rieksts-Riekstiņš, J.; Jansons, Ā. Intra-annual radial growth of European beech-a case study in north easternmost stand in Europe. *For. Stud. Metsanduslikud Uurim.* **2016**, *65*, 34–42. [CrossRef]
66. Cawley, K.M.; Campbell, J.; Zwilling, M.; Jaffé, R. Evaluation of forest disturbance legacy effects on dissolved organic matter characteristics in streams at the Hubbard Brook Experimental Forest, New Hampshire. *Aquat. Sci.* **2014**, *76*, 611–622. [CrossRef]
67. Piri, T. Early development of root rot in young Norway spruce planted on sites infected by Heterobasidion in southern Finland. *Can. J. For. Res.* **2003**, *33*, 604–611. [CrossRef]
68. Piri, T.; Korhonen, K.; Sairanen, A. Occurrence of heterobasidion annosum in pure and mixed spruce stands in Southern Finland. *Scand. J. For. Res.* **1990**, *5*, 113–125. [CrossRef]
69. 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]

70. Krišāns, 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]
71. 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]