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Root-Soil Plate Characteristics of Silver Birch on Wet and Dry Mineral Soils in Latvia

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Abstract: Climate change manifests itself as a change in the probability of extreme weather events, and it is projected that windstorms will become more frequent and intense in Northern Europe. Additionally, the frequency and length of warm periods with wet, unfrozen soil in winter will rise in this region. These factors will lead to an increased risk of storm damages in forests. Factors affecting trees' resistance to wind uprooting have been well quantified for some species but not for a common and economically important tree, the silver birch (*Betula pendula* Roth.). Therefore, this study aimed to assess the root-soil plate characteristics of silver birch on wet and dry mineral soils in hemiboreal forests. The root-soil plate and aboveground parameters were measured for 56 canopy trees uprooted in destructive, static-pulling experiments. The shape of the root-soil plate corresponds to the elliptic paraboloid. A decreasing yet slightly different trend was observed in root depth distribution with increasing distance from the stem in both soils. The main factors determining root-soil plate volume were width, which was notably larger on wet mineral soils, and tree diameter at breast height. Consequently, the root-soil plate volume was significantly larger for trees growing on wet mineral soils than for trees growing on dry soils, indicating a wind adaptation.

Keywords: climate change; root distribution; root-plate; wind resistance; windthrow

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1. Introduction

Storm damage intensity (primary damage/total growing stock) in Europe increased notably and significantly in the last three decades, indicating the impact of climate change on the North Atlantic weather system [1]. It is projected that the frequency of extreme weather events, including windstorms, will increase in the near future [2]. These storms will lead to lost productivity and carbon stock in forests, causing notable economic damages, as well as reduced value of other ecosystem services [3–5]. One of the effects of climate change is the projected warming of the winter season, causing longer and more frequent periods of wet, unfrozen soil [3]. In such conditions, tree anchorage in the soil is weak. In the future, with increasing climate change, northern forests are expected to be more susceptible to wind impact during summer thunderstorms and extra-tropical cyclones [6,7].

The risk from climate change impacts on forest stand and individual tree susceptibility to wind damage is determined by the interaction of vulnerability, exposure, and hazards [8]. In the case of forest damage caused by a storm, hazard corresponds to strong winds and heavy rain, exposure implies the presence of forest ecosystems in places and settings that could be damaged, and vulnerability is the forest susceptibility to strong winds. Thus, a non-fragmented landscape (in terms of tree height) and the absence of new edges reduces the probability of damage [8–10]. Susceptibility is also affected by stand characteristics (for example, stand density and structure, tree species and composition, tree dimensions, crown, and root architecture) and soil conditions [3,7]. Forest management also affects wind stability—damage will most likely occur in recently thinned stands or stands next to new clear-cut areas [11].

The mechanical stability of a tree is proportional to the weight of the root-soil plate—larger below-ground biomass provides stability, which depends on the root-soil plate volume and the granulometric composition of the soil. Additionally, stability is affected by the anchorage of roots in the soil (ensuring that the root-soil plate remains compact, depending on soil type and condition) and the mechanical strength of roots, especially, the lateral roots [12]. Adaptation to windier conditions (or higher wind-load in general, such as growing on steep slopes) or to ensure survival on less stable soils usually leads to changes in root parameters [13]. The mechanical strength of the root system is dependent on root-plate width (radius) and depth [14], as well as the ratio between different root types and parameters of individual roots. Individual roots and the root location influence the tree's mechanical stability [13]; trees tend to develop oval or I-beam roots in response to steep slopes and wind [15] to maintain anchorage. High soil moisture content notably reduces tree stability due to loose soil–root contact, and high groundwater levels affect the rooting depth [6].

Silver birch (*Betula pendula* Roth.) is widespread in Eurasia, and it is an economically important tree species [16,17]. Birch is a light-demanding, early successional pioneer species with high morphological plasticity [9]. Birch has a plate root system, described as shallow, yet wide [14]. The main elements of the plate root system are the large lateral roots, which at first descend diagonally from the stump and then continue to grow horizontally, before tapering and branching into narrower absorption roots [18]. The second important element in plate root systems is the sinker roots which emerge vertically from the lateral roots and branch downwards into the subsoil to strengthen the anchorage of root systems [18]. Plate root systems maximise mechanical leverage by increasing the length of lateral (horizontal) roots growing away from the stump to maximise the effective moment arm of resistance forces [14]. Wide horizontal distribution of root systems serves as the major resistance to windthrow under wet soil conditions [19]. In addition, birch is more susceptible to uprooting than Scots pine (*Pinus sylvestris* L.) but less susceptible to stem breakage [20].

Several models are used to predict tree susceptibility to wind damage [21–23]. The models are as good as the data used for their construction. Limited information about birch from tree pulling experiments is available [20]. Therefore, our study aimed to assess the root-soil plate characteristics of silver birch on dry and wet mineral soils in hemiboreal forests. We hypothesised that root-plate depth and volume would be affected by soil.

2. Materials and Methods

The study material was collected in silver birch-dominated (70–100% of standing volume in canopy layer) stands in hemiboreal forests in central Latvia (56°31′–40′ N, 22°58′–23°53′ E). The climate is described as temperate, with a strong influence of the Baltic Sea and North Atlantic. According to the Latvian Environment, Geology, and Meteorology Centre data (during 1981–2010) the mean annual sum of precipitation was 692 mm. The mean annual air temperature was +6.4 °C; the coldest month was February (−3.7 °C), and the warmest was July (+17.4 °C) [24]. The dominant winds in the Baltic region are the westerlies, and the strongest windstorms occur in winter and autumn seasons [25]. Even-aged stands with no recent (last 10 years) management were selected randomly from the research forest inventory database to represent the diameter distribution typical of middle-aged and mature (30–60 years old) birch forests in our country. Selected stands were located in relatively flat areas (without slope effect) in elevations between 100 and 200 m above sea level. Stands were divided into two groups based on forest type and gravimetric water content (GWC_{soil}) in soil: dry—fresh mineral soil, *Hylocomiosa* forest type [26] and wet—wet (periodically waterlogged) mineral soils, *Myrtilloso-sphagnosa* forest type [26]. Dry mineral soils are characterised as deep podzolic soils with variable soil texture: sand with abundant silt, clay sands, and compact clay. Forest litter and the fibric humus layer are thin. Wet mineral soils are characterised as rich, not well aerated, deeply podzolised or gleyed mineral soils. The organic horizon is thick fibric humus litter, and soil parent material is sand, often with a clay layer (clay-sands or clay) [26].

Destructive static tree-pulling experiments were carried out (for more details, see [27]) to uproot the trees and assess the root-plates. The pulling line was anchored at 50% of the total tree height. Before performing pulling tests, every sample tree was topped 1 m above the pulling line to exclude the influence of wind and canopy weight on the measurements. Static pulling tests were performed using a manual winch (working load limit 32 kN) and a steel cable anchored at the ground level of the opposite tree.

Root-plate measurements were performed for every uprooted tree. Altogether, 46 trees were analysed from dry mineral soil and 10 trees from wet mineral soil with a similar mix of diameters. For each tree the height (*H*), diameter at breast height (*DBH*), root-soil depth (from the ground surface to the depth of roots with a diameter greater than 1 cm), and width (from the centre to the edge of the root plate) were measured (including soil particles attached) (Table 1). Root-plate surface width measurements covered 180° of the root-plate in five cardinal directions from the stem side: left side (L), halfway left to the centre (L45), centre (C), halfway right to centre (R45), and right side (R) (at 0°, 45°, 90°, 135°, and 180°, respectively) (Figure 1). Root-plate cardinal directions did not correspond to actual geographic azimuth. In cases where the root length exceeded the root-soil plate length, the width was measured to the furthest root. These values were used as the radii of the root plate for root-plate shape and volume calculations. Rooting depth was assessed on the vertical and horizontal axes (at 90° and 180°, respectively), where the rooting depth of root-soil plate was measured (Figure 1) 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.

Table 1. Dimensions of sampled trees (N—number of samples, DBH—diameter at breast height, H —tree height, root-soil plate parameters (width and depth), and soil gravimetric water content (GWC_{soil}) in wet and dry mineral soils).

Variable	Dry Mineral Soil			Wet Mineral Soil		
	Min	**Max**	**Mean (±95% CI)**	**Min**	**Max**	**Mean (±95% CI)**
N		46			10	
DBH (cm)	13.6	27.4	22.19 ± 0.95	15.7	27.5	22.37 ± 2.72
H (m)	18.3	31.4	25.13 ± 1.08	17	27.3	21.86 ± 2.41
Root-plate width (m)	0.45	1.9	1.05 ± 0.04	0.5	2.35	1.48 ± 0.10
Root-plate depth (m)	0.05	1.0	0.52 ± 0.02	0.1	0.9	0.52 ± 0.3
GWC_{soil} (%)	6.5	26.6	16.9 ± 8.4	24.6	83.7	38.9 ± 19.3

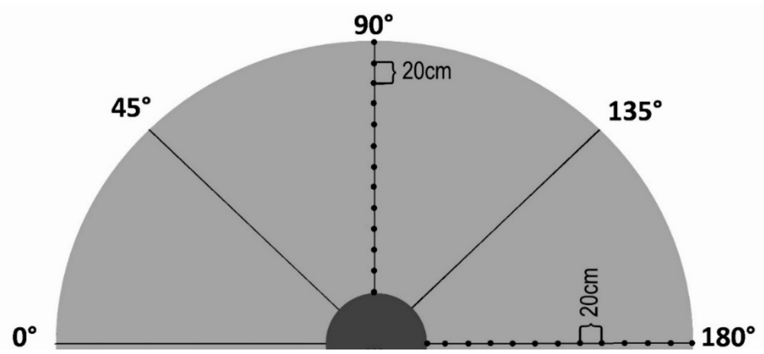

Figure 1. Root-soil plate measurement methodology [28] (light grey half-circle—root-soil plate surface; dark grey half-circle—tree stem; black dots—depth measurement points; black lines at cardinal directions—width measurement distance).

Root-plate volume was estimated based on the structural root depth distribution, using an elliptic paraboloid volume equation:

$$V = \left(\frac{1}{2}\right) \times \pi \times a \times b \times h \quad (1)$$

where h is the mean root-plate centre depth; a and b are the longest and shortest mean radius of the root-plate width, respectively.

A linear mixed-effect model was used to evaluate stand- and tree-level factors affecting root-soil plate volume and wind resistance estimate. The model was based on soil condition (wet or dry), and the study stand was used as the random effect:

$$y_{ij} = \mu + cond_{ij} + stand_j + \varepsilon_{ij} \quad (2)$$

where $cond_{ij}$ is the soil condition (two levels); $stand_j$ is the random effect of the selected forest stand.

The overall significance of the model was estimated using the maximum likelihood approach.

Pearson's correlations were calculated to assess the relationship between measured and calculated variables (H, DBH, tree wind resistance (HD^2), and root-plate width, depth, volume). Tree wind resistance (HD^2) to uprooting was estimated using Peltola's [20] approach, where tree height was multiplied by DBH^2 to determine tree stem susceptibility to wind damage. A generalised additive model was used to calculate structural root depth distribution, where relative root depth and relative distance from the stem were used as model predictors. All steps of the data analysis were carried out using the statistical software R 4.0.0. [29].

3. Results

3.1. Root-Soil Plate Depth Distribution

Rooting depth is an important factor affecting tree resilience to windthrows [14]. The maximum depth values (0.9 and 1.0 m) were observed in the first 20 cm from the centre of the root-plate on wet and dry mineral soil, respectively; thus, the deepest rooting was observed close to the centre of the root plate in both analysed soils. The mean depth in the centre of the root-soil plate was 0.72 $\pm$ 0.04 m (mean $\pm$ 95% CI) and 0.78 $\pm$ 0.08 m (mean $\pm$ 95% CI) on dry and wet mineral soil, respectively, but the mean depth in the first metre (from the centre) of the root was slightly deeper in wet mineral soils (0.60 $\pm$ 0.03 m) compared to dry (0.55 $\pm$ 0.02 m).

The relative root-soil depth and relative distance from the stem were used as model predictors to assess the root-soil depth distribution of birch (Figure 2). The study data confirm the strong, negative linear relationship ($r = -99$) between relative root-soil depth and relative distance from the stem in both analysed soils. At the edge of the root-soil plate, relative rooting depth was 15% and 17% of the total rooting depth on dry and wet mineral soils.

To assume the root-plate ground surface shape as an ellipse, the horizontal and vertical width can be used to calculate the 45° angle of an actual geometric ellipse. The mean of the 45° and 135° angle width of the root plate was 1.02 $\pm$ 0.04 and 1.10 $\pm$ 0.08; thus, L45 and R45 were 2% and 10% larger than radii of an actual geometric ellipse on dry and wet mineral soils. Based on this information, we assumed that an ellipse was a good approximation of the horizontal root-plate surface shape. In addition, based on the assessed information about relative root-soil depth distribution and ground surface shape (Figure 2), the assumption of the root-soil plate volume equation as elliptic paraboloid was appropriate.

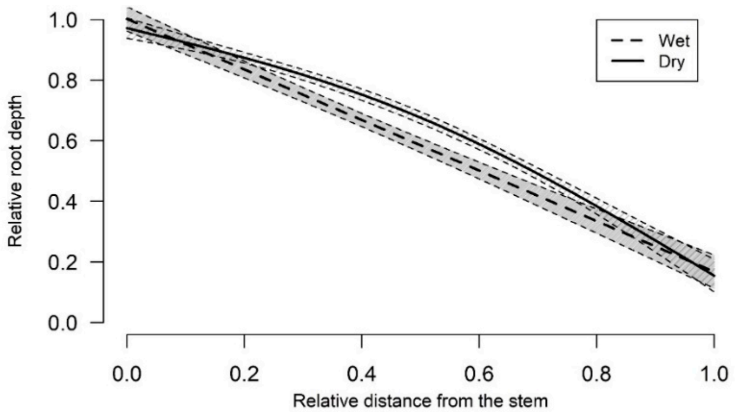

Figure 2. Relative root-soil plate depth distribution at a relative distance from the stem on wet and dry mineral soils. The grey area denotes 95% confidence interval.

3.2. Root-Plate Volume

Root-plate volume on dry mineral soil ranged from 0.41 m^3 to 3.80 m^3, and the mean value was 1.28 ± 0.22 m^3 (mean ± 95% CI). On wet mineral soil, the root-plate volume ranged from 0.65 m^3 to 3.95 m^3; the mean value was 2.40 ± 0.71 m^3 (mean ± 95% CI). The difference between root-plate volume on dry and wet mineral soils was statistically significant ($p < 0.05$); a similar tree (by size) is supported by a notably larger root-soil plate on wet soils. The random effect of stand accounted for ca. 30% of the variance in volume, indicating individuality and, therefore, an influence of stand-level factors. The root-soil plate volume and *DBH* had moderate correlation ($r = 0.52$; $r = 0.61$) on dry and wet mineral soil, respectively (Figure 3). However, root-plate volume had a high correlation ($r = 0.89$; $r = 0.82$) with mean root-plate width on dry and wet mineral soils, respectively.

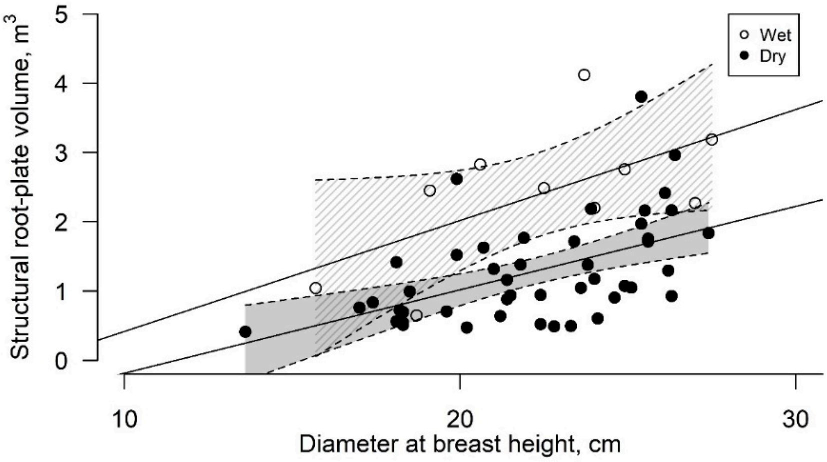

Figure 3. Root-plate volume against diameter at breast height on wet and dry mineral soils. The grey area denotes the 95% confidence interval.

HD^2 was calculated to indicate tree wind resistance to uprooting in mineral soils [20]. Tree wind-resistance values varied from 0.35 to 2.36, and the mean value was 1.30 ± 0.14 (mean ± 95% CI) on dry mineral soil. On wet mineral soils, the tree wind-resistance value ranged from 0.42 to 2.06, and the mean value was 1.16 ± 0.37 (mean ± 95% CI). The results present a moderate correlation ($r = 0.42$; $r = 0.54$) between HD^2 and root-soil plate volume on dry and wet mineral soils, thus with increasing root-plate volume, an increase in HD^2 can be observed in birch stands on mineral soils (Figure 4). However, no statistically significant difference was found ($p > 0.05$) between soils.

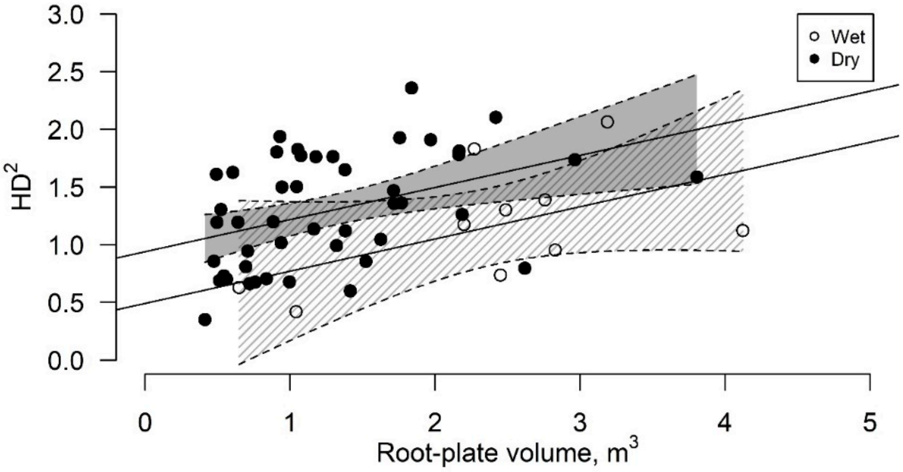

Figure 4. Tree wind-resistance indicator (HD^2) in relation to root-plate volume on wet and dry mineral soils. The grey area denotes 95% confidence interval.

4. Discussion

The stability of a tree to resist windthrows is determined by its dimensions, relative crown height, and well-established root system that provides anchorage and ensures structural support [12]. In our study, assumption of the structural root-soil plate shape as an elliptic paraboloid was appropriate as indicated by relative root depth distribution shape and the fact that length of L45 and R45 were only 2% and 10% larger than a true ellipse on dry and wet mineral soils, respectively (Figure 2). The deepest root distribution was found close to the centre of the root-plate, and root depth at the edge of the root-soil plate on dry and wet mineral soil decreased to 15% and 17% of the total rooting depth, respectively. In contrast to our hypothesis, periodic waterlogging on wet mineral soils had no significant effect on the depth of roots [30]. A close negative relationship ($r = -99$) between relative root depth and relative distance from the stem in both soil types was observed. Statistically significant differences were observed between trees on wet and dry mineral soils for root-plate width, but not for depth (Table 1). Even so, the average roots close to the stump (in the first metre) were slightly deeper (depths of root-soil plate larger) in wet soils than dry. In general, thick and large taproots have anchoring properties that prevent uprooting. However, horizontal distribution of the root system serves as a major resistance to windthrow under wet soil conditions [19,31]. Large trees generally cannot rely solely on taproots and need to develop thick lateral roots to prevent uprooting [32]. Our study results are in accordance with [19,31,32] as horizontal rooting was greater in wet mineral soils compared to dry. This result indicates adaptation [14,19] in conditions with a higher groundwater level and lower mechanical stability—a more frequent and longer period of periodically waterlogged soils, and thus relatively weaker root–soil contact.

In our study, the *DBH* of silver birch had a moderate correlation with root-plate volume (Figure 3). A direct close relationship between root-plate volume and tree *DBH* has been found for European beech (*Fagus sylvatica* L.) and Norway spruce; thus, *DBH* can be used to predict root-system volume and biomass [28,33]. The findings are in accordance with several other studies [15,20,23,34,35] that found a direct relationship between tree aboveground parts (*DBH, H*) and various tree wind-resistance predictors in mineral and organic (peat) soils. However, in those studies, the relationship was close instead of moderate as in our study. This finding suggests different adaptation mechanisms to various local wind conditions for different tree species, which affect the reaction manifested by different root system traits, such as root-ball shape or the size of the root-soil plate. The main root-plate volume-determining factor for birch is root-plate width, as indicated by the strong correlation ($r = 0.89$; $r = 0.82$) between variables on dry and wet mineral soils. In addition, the random effect of forest stand accounted for ca. 30% of the variance of root-plate volume, which could be explained by differences in stand density and exposure to wind. Trees often subjected to wind form larger (wider) root systems to improve stability. The results indicate that root-soil plate volume on wet mineral soils is significantly higher than on dry mineral soils with the same *DBH* values. Similar results have been reported for Norway spruce in previous studies [28], where trees on wet and organic soils tend to have a larger root-plate volume to provide stronger linkage between roots and soil [36–38]. Our study hypothesis was partly confirmed, as root-plate volume significantly differed between soil types, but mean rooting depth in the centre of the root plate was equal, with slight differences in the first metre.

With increasing root-plate volume, an increase in tree wind resistance was observed (Figure 4), and the relationship between HD^2 and root-plate volume was moderate (r = 0.42; r = 0.54) on dry and wet mineral soils. However, the differences between soils were not statistically significant, which could be explained by a relatively small data set and large variation for wet mineral soils. Therefore, further research is needed on root characteristics in wet mineral soils. The determined difference between analysed soils could be explained by disparity in soil conditions, water table depth, and rigidity and structural root system architecture that might differ at the stand or forest scale [38,39]. Despite the larger tree root systems (in terms of volume and width) in wet mineral soils, the wind resistance is still lower compared to dry mineral soils. This finding could be explained with results obtained in other studies showing that high soil moisture content reduces tree stability and anchorage due to loose soil–root contact [6]. Observed results indicate that management practices that expose stands to even minimal wind risk can result in serious damage for stands growing on wet mineral soils. Lower initial stand density or less frequent commercial thinning can reduce such risk.

5. Conclusions

The root-soil plate shape of silver birch corresponds to an elliptic paraboloid. A close negative relationship between relative root-soil depth and relative distance from the stem was observed in both analysed soil groups. Mean rooting depth did not differ between soils; thus, root-plate width was the main factor resulting in notable and statistically significant root-soil plate volume differences between wet and dry mineral soils. Tree wind-resistance values are higher on dry mineral soils, and trees with larger root-soil plates are less prone to wind damage as tree wind resistance increases with root-plate volume increase. Thus, the results indicate a natural adaptation by increasing the root area to improve tree stability in soil conditions where root-soil anchorage is reduced.

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

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