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# Structural Root-Plate Characteristics of Wind-Thrown Norway Spruce in Hemiboreal Forests of Latvia

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**Abstract:** An increase in extreme weather events is predicted with increasing climate changes. Changes indicate major problems in the future, as Norway spruce (*Picea abies* L. Karst.) is one of the most important forestry species in Northern Europe and one of the most susceptible to damage from extreme weather events, like windstorms. Root architecture is essential for tree anchorage. However, information of structural root-plate volume and characteristics in relation to tree wind resistance in drained deep peat soils is lacking. Individual tree susceptibility to wind damage is dependent on tree species, soil properties, tree health and root-plate volume. We assessed the structural root-plate dimensions of wind-thrown Norway spruce on freely drained mineral and drained deep peat soils at four trial sites in Latvia, and root-plate measurements were made on 65 recently tipped-up trees and 36 trees from tree-pulling tests on similar soils. Tree height, diameter at breast height, root-plate width and depth were measured. Measurements of structural root-plate width were done in five directions covering 180° of the root-plate; rooting depth was measured on the horizontal and vertical axes of root-plate. Root-plate volume was higher in drained peat soils in comparison to mineral soils, and root-plate width was the main driver of root-plate volume. A decreasing trend was observed in structural root depth distribution with increasing distance from the stem (i.e., from the center to the edge of the root plate) with a greater decrease in mineral soils.

**Keywords:** root architecture; root depth; structural roots; wind resistance

## 1. Introduction

Climate change scenarios predict an increase in extreme weather events (windstorm frequency and intensity) [1]. Increasing frequency of storms causes loss of economic and ecological value in European forests [2]. Yet another effect of climate change is warming of the winter season, which causes long periods of unfrozen, wet soil [3], when tree anchorage is the weakest and wind damage probability is higher. Fully measured tree anchorage properties can help predict the response of trees to more severe climate change induced storms. Furthermore, trees deploy their roots in response to mechanical forces (slope and/or prevailing wind) by devoting increased root resources downslope and toward the windward direction to improve stability [4].

Individual tree stability varies among tree species and in regard to stand properties and tree health [5,6]. Tree rooting strategy is an important part of the general growth strategy for trees, and it determines root architecture [7]. The formation of tree roots depends mainly on the soil conditions because roots continuously adapt to the temporal and spatial fluctuations in their growth [8]. Root architecture and the size of root-soil plates determines tree anchorage and stability [7]. However, tree mechanical stability can be reduced by diseases such as root rot (*Heterobasidion* spp.) [9,10].

Norway spruce (*Picea abies* (L.) Karst.) is an economically important tree species in Northern Eurasia, including Latvia [11,12]. Norway spruce is able to grow under a wide range of soil (physical and chemical) and climatic conditions [13]. In addition, Norway spruce has a high susceptibility to windstorm damages because of its shallow root system and relatively dense crown [14–16].

Windstorms can create large gaps in forest stands, from which rapid natural regeneration emerges [17], because wind-throw damage in spruce forests causes many tree tip-ups, and root-plate volume determines the size of patches with open soil after the wind-throw. The most favorable microsites (suitable seed beds) for tree regeneration are tree-fall (root-plate) pits, tip-up mounds and logs [18–20]. However, in most cases, natural regeneration results in the establishment of dominant species other than Norway spruce [21]. In fact, spruce forms larger root-plate areas than other native tree species of the hemiboreal region [22], and thus creates large areas of open soil in the stand. After the collapse of the uprooted (tipped-up) root-ball, as the roots decay, the soil mass typically settles into the mound [23]. Thus, larger root-plate systems will create diverse microsite legacy effects.

Previous studies have analyzed root system development [8], belowground biomass [24,25], fine root or coarse root distribution in spruce stands [26,27] and mixed forest stands [26,28]. In addition, several studies of tree-pulling (winching) experiments have been conducted to assess the mechanical stability of Norway spruce [10,29,30]. However, root-plate volume for wind resistance assessment has been studied less [31], and in deep peat soils such information is even more scarce. Currently, the most common methods for root-plate measurements are direct measurements in laboratory or on site that involve excavating roots from the soil [32] and high-resolution geophysical imaging, such as ground-penetrating radar (georadar) [33]. Root measurements usually include length, density, growth angle and topological structure; however, as technology has improved, image processing has evolved to automatic detection and analysis [34]. Root distribution is dependent on soil characteristics, tree size and tree species; therefore, we assessed the root-plate volume of Norway spruce across many trees from diverse forest stands on two soil types.

The aim of the study was to assess the root-plate dimensions of uprooted Norway spruce in mineral and drained peat soils. We hypothesized that root-plate volume would be higher in drained peat soils compared to mineral soils.

## 2. Materials and Methods

This study was carried out in Latvia, with study sites located in North-West Latvia—Skede (57°14′ N 22°42′ E), Neveja (57°34′ N 22°18′ E), Central Latvia—Jelgava (56°40′ N, 23°53′ E) and East Latvia—Kalsnava (56°41′ N, 23°88′ E).

Altogether, 64 recently (no longer than 1 year) tipped-up trees by wind-throw (all available tipped-up trees in study sites) were selected for structural root-plate measurements to characterize the rooting of wind-thrown spruce trees. Materials were collected in similar stands in terms of age and parameters, such as stand density and tree dimensions of canopy trees, soil conditions, wind climate and species composition. These were pure even-aged commercial Norway spruce stands growing on freely drained mineral and drained deep peat soils (peat layer > 50 cm) [35]. In Latvia, stand density before the final harvest in such stands is reduced to approximately 700–900 trees per $ha^{-1}$. These soil types are common in Latvia, representing 51% and 12% of the soils in spruce forests, respectively [36]. The territory of Latvia is covered by a thick layer of sediments; thus, bedrock cannot limit rooting depth. In the studied sites, naturally well-drained podzolic soils formed on well-drained fine/loamy sand parent materials, and artificially drained deep peat soils were also found.

For a control, we selected data from tree-pulling (winching) tests conducted in commercial Norway spruce stands with similar characteristics as the wind-thrown stands. Control data from trees situated on drained peat soils were obtained from a study published previously [10]. For mineral soils, root-plate dimension data from pulling tests carried out in summer 2020 at the Jelgava site were used.

For each tree height (H), diameter at breast height (DBH), root-plate width, height and depth were measured (including soil particles attached) (Table 1). Structural root-plate width was measured parallel to the land surface and perpendicular to the tree stem. Root-plate surface width measurements covered 180° of the root-plate in five directions from stem side: left side (L), halfway left to center (L45), center (C), halfway right to center (R45) and right side (R) (at 0°, 45°, 90°, 135° and 180°, respectively) (Figure S1). In cases where the length of the root exceeded the length of the root-soil ball, the width was measured to the furthest root. These values were used as the radius of the root-plate for root-ball shape and volume calculations.

**Table 1.** Dimensions of sampled trees.

| Variable | | Wind-Throw | | Tree-Pulling Tests (Control) | |
|---|---|---|---|---|---|
| Site | | Neveja-Skede | Kalsnava | Jelgava | Kalsnava |
| Soil Type | | Freely Drained Mineral Soil | Drained Deep Peat Soil | Freely Drained Mineral Soil | Drained Deep Peat Soil |
| N | | 39 | 25 | 26 | 10 |
| DBH (cm) | Min | 13.0 | 23.3 | 17.8 | 26.5 |
| | Max | 50.0 | 46.5 | 42.0 | 37.7 |
| | Mean | 25.5 ± 2.7 | 31.2 ± 2.6 | 28.0 ± 2.4 | 32.0 ± 3.0 |
| Height (m) | Min | 12.7 | 21.6 | 16.9 | 24.8 |
| | Max | 32.3 | 31.7 | 33.4 | 29.6 |
| | Mean | 21.6 ± 1.6 | 26.0 ± 1.1 | 25.6 ± 1.6 | 27.2 ± 0.9 |
| Root-plate width (m) | Min | 0.3 | 0.7 | 0.9 | 3.4 |
| | Max | 3.6 | 3.5 | 3.0 | 5.5 |
| | Mean | 1.4 ± 0.2 | 2.0 ± 0.3 | 1.7 ± 0.2 | 4.5 ± 0.4 |
| Root-plate height (m) | Min | 0.2 | 1.0 | 0.5 | 1.5 |
| | Max | 1.8 | 2.4 | 2.8 | 2.5 |
| | Mean | 1.1 ± 0.1 | 1.6 ± 0.1 | 1.2 ± 0.2 | 2.1 ± 0.2 |
| Root-plate depth (cm) | Min | 9.3 | 23.3 | 26.8 | 40.0 |
| | Max | 45.5 | 82.5 | 84.0 | 80.0 |
| | Mean | 28.3 ± 2.3 | 44.7 ± 5.3 | 49.2 ± 6.6 | 57.1 ± 8.5 |

For structural root-plate depth distribution assessment, we measured roots with diameters greater than 10 mm instead of total rooting depth (due to the fact that fine roots could be found in deeper layers than coarse roots). Rooting depth was assessed on the vertical and horizontal axes (center and right), where root-plate depth, including root-soil ball, was measured (Figure S1) for assessment of the structural root depth distribution. The first depth measurement was taken as close as possible to the stem, and the rest were taken every 0.2 m.

Pearson's correlations were calculated to assess the relationship between tree size, measured and calculated variables, such as H, DBH, root-plate width, depth, volume and the relationship between H and DBH ($HD^2$). Root-plate volume was estimated based on calculating the structural root depth distribution shape using an elliptic cone volume equation:

$$V = \left(\frac{1}{3}\right) * \pi * a * b * h, \quad (1)$$

where $h$ is the mean root-plate center (0–20 cm) height (depth); $a$ is the vertical radius of the root-plate; $b$ is the mean horizontal radius of the root-plate.

Tree wind resistance was estimated using Peltola's [29] approach where tree height was multiplied by DBH squared to get an idea of tree stem susceptibility to tip-up. In the generalized additive model, relative root depth and relative distance from the stem were used as predictors to calculate structural root depth distribution. All steps of the data analysis were carried out using the statistical software R 4.0.0. [37].

## 3. Results

### 3.1. Structural Root Horizontal Surface Shape

To assume the structural root-plate horizontal surface is an ellipse, the horizontal and vertical measured width can be used to calculate the 45° angle of the actual geometric ellipse. The halfway left to center (L45) and halfway right to center (R45) radius was on average 0.89 ± 0.22 (mean ±95% CI) and 0.93 ± 0.32 (mean ±95% CI) of the center (C) height for mineral and drained peat soils, respectively. Taking into account the average of the vertical and horizontal widths, the average of L45 and R45 was 1.09 ± 0.06 (mean ±95% CI) and 1.01 ± 0.04 (mean ±95% CI) of a true ellipse in mineral and drained peat soil, respectively; thus, L45 and R45 were 9% and 1% higher than radii of an actual geometric ellipse, respectively. Therefore, we assumed that an ellipse is a good approximation of the horizontal root-plate shape.

### 3.2. Structural Root Depth Distribution of Tipped-Up Trees

Structural root-plate depth was assessed using the relative root-plate depth distribution and the relative distance from the stem (Figure 1). If the measurement point distance from the stem increased, the root-depth decreased; thus, a negative relationship ($r = -0.99$) between the distance from the stem and rooting depth was measured in both drained peat and mineral soils. No limitations to root vertical growth were observed, as no compacted soil layers were found in the studied stands or below the wind-thrown trees. In addition, the shape of the vertical roots did not indicate difficulties of penetration.

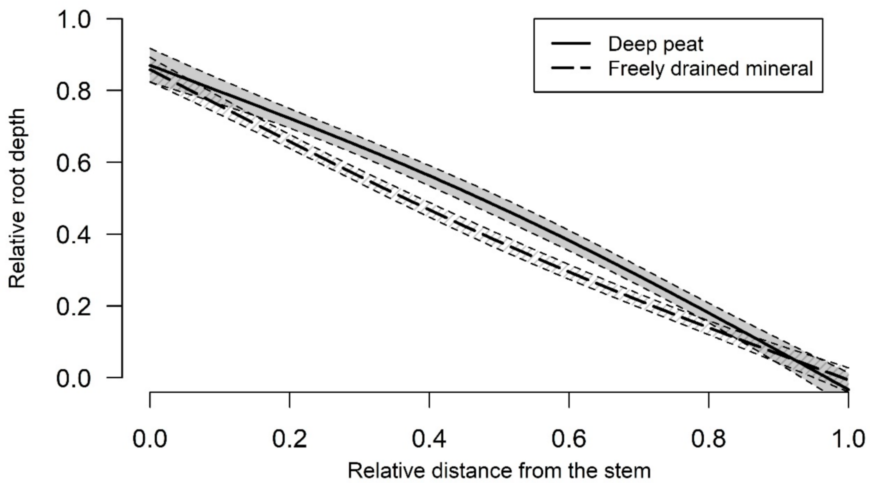


**Figure 1.** Relative structural root-plate depth distribution of measurement points at relative distance from the stem of wind-thrown trees. (Grey area denotes 95% confidence interval.)

Vertical rooting depth governs tree susceptibility to wind-throw. Mean depth at the center of the root-plate was 28.3 ± 2.3 (mean ±95% CI) cm and 49.2 ± 6.6 (mean ±95% CI) cm for mineral and drained peat soil, respectively. Mean rooting depth in the first meter (from the center to the edge of the root plate) was 22.4 ± 3.4 (mean ±95% CI) cm for mineral soil and 38.9 ± 5.8 (mean ±95% CI) cm for drained peat soil. The maximum depth values were observed in the center of the root-plate (0 cm from the stem). Maximum depth value in drained peat soils was 82.5 cm, while in mineral soils it reached the highest value of 45.5 cm. With increasing distance from the stem, relative rooting depth in mineral soil decreased more rapidly than in drained peat soils. Relative rooting depth differed significantly ($p < 0.05$) between soil types except at the center and the edge of the root-plate.

### *3.3. Root-Plate Volume*

Root-plate volume of tipped-up trees in mineral soil varied from 0.02 $m^3$ to 2.01 $m^3$, and in drained peat soil the root-plate volume ranged from 0.4 $m^3$ to 3.2 $m^3$. In tree-pulling tests (control), root plate volume ranged from 0.3 $m^3$ to 5.9 $m^3$ and from 4.0 $m^3$ to 7.6 $m^3$ in mineral and drained peat soil, respectively. The difference of root-plate volume between soil types was statistically significant ($p < 0.001$), and the results differ noticeably (Figure 2). Root-plate volume was lower for trees growing on mineral soil, while trees on drained peat soils tended to have larger values. Mean root-plate volume of tipped-up trees in mineral soil was 0.50 ± 0.14 (mean ±95% CI) $m^3$ and 1.5 ± 0.3 (mean ±95% CI) $m^3$ in drained peat soils. In addition, mean root-plate volume of control trees was significantly higher than that of root-plate volume of tipped-up trees, as the mean volume was 1.3 ± 0.5 (mean ±95% CI) $m^3$ and 5.5 ± 1.0 (mean ±95% CI) $m^3$ in mineral and drained peat soils.

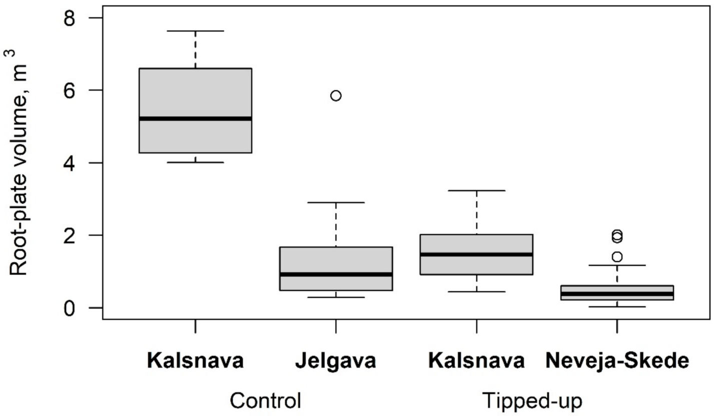


**Figure 2.** Root-plate volume of tipped-up trees and control (tree-pulling test) in two different soil types: deep peat (Kalsnava) and freely drained mineral soil (Jelgava and Neveja-Skede).

Results indicate differences in root-plate volume of tipped-up trees and trees from pulling (winching) experiments (Figures 3 and 4), as root-plate volume of tipped-up trees was significantly smaller than those of control. Differences between tipped-up and control trees were marked in both soil types; however, in drained peat soil the differences were even more pronounced (Figure 4). In addition, the mean width of the root-plate was highly correlated ($r = 0.92$) with root-plate volume; therefore, as tree roots grow wider (i.e., further from the stem), the root plate volume also increases. Moderate correlation ($r = 0.47$) was observed for root-plate center depth and root-plate width.

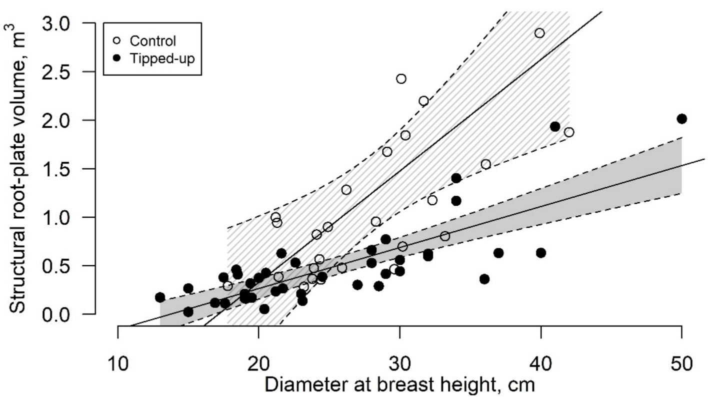


**Figure 3.** Root-plate volume *vs.* diameter at breast height in freely drained mineral soil. Grey area indicates 95% confidence interval.

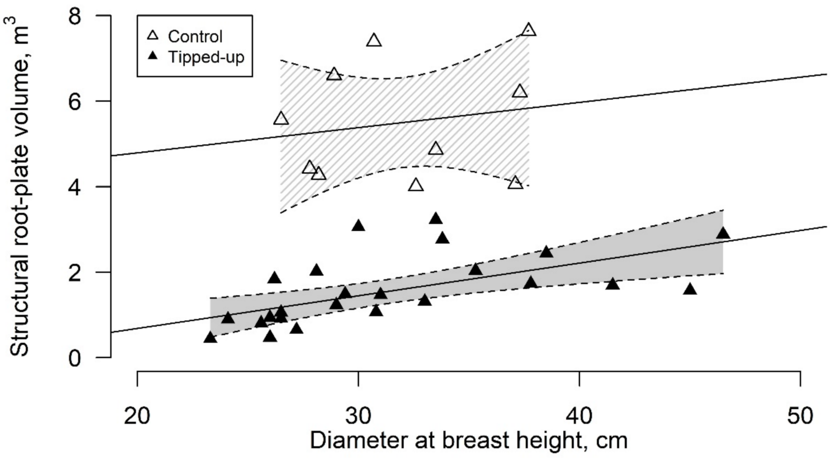


**Figure 4.** Root-plate volume *vs.* diameter at breast height in drained deep peat soil. Grey area indicates 95% confidence interval.

Our results indicate the importance of DBH in determining root-plate volume (Figure 3) and potentially in increasing tree wind resistance to uprooting from wind disturbances. Therefore, we calculated $HD^2$, which is known to indicate tree wind resistance to uprooting in mineral soils [29]. Results show the difference of tree wind resistance between soil types, as $HD^2$ values in mineral and drained peat soils were 1.94 ± 0.66 (mean ±95% CI) $m^3$ and 2.46 ± 0.57 (mean ±95% CI) $m^3$, respectively. Even though mean values for mineral soil were lower, with increasing root-plate volume, the estimated wind resistance values increased more rapidly in mineral soils in comparison to drained peat soils (Figure 5). The $HD^2$ values showed a good linear model fit as indicated by the coefficient of determination in mineral ($r^2$ = 0.84) and drained peat ($r^2$ = 0.39) soils.

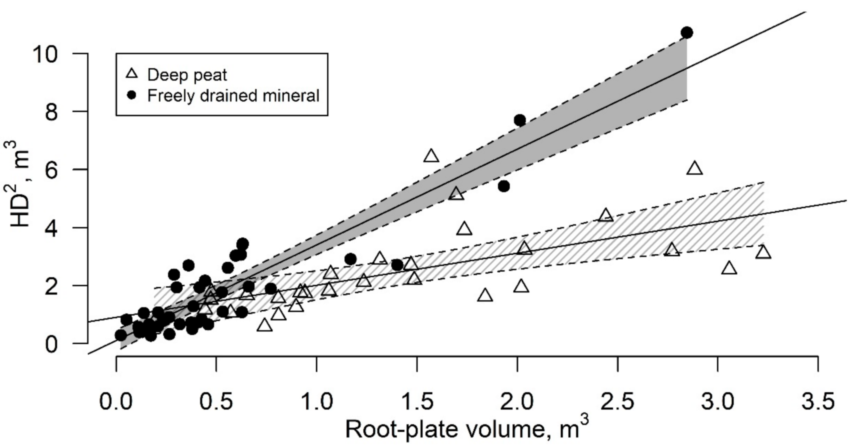


**Figure 5.** $HD^2$ in relation to root-plate volume in two soil types. Grey area indicates 95% confidence intervals.

## 4. Discussion

Assuming the structural root-plate horizontal surface shape as an ellipse was appropriate, the average lengths of L45 and R45 were only 9% and 1% larger in comparison to a true ellipse in mineral and drained peat soil, respectively. Structural root distributions provide physical stability of trees to windthrow, and deep penetration by roots is important for the anchorage; trees with varying root-plate morphologies respond differently to stress and competition [8]. The maximum depth values differed between soil types, with drained peat soils having higher maximum depth values than mineral soils. Overall, a decreasing trend was observed in structural root depth distribution with increasing distance from the stem (Figure 1). Mean depth in the center and first meter of the root-plate was higher for drained peat soils than for mineral soils; however, with increasing distance from the stem, a more rapid decrease was observed for mineral soils than for drained peat. The exception was the edge of the root-plate of drained peat soils where a rapid depth decrease in the relative rooting depth was observed. In addition, if the vertical root system is weakly developed, spruce depends on a horizontal network of supporting lateral roots [8]. With increasing tree age, the capacity of the root system to adapt or rebuild anchorage is lowered [8], thus affecting capability to recover and continually resist wind damage.

Root-plate volume in drained peat soils was more than three times higher than root-plate volume in mineral soils (Figure 2); thus, the hypothesis of the study was confirmed. This could be explained by the fact, as reported in other studies, that trees on deep peat soils flex more as trees sway and adapt their roots to the wind environment (develop eccentric cross-sectional root-system shape) and are better prepared to resist bending in the stronger winds than trees on mineral soil [30]. In both soil types, an increase in root-plate volume was observed with an increase in tree DBH (Figures 3 and 4). A close relationship between tree size parameters and root-plate system development has been reported in previous studies, where dominant large trees form the largest root systems, while average-sized trees develop well-shaped root systems and suppressed trees form poorly developed root systems [8]. Results show that the main determining factor of root-plate volume is root-plate width ($r$ = 0.92). Thus, if the root distribution (i.e., root-plate diameter) is wider, the root-plate volume is greater, as also reported in other studies [38]. With similar tree dimensions, root-plate depth and width was larger for drained peat soils in comparison to mineral soils (Table 1). Therefore, larger patches of open soil in the forest stand after wind-throw are formed by trees with larger root-plate width and by trees growing on drained peat soils than for trees with the same dimensions on mineral soil. In addition, trees adapt their root systems to the applied mechanical forces by the prevailing winds and slope and devote additional root resources towards improving tree stability, thus increasing root volume, resistance and adapting root shape [4].

Comparison of root-plate volume between tipped-up trees and control trees, as well as trees from tree winching experiments, indicates significantly higher root-plate volume compared to windthrown trees, especially in drained peat soils (Figure 4). Trees with the weakest root systems are the first ones tipped-up in storms in both soil types. However, with increasing climate change and prolonged periods of wet, unfrozen soil in the winter, the wind damage probability increases [3]. Furthermore, comparisons of data obtained from windthrows and tree-winching tests can be applied in wind risk models to improve the model parametrization of tree resistance against overturning. Nevertheless, a larger root-ball does not always ensure greater wind resistance, as root binding with drained peat soils is weaker and soil mass is lighter in comparison to root binding with mineral soils [4]. In our research, root adaptation was not studied, but root distribution against the prevailing wind direction and root shape was found to be important for wind resistance. However, there are many other factors affecting wind resistance and wind damage probability, such as tree stem and root system adaptation, soil conditions in winter, recent silvicultural measures (thinning) and even diseases such as root and stem rot (*Heterobasidion* spp.) [10,39,40].

Differences in tree wind resistance between soil types were indicated, as spruce trees on drained peat soils had larger root-plate volumes and greater mean tree wind resistance values (Figure 5). Yet, spruce on mineral soil had a more rapid increase in wind resistance values with increasing root-plate volumes, indicating higher overall wind resistance than drained peat soils. This assumption is in accordance with previous studies that show trees on drained peat soils are more susceptible to wind damage than trees on mineral soils [30]. Observed differences could be explained by differences in soil conditions, rigidity, water table depth and structural root-system architecture that might differ between forest and soil types [41,42]. In our study, we used root-plate measurement data from tipped-up trees, which introduces a systematic bias since trees with weaker root systems are uprooted in storms [40] and because some soil from the root-soil plate might be lost before the measurements, even if the measurements were done shortly after the wind-throw.

From an economic point of view, in order to reduce wind damage risks, timely applied thinning of the stands could improve and help develop larger and stronger tree root systems. In addition, low-density Norway spruce stand establishment could help to improve the root system due to reduced competition in the stand.

## 5. Conclusions

An overall decreasing trend of structural rooting depth was observed in both (mineral and drained peat) soil types, with more rapid depth decrease for mineral soils. Root-plate volume differed significantly between soil types, and it was higher for drained peat soils in comparison to mineral soil even with equal tree parameters (DBH). The width of the root-plate was the main determining factor for root-plate volume. However, tree wind resistance in mineral soils increased more rapidly with increasing root-plate volume in comparison to drained peat soils.

**Supplementary Materials:** The following are available online at http://www.mdpi.com/1999-4907/11/11/1143/s1, Figure S1: Schematic image of root-plate measurement methodology.

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

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

## References

1. IPCC. Summary for Policymakers. In *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*; Shukla, P.R., Skea, J., Buendia, E.C., Masson-Delmotte, V.H.-O., Roberts, P.D.C., Malley, J., Eds.; IPCC: Geneva, Switzerland, 2019; In press.
2. Nabuurs, G.J.; Lindner, M.; Verkerk, P.J.; Gunia, K.; Deda, P.; Michalak, R.; Grassi, G. First sign of carbon sink saturation in European forest biomass. *Nat. Clim. Chang.* **2013**, *3*, 792–796.
3. Peltola, H.; Ikonen, V.P.; Gregow, H.; Strandman, H.; Kilpeläinen, A.; Venäläinen, A.; Kellomäki, S. Impacts of climate change on timber production and regional risks of win-induced damage to forests in Finland. *For. Ecol. Manag.* **2010**, *260*, 833–845. [CrossRef]
4. Dumroese, K.R.; Terzaghi, M.; Chiatante, D.; Scippa, S.G.; Lasserre, B.; Montagnoli, A. Functional traits of Pinus ponderosa coarse roots in response to slope conditions. *Front. Plant Sci.* **2019**, *10*, 947. [CrossRef]
5. Gardiner, B.; Schuck, A.R.T.; Schelhaas, M.J.; Orazio, C.; Blennow, K.; Nicoll, B. *Living with Storm Damage to Forests: What Science Can Tell US*, 3rd ed.; European Forest Institute: Joensuu, Finland, 2013; p. 133.
6. 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]
7. Grime, J.P. *Plant Strategies, Vegetation Processes and Ecosystem Properties*; Wiley: Chichester, UK, 2001; p. 456.
8. Puhe, J. Growth and development of the root system of Norway spruce (*Picea abies*) in forest stands—A review. *For. Ecol. Manag.* **2003**, *175*, 253–273. [CrossRef]
9. Honkaniemi, J.; Lehtonen, M.; Väisänen, H.; Peltola, H. Effects of wood decay by Heterobasidion annosum on the vulnerability of Norway spruce stands to wind damage: A mechanistic modelling approach. *Can. J. For. Res.* **2017**, *47*, 777–787. [CrossRef]
10. 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]
11. Pretzsch, H.; Biber, P.; Schütze, G.; Uhl, E.; Rötzer, T. Forest stand growth dynamics in Central Europe have accelerated since 1870. *Nat. Commun.* **2014**, *5*, 1–10. [CrossRef]
12. Ministry of Agriculture. *Latvian Forest Sector in Facts and Figures 2019*; Zaļās mājas: Riga, Latvia, 2019; p. 53.

13. Puhe, J.; Ulrich, B. Global climate change and human impacts on forest ecosystems: Post-glacial development, present situation and future trends in central Europe. In *Ecological Studies—Analysis and Synthesis*; Springer: Berlin/Heidelberg, Germany, 2001; Volume 143.
14. Albrecht, A.; Hanewinkel, M.; Bauhus, J.; Kohnle, U. How does silviculture affect storm damage in forests of south-western Germany? Results from empirical modelling based on long-term observations. *Eur. J. For. Res.* **2010**, *131*, 229–247. [CrossRef]
15. Richter, C. *Wood Characteristics: Description, Causes, Prevention, Impact on Use and Technological Adaptation*; Springer Internationale Publishing: Cham, Switzerland, 2015; p. 222.
16. Lodin, I. Choice of Tree Species in the Aftermath of Two Major Storms—A Qualitative Study of Private Forest Owners in Southern Sweden. Master's Thesis, Swedish University of Agricultural Sciences, Alnarp, Sweden, 2016.
17. Šņepsts, G.; Donis, J.; Strēlnieks, K.; Krišāns, O.; Desaine, I.; Adamovičs, A. Post-storm regeneration of Norway spruce. In Proceedings of the 25th Annual International Scientific Conference "Research for Rural Development 2019", Jelgava, Latvia, 17–19 May 2019; pp. 71–75. [CrossRef]
18. Clinton, B.D.; Baker, C.R. Catastrophic windthrow in the southern Appalachians: Characteristics of pits and mounds and initial vegetation responses. *For. Ecol. Manag.* **2000**, *126*, 51–60. [CrossRef]
19. Harrington, T.B.; Bluhm, A.A. Tree regeneration responses to microsite characteristics following a severetornado in the Georgia Piedmnont, USA. *For. Ecol. Manag.* **2001**, *140*, 265–275. [CrossRef]
20. Zielonka, T. When does dead wood turn into a substrate for spruce replacement. *J. Veg. Sci.* **2006**, *17*, 739–746. [CrossRef]
21. Baders, E.; Senhofa, S.; Purina, L.; Jansons, A. Natural succession of Norway spruce stands in hemiboreal forests: Case study in Slitere National Park, Latvia. *Balt. For.* **2017**, *23*, 522–528.
22. Lõhmus, P.; Turja, K.; Lõhmus, A. Lichen communities on tree-fall mounds depend more on root-plate than stand characteristics. *For. Ecol. Manag.* **2010**, *260*, 1754–1761. [CrossRef]
23. Valtera, M.; Schaetzl, R.J. Pit-mound microrelief in forest soil: Review of implications for water retention and hydrologic modelling. *For. Ecol. Manag.* **2017**, *393*, 40–51. [CrossRef]
24. Repola, J. Biomass equations for Scots pine and Norway spruce in Finland. *Silva Fenn.* **2009**, *43*, 625–647. [CrossRef]
25. Konôpka, B.; Pajtík, J.; Šebeň, V.; Lukac, M. Belowground biomass functions and expansion factors in high elevation Norway spruce. *For. Int. J. For. Res.* **2011**, *84*, 41–48. [CrossRef]
26. Schmid, I.; Kazda, M. Root distribution of Norway spruce in monospecific and mixed stands on different soils. *For. Ecol. Manag.* **2002**, *159*, 37–47. [CrossRef]
27. Persson, H.Å.; Stadenberg, I. Fine root dynamics in a Norway spruce forest (*Picea abies* (L.) Karst) in eastern Sweden. *Plant Soil* **2010**, *330*, 329–344. [CrossRef]
28. Schmid, I. The influence of soil type and interspecific competition on the fine root system of Norway spruce and European beech. *Basic Appl. Ecol.* **2002**, *3*, 339–346. [CrossRef]
29. 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]
30. Nicoll, B.C.; Gardiner, B.A.; Rayner, B.; Peace, A.J. Anchorage of coniferous trees in relation to species, soil type, and rooting depth. *Can. J. For. Res.* **2006**, *36*, 1871–1883. [CrossRef]
31. Štofko, P.; Kodrík, M. Comparison of the root system architecture between windthrown and undamaged spruces growing in poorly drained sites. *J. For. Sci.* **2008**, *54*, 150–160. [CrossRef]
32. Moore, G.M.; Ryder, C.M. The use of ground–penetrating radar to locate tree roots. *Arboric. Urban For.* **2015**, *41*, 245–259.
33. Bristow, C.S. Ground penetrating radar in aeolian dune sands. In *Ground Penetrating Radar: Theory and Applications*; Jol, H.M., Ed.; Elsevier: Amsterdam, The Netherlands, 2009; pp. 273–297.
34. Vansteenkiste, J.; Loon, J.V.; Garré, S.; Pagès, L.; Schrevens, E.; Diels, J. Estimating the parameters of a 3–D root distribution function from root observations with the trench profile method: Case study with simulated and field–observed root data. *Plant Soil* **2014**, *375*, 75–88. [CrossRef]
35. Kennedy, F. *The Identification of Soils for Forest Management*; Forestry Commission Field Guide; Forestry Commission: Edinburgh, Scotland, 2002; p. 56.
36. NFI. National Forest Monitoring. 2018. Available online: http://www.silava.lv/petijumi/nacionlais-mea-monitorings.aspx (accessed on 10 February 2020). (In Latvian).

37. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2019; Available online: https://www.R-project.org/ (accessed on 22 April 2020).
38. Schelhaas, M.J.; Nabuurs, G.J.; Schuck, A. Natural disturbances in the European forests in the 19th and 20th centuries. *Glob. Change Biol.* **2003**, *9*, 1620–1633. [CrossRef]
39. 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]
40. Fourcaud, T.; Zhang, J.-N.; Ji, Z.-Q.; Stokes, A. Understanding the impact of root morphology on overturning mechanisms: A modeling approach. *Ann. Bot.* **2008**, *101*, 1267–1280. [CrossRef]
41. Ray, D.; Nicoll, C.B. The effect of soil water-table depth on root-plate development and stability of Sitka spruce. *Forestry* **1998**, *71*, 169–182. [CrossRef]
42. 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]