




Article

Wind Resistance of Eastern Baltic Silver Birch (*Betula pendula* Roth.) Suggests Its Suitability for Periodically Waterlogged Sites

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Abstract: Storms and wind damage are the main cause of biomass loss in forests of Northern Europe, as well as they are synergic with the disturbances causing intense water and temperature stress. This highlights the necessity for climate-smart management at landscape level coupling ecological demands of forestry species with their wind resistance. Silver birch (*Betula pendula* Roth.), which is highly plastic species, appears to be promising for a wider application under such conditions, as it is believed to tolerate wide range of weather conditions. Though silver birch can be sensitive to water deficit and windthrow, local information on its wind tolerance in sites with different moisture regimes is advantageous. Mechanical stability of 71 mid-aged silver birches (*Betula pendula* Roth.) growing in seven dry (*Hylocomiosa*) and five periodically waterlogged (*Myrtilloso-sphagnosa*) sites with mineral soils in Latvia (hemiboreal lowland conditions) were assessed by the destructive static pulling tests. Site type had a significant, yet intermediate effect on the stability of silver birch. As expected, trees under periodically waterlogged conditions were more prone to collapse under static loading, however, they showed a better resistance to primary failure (beginning of wood structure deformation). Uprooting was the most common form of tree collapse. Surprisingly, considering similar root depths, stem breakage was more frequent in the periodically waterlogged than dry sites (21.9 vs. 5.1%, respectively), indicating high loading resistance of roots, supporting high plasticity and wind resistance of the studied metapopulation of silver birch. Nevertheless, in the periodically waterlogged sites, the difference between forces needed to cause primary and secondary (collapse) failures of stem decreased with age/size, implying necessity for optimization of rotation length. Accordingly, quantification of wind resistance can aid climate-smart selection of species for forest regeneration depending on landscape, suggesting birch as wind resistant option under periodically waterlogged conditions.

Keywords: wind storm; natural disturbance; basal bending moment; primary failure



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1. Introduction

Climate changes are subjecting forests of Northern Europe to a spectrum of intensifying natural disturbances such as storms, temperature stress, and droughts [1], which often have synergic legacy effects [2,3]. For instance, droughts weaken trees, making them more susceptible to windthrow (wind damage), while intrinsic wood damage following storms in turn can make trees more prone to droughts and their legacy effects [2,4]. Such effects are further enhanced by the extending frost-free (unfrozen soil) periods, which make forests particularly prone to wind damage [5–7], highlighting the key role of storms

regarding sustainability of northern forests [1,8]. The synergic enhancement of the influence of natural disturbances in combination with growing area of forests, particularly in hemiboreal zone [9,10], is resulting in growing economic consequences [11] and reduced productivity of forests [1]. Accordingly, adaptive (climate-smart) management is necessary to counteract growing negative effects of natural disturbances, ensuring sustainability of future forests [12].

Climate-smart selection of reproductive material according to landscape specifics is one of the means for improving resilience of forests [13], which is knowledge-intensive. For instance, coupling site properties (e.g., fertility, soil moisture regime) with the ecological demands of a species can minimize effects of water deficit and temperature stress [14]. Although in waterlogged sites trees are less prone to drought, they are also more susceptible to wind due to limited rooting depth and decreased root-soil anchorage [5,15,16], which is particular when soil is not frozen [5,6]. Hence, climate-smart selection of the reproductive material (species or provenances) minimizing risks due to both wind and water shortage is particularly topical [17–19], especially considering the increasing frequency of gale days in the hemiboreal zone [6,10,20,21].

The mechanical stability, hence wind resistance of a forest stand depends on each individual tree as the failure of a single trees can initiate the collapse of the whole stand [22,23]. Accordingly, species, dimensions, and especially stand characteristics, such as soil, are principal factors determining collective stability of trees [8,24,25]. Among these, soil moisture regime is crucial for wind damage [26–28], as contact between roots and soil is determined by structure, density, and actual moisture of soil which concomitantly affects the distribution (depth and width) of roots [15,16].

Static tree-pulling testing is widely used method to assess tree mechanical stability by examining the strength of root anchorage and stem durability under physical loading [16,29]. Thus, such tests can indicate the level of susceptibility to potential wind damage on forest stands. Considering the expected extension of periods with increased risk of wind damage [5], it is crucial to estimate tree loading resistance for commercially important deciduous trees under different soil moisture regimes. Furthermore, defoliated deciduous trees (during the dormant period) are prone to failure under wind loading [7]. However, the effects of stand factors on the vulnerability of forest to wind damage cannot be widely extrapolated, raising a necessity for information regarding diverse growing conditions [16,24].

In the southern boreal and hemiboreal forests, silver birch (*Betula pendula* Roth.) is a common tree species with high economic and ecological value [22,23,30]. Birch is a shade-intolerant pioneer tree species with high morphological plasticity [15,31,32], which is believed to tolerate a wide range of weather conditions, though show some sensitivity to water deficit in summer [33]. Therefore, more extensive use of this tree species in commercial forests following the adaptive management approach is expected under the changing climate in the future [30]. Considering the synergic effects of natural disturbances [2,3] and occasional sensitivity to water deficit [33], it is important to assess and quantify the mechanical stability of the most productive birch stands on both, dry and periodically waterlogged sites. Such information is beneficial to improve the accuracy of wind damage assessment as well as for the adaptive forest management (and policy decision support) [16,24,34].

Although in Northern Europe the information about the most appropriate management practices to maintain high productivity and resilience of birch forests is highly valuable, only a small number of sample trees of this species in boreal forests has been tested for mechanical stability [34]. Extrapolation of the data to other regions and site (soil) conditions, however, may lead to substantial bias due to local specialization of metapopulations of trees [32,35], highlighting the necessity for local information. Accordingly, the aim of the study was to evaluate the mechanical stability of birch growing in mesotrophic stands (on mineral soils) with different moisture regimes (dry and periodically waterlogged). We hypothesize that trees would have reduced mechanical stability when growing

in periodically waterlogged sites due to shallower rooting depth and weaker root-soil anchorage [36], thus facilitating uprooting.

2. Materials and Methods

2.1. Study Site and Sample Trees

The study was conducted in the hemiboreal zone [37] in Latvia, where forests occupy ca. 50% of the territory, among which ca. 19% are periodically waterlogged. According to data from the national forest inventory, silver birch, Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) H.Karst.) are the main tree species forming most of the standing volume. Silver birch is common species in the periodically waterlogged sites. Both pure and mixed stands of these species are common. Forest landscape can be described as highly fragmented [38]. Forest patches are mixed with agricultural land, as well as forest areas are fragmented in terms of stand structure and age [38].

The climate in Latvia is temperate, with a strong influence of the Baltic Sea and North Atlantic. According to the Latvian Environment, Geology, and Meteorology Centre (LEGMC) data, during the period 1981–2010, the coldest month was February (-3.7 °C), the warmest July ($+17.4$ °C), and the mean annual temperature was $+6.4$ °C. The annual sum of precipitation has slightly increased during the last 60 years, reaching 692 mm with a monthly mean maximum in July (77 ± 37 mm). A gradual decrease of monthly mean sum continues till mid-spring as 34 ± 22 mm is reached in April. However, a notable decrease in soil moisture begins in May, along with the increase in evapotranspiration. Stable snow cover forms around mid-December and lasts until mid-March, though it varies annually. Snow cover lasts ca. two weeks longer in the inland part of the country. The climate changes are expressed as warming (by ca. 0.7 °C during the recent 30 years) particularly during the autumn-spring period, hence as an extension of vegetation as well as frost and snow free periods [39]. This is coupled with increasing heterogeneity of summer precipitation regime [39,40].

In the Baltic region, the dominant winds are the westerlies, which bring cool and warm air masses from the Atlantic across the Baltic Sea [10,24]. The mean annual wind velocity ranges 2.6 – 4.1 ms^{-1} in the inland and coastal parts of the country. The inter-annual distribution of winds is heterogeneous, with the strongest windstorms with wind velocities > 20 ms^{-1} occurring almost annually in the October–December period [41], particularly in the western (coastal) part of the country [42]. During summer, particularly July and August, winds exceeding 20 ms^{-1} occur locally (affecting few km^2 of area) during thunderstorms [43], irrespectively of the distance from the sea [42]. The storminess also shows an explicit intensifying trend, both in frequency and strength of storms causing increasing damage to forests in autumn and summer periods across Northern Europe [10,20,44].

Three study localities in the research forests—Skede ($57^{\circ}13'$ N; $22^{\circ}48'$ E), Auce ($56^{\circ}25'$ N; $22^{\circ}46'$ E) and Kalsnava ($56^{\circ}41'$ N; $22^{\circ}54'$ E), represent increasing distance from the Baltic sea, hence decreasing wind loads were selected. For the study, sites (stands) without recent (last 10 years) management were chosen randomly to represent the diameter distribution common for middle age to mature birch situated in the mid-part of forest district. All studied sites were dominated by birch ($\geq 70\%$ of standing volume) though some admixture of grey alder (*Alnus incana* (L.) Moench), Norway spruce, common aspen (*Populus tremula* L.) or oak (*Quercus robur* L.) was also present (Table 1). All sampled sites were located in relatively flat areas without slope effects in elevation between 100 and 220 m above mean sea level, which covers most of the Latvia's elevation gradient (maximum absolute elevation of 312 m. a.s.l.).

Table 1. Tree species composition (number in brackets show relative amount according to standing volume), mean (\pm standard deviation) diameter at breast height (DBH), height (H), and stem-wood volume (V_{stem}) of sample trees (Tree N), root depth, and the mean (\pm standard deviation) gravimetric water content of soil (GWC_{soil}) of each sampled site. Tree species abbreviated as follows: A—common aspen (*Populus tremula* L.); B—birch (*Betula pendula* Roth.), G—grey alder (*Alnus incana* (L.) Moench.); O—pedunculate oak (*Quercus robur* L.) and S—Norway spruce (*Picea abies* (L.) H. Karst.).

Site No.	Locality	Composition (%)	N	DBH (cm)	H (m)	V_{stem} (m ³)	Root Depth (m)	GWC_{soil} (%)	Soil Density (kg m ⁻³)	Soil Type
Dry			39	22.5 \pm 4.4	24.3 \pm 3.5	0.47 \pm 0.25	0.74 \pm 0.19	16.9 \pm 8.4	1352 \pm 98	
1	Auce	B(100)	5	21.4 \pm 3.7	21.2 \pm 1.7	0.36 \pm 0.14	0.72 \pm 0.10	18.2 \pm 0.3	1467 \pm 70	Loamy
2	Auce	B(70), A(20), G(10)	4	25.9 \pm 0.6	24.5 \pm 1.7	0.58 \pm 0.07	0.79 \pm 0.40	26.6 \pm 4.9	1345 \pm 124	Loamy
3	Kalsnava	B(100)	5	18.7 \pm 3.5	21.6 \pm 1.9	0.28 \pm 0.11	0.64 \pm 0.10	7.8 \pm 1.2	1357 \pm 52	Loamy
4	Kalsnava	B(100)	5	21.1 \pm 3.9	24.4 \pm 1.1	0.40 \pm 0.17	0.84 \pm 0.24	6.5 \pm 0.7	1446 \pm 133	Loamy
5	Kalsnava	B(70), O(30)	5	20.6 \pm 1.7	22.5 \pm 1.3	0.34 \pm 0.07	0.70 \pm 0.12	11.6 \pm 1.5	1288 \pm 116	Loamy
6	Kalsnava	B(90), S(10)	5	21.3 \pm 2.8	22.0 \pm 2.6	0.37 \pm 0.14	0.64 \pm 0.11	13.6 \pm 0.9	1306 \pm 110	Loamy podzolic
7	Skede	B(80), G(20)	10	25.7 \pm 5.6	29.2 \pm 1.4	0.71 \pm 0.32	0.79 \pm 0.32	26.3 \pm 4.3	1256 \pm 79	Silty
Periodically waterlogged			32	19.8 \pm 3.6	21.7 \pm 2.4	0.32 \pm 0.15	0.62 \pm 0.20	38.9 \pm 19.3	1268 \pm 108	
8	Auce	B(70), S(30)	6	25.3 \pm 2.6	25.1 \pm 2.2	0.57 \pm 0.14	0.85 \pm 0.06	24.6 \pm 0.7	1348 \pm 132	Loamy grayed
9	Kalsnava	B(70), G(30)	3	19.9 \pm 4.4	18.5 \pm 1.7	0.28 \pm 0.15	0.67 \pm 0.12	30.3 \pm 0.6	1201 \pm 67	Loamy grayed
10	Kalsnava	B(100)	4	19.0 \pm 1.9	20.7 \pm 0.7	0.27 \pm 0.06	0.45 \pm 0.21	83.7 \pm 0.9	1276 \pm 192	Loamy grayed
11	Skede	B(90), G(10)	9	18.7 \pm 2.2	21.3 \pm 1.2	0.27 \pm 0.06	0.54 \pm 0.22	36.4 \pm 11.2	1269 \pm 68	Silty grayed
12	Skede	B(80), G(20)	10	17.7 \pm 2.3	21.2 \pm 1.5	0.24 \pm 0.07	0.48 \pm 0.10	34.3 \pm 9.5	1248 \pm 84	Silty grayed

In each site, 3–10 healthy canopy trees were sampled, and edge (in the respect to a forest patch) trees were avoided. In total 71 trees were selected—39 were growing on well-drained (dry) mesotrophic mineral soils (*Hylocomiosa* forest type) [45] and 32 in the periodically waterlogged (wet) mesotrophic mineral soils (*Myrtilloso-sphagnosa* forest type; Table 1). Silver birch is common in both site types in Latvia. Stand age ranged 44–60 years. The soils were loamy or silty, though the soil density was similar in all sites. Soil moisture was ca. twice higher in the periodically waterlogged sites. Dimensions of trees were measured. Trees in the dry sites were slightly larger (mean height, diameter) than trees in the periodically waterlogged sites (Table 1); however, differences were not significant.

To determine soil moisture, after pulling tests within the distance of 2 m from each tree, 100 mL soil samples were taken from depths of 0–10, 10–20, 20–40, and 40–80 cm, packed in a hermetic package and delivered to the laboratory. After initial weighting, samples were dried in 105 °C temperature for 24 h, and gravimetric water content of soil (GWC_{soil}) was expressed as the weight loss after drying. GWC_{soil} for each tree was calculated as means from all sampled depths (Table 1).

2.2. Static Pulling Tests

Pulling tests were conducted in the autumn periods of 2019 and 2020, while soil was not frozen nor snow cover had formed. Though trees were leafless (after leaf fall). In this study, the destructive static pulling tests were operated according to previously applied methods [46,47]. In brief, steel cable and manual winch, which was fixed at the base of the opposite tree, were used (Supplementary Material, Figures S1 and S2). Depending on the distance from the anchor tree to the sample tree, the pulling line was extended with a static polyester rope. Pulling was performed in all directions, particularly northwards. Pulling direction was recorded with the accuracy of 15° for each tree. On the sample tree, the pulling line was fixed at 50 % of the height. To avoid the impact of wind and canopy weight on the measurement, 1 m above this point, the tree was topped. The TreeQinetic System (Argus Electronic GmbH, Rostock, Germany) was used to process measurements. Pulling force and line angle were measured using a dynamometer. The inclinometers were used for simultaneous tilt measurements of the sample tree at two heights on the stem—at the base and at the height of 5 m [46,47]. For the uprooted trees, root depth was measured

on the surface of root-plate as close as possible as the distance from stem to the tips of the vertical roots [48]. Considering that dimensions of root-plate are tightly linked [48], root depth was measured as the simplest proxy for shape and volume of root-plate.

2.3. Data Processing and Analysis

For each tree, bending moment at the base of the stem (BBM, in kNm) was calculated using the continuously measured pulling force and line angle as follows:

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

where F is the applied force, h_{anchor} is the height of attachment of pulling line on the sample tree, and α_{line} is the line angle. The data obtained from simultaneous measurements of two inclinometers were used to calculate stem curvature (N_{Δ} , °):

$$N_{\Delta} = N_{5m} - N_{\text{base}} \quad (2)$$

where N_{base} and N_{5m} is the stem tilt at the stem base and at the height of 5 m, respectively. Afterwards, stability proxies—primary (PF) and secondary (SF) failures were determined for each tree based on the calculated BBM and N_{Δ} . The beginning of wood structure deformation under the loading is considered as the PF. This type of damage is not visually observable, as internal damage of wood (kinking of wood fibers) occurs due to compression of wood under stem bending [49,50]. During the initial part of the static pulling, a proportional increase of BBM and N_{Δ} occurs; however, the proportionality is lost at one certain point, thus signifying the occurrence of the primary failure PF [49–51]. This was determined by a graphical inspection. The reaching of the maximum BBM was considered as the occurrence of SF, when the collapse of the sample tree, either as uprooting or stem breakage, happened. The difference (BBM_{DIF}) between BBM at the PF (BBM_{PF}) and SF (BBM_{SF}) was calculated to estimate the vulnerability of trees against SF after the occurrence of PF.

To evaluate the effect of site type (soil moisture regime) on the stability proxies of trees (BBM_{PF} , BBM_{SF} , and BBM_{DIF}) and root depth, linear mixed models were used. The model in general form was:

$$y_{ij} = \mu + \text{dim}_{ij} + \text{sity}_j + \text{dim}_{ij} \times \text{ty}_j + (\text{site}_j) + \varepsilon \quad (3)$$

where dim_{ij} is the covariate of tree dimensions, ty_j is the fixed effect of site type (two levels: dry and periodically waterlogged), and $\text{dim}_{ij} \times \text{ty}_j$ is their interaction. To account for the dependencies in data, arising from the different forest patches sampled, site (site_j ; 12 levels) was included in the models as a random effect. Stem diameter, tree height, stem taper, and stem volume (V_{stem}) were tested as the covariates representing the dimensions of trees (dim_{ij}). Locally developed functions were used to calculate V_{stem} :

$$V_{\text{stem}} = 0.0000909 \times H^{0.71677} \times \text{DBH}^{0.16692} \times 0.4343 \times \text{LN}(H) + 1.7570 \quad (4)$$

where DBH is the stem diameter at 1.3 m height (in cm) and H is the tree height (in m). Additionally, pulling direction (with four levels), mean gravimetric water content of soil, root depth, soil density, and soil type were tested as extra proxies for site conditions. Models were fit using maximum likelihood approach. Covariates were selected arbitrarily. Normality and homogeneity of the model residuals were assessed by diagnostic plots. Variance inflation was used to check for collinearity among the variables included in the model, the predictors with the criterion < 5 were included. Model overall significance was estimated using the maximum likelihood approach. The differences in tree dimensions according to SF type (breakage and uprooting) were assessed by mixed effects model with the same random effect. Statistical analysis of data was conducted in R (version 4.0.3.) [52] using the packages “lme4” [53], “lmerTest” [54], “MuMIn” [55].

3. Results and Discussion

Site type, hence soil moisture regime affected mechanical stability of silver birch on mineral soils. The mean values of BBM_{PF} , BBM_{SF} , and BBM_{DIF} differed by sites (Table 2), which followed the differences in tree size (Table 1), as previously observed for other species [34,46,47]. Accordingly, the refined linear mixed effects models indicated that the combination of tree size and site type were the best predictors of mechanical stability of stems during the static pulling test (Table 3). Among the tested tree size proxies, V_{stem} appeared the most sufficient, as observed in other studies [34]. The additional covariates tested—pulling direction, soil density, and soil type lacked statistical significance (p -values > 0.10), while soil moisture and root depth was colinear to site type. Along with tree size [34,46,47], root distribution is one of tree stability key-factors as deeper rooting facilitates root anchorage [15,16]. However, considering the data structure differences in root depth among the site types were not significant (Table 3), suggesting suitability of birch for forest regeneration in the periodically waterlogged sites, particularly under increasing synergic effects of disturbances [2,3,40] and growing water stress [39,56]. Accordingly, the differences in stability of silver birch according to stand type arose from soil moisture regime and its effect on soil formation and particle binding [5,15,16].

The individual effect of site type on the stability proxies was not significant (Table 3), implying similar baseline of stem BBM of the studied trees. Nevertheless, the significant interactions between V_{stem} and site type (Table 3) indicated that soil moisture regime affected sensitivity of silver birch to wind damage (loading resistance), particularly when reaching larger dimensions. The fit of the models was good, though it differed among the stability proxies with the highest and lowest marginal R^2 observed for SF and BBM_{DIF} , respectively (Table 3), implying varying influence of site type on tree adaptations to wind [57]. This suggests morphological plasticity of the eastern Baltic population of silver birch as an adaptation to local conditions [32,35].

Regarding PF, which cannot be visually observed, yet affects tree vigour water relations [49,50], hence legacy effects of storms [58,59], higher susceptibility of silver birch was observed in the dry sites (Figure 1). Such effect might be explained by the synergic effects of storms and summer water deficit [2,3], as well as the differences in tree height (Table 2), which subjected trees to higher wind loads in the dry sites. It might also be speculated that the damages (PF) of several storm events could have accumulated [4,51]. Nevertheless, under the increasing frequency of water deficit conditions [40,41], such relationships indicate certain advantages for silver birch forestry in the periodically waterlogged sites, reducing the risks of physiological and soil droughts [56,59], thus aiding sustainability of stands [1–3].

Inverse effect of soil type (in the interaction), however, was observed for the resistance of trees to SF (Figure 1), which was higher in the periodically waterlogged sites. Considering that uprooting was the most common form of SF as only 9 of 71 (ca. 13%) trees broke (Table 2), such differences can be explained by moisture-reduced soil-root anchorage [5,15,16]. Accordingly, in the periodically waterlogged sites, trees still appeared more susceptible to uprooting under high wind loads [15,26–28], implying higher risk for the entire stands to collapse [24,25], particularly when reaching higher age/larger dimensions [27]. Nevertheless, the effect of soil type on resistance of silver birch to SF was weaker compared to other species [34,46].

It is widely applied that higher soil moisture facilitates uprooting due to reduced soil-root anchorage [15,26–28], yet surprisingly, stem breakage was ca. four times more common in the periodically waterlogged than in the dry sites (21.9 vs 5.1% of trees, respectively). This implies high mechanical durability and anchorage of root system of silver birch, supporting suitability of silver birch for periodically waterlogged sites under intensifying water stress [39,40,45]. The limited sample size of the broken tree group, though, did not allow to evaluate statistical significance of site type on the form of SF. Nevertheless, the broken and the uprooted trees were of similar dimensions (p -value = 0.28), suggesting

influence of microsite conditions on root strength and form of SF [24,25], implying high local variability (uncertainties).

The recovery of trees after PF can be long, during which additional cumulative damages can occur further extending the recovery period, bringing trees closer to the collapse (SF) [24,51]. Accordingly, BBM_{DIF} can be thought as a proxy for the long-term resistance to wind damage. Similarly, to others, BBM_{DIF} showed significant interaction between V_{stem} and site type (Table 3), though the differences according to soil type were more explicit (Table 2, Figure 1). In the dry stands, BBM_{DIF} was proportional to tree size, implying that resistance to cumulative damages increased as trees grew. In contrast, in the periodically waterlogged sites, BBM_{DIF} was independent of tree size (V_{stem}), indicating age-related increase in susceptibility to accumulating damage, hence long-term risks related to wind damage (collapse) [51]. This can be related to easier occurrence of SF in the periodically waterlogged sites (Figure 1), or alternatively such relationships might be an artefact of different tree size (Table 1) or landscape [38]. Nevertheless, the interactions affecting BBM_{DIF} supports plasticity of the eastern Baltic population of silver birch to adapt to intensifying effect of disturbances. Thought, considering that dynamic loads during wind gusts can significantly exceed static loads [8], all available methods for improving wind resistance of trees is necessary to ensure sustainability of future forests.

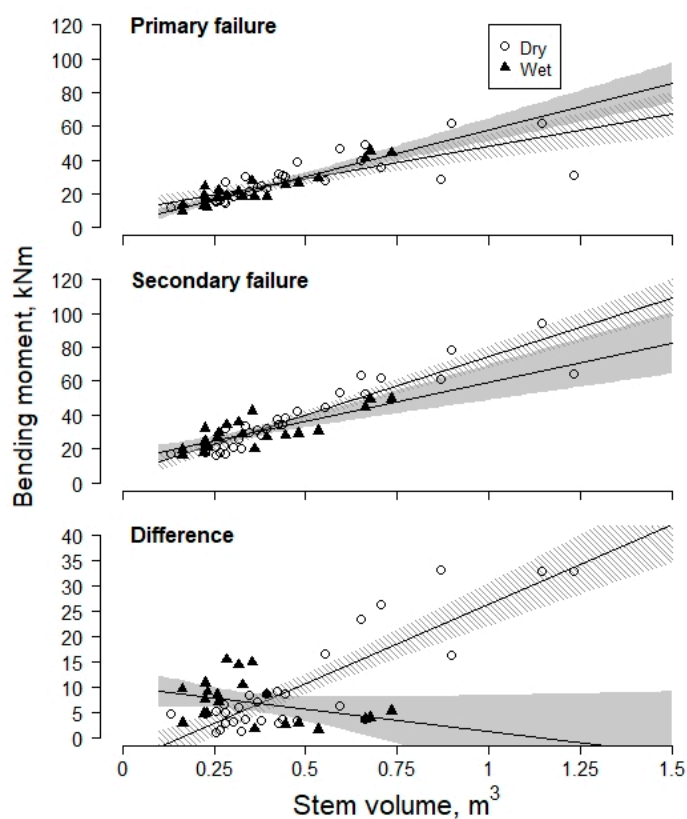


Figure 1. Basal bending moment of birch stems at the primary failure (BBM_{PF}) and the secondary failure (BBM_{SF}) as well as the difference (BBM_{dif}) between both BBM_{PF} and BBM_{SF} on well-drained mesotrophic (dry; stripped) and periodically waterlogged (wet; grey) mesotrophic mineral soils. The shaded area denotes 95% confidence interval.

Table 2. Mean (\pm standard deviation) basal bending moment of birch stems at primary (BBM_{PF}) and (BBM_{SF}) secondary failures and difference (BBM_{dif}) between BBM_{PF} and BBM_{SF} , and the number of broken trees in each sampled site.

Site No.	BBM_{PF} (kNm)	BBM_{SF} (kNm)	BBM_{dif} (kNm)	Stem Breakage, N
Dry	27.36 \pm 12.35	37.04 \pm 18.36	9.68 \pm 8.92	2
1	22.06 \pm 7.39	28.14 \pm 8.59	6.08 \pm 2.07	0
2	30.50 \pm 6.65	43.57 \pm 8.84	13.07 \pm 3.86	0
3	20.75 \pm 7.78	24.18 \pm 8.40	3.43 \pm 1.63	1
4	29.90 \pm 14.69	34.30 \pm 13.56	4.40 \pm 1.36	0
5	22.19 \pm 7.00	25.65 \pm 7.91	3.47 \pm 2.04	0
6	24.39 \pm 13.10	29.78 \pm 14.12	5.38 \pm 2.69	0
7	34.84 \pm 15.95	55.99 \pm 21.79	21.15 \pm 9.72	1
Periodically waterlogged	20.56 \pm 9.66	27.67 \pm 10.13	7.11 \pm 4.05	7
8	34.06 \pm 11.09	37.11 \pm 12.33	3.06 \pm 1.42	0
9	18.41 \pm 6.01	21.77 \pm 5.67	3.37 \pm 1.23	2
10	19.39 \pm 6.06	29.31 \pm 10.97	9.92 \pm 5.96	1
11	16.77 \pm 4.46	26.20 \pm 5.30	9.43 \pm 2.15	4
12	16.99 \pm 7.92	24.45 \pm 10.52	7.46 \pm 3.81	0

Table 3. Statistics of the refined mixed models relating basal bending moment at the primary (BBM_{PF}) and secondary (BBM_{SF}) failures of birch stem under destructive static loading as well as the difference (BBM_{dif}) between both BBM_{PF} and BBM_{SF} and root depth. Variances of the random effects of site and strength (χ^2 -value) and significance (p -values) of the fixed effects (significant effects are highlighted in bold) are shown. V_{stem} —stem volume; SD—Standard deviation.

	BBM_{PF}		BBM_{SF}		BBM_{dif}		Root depth	
Random effects	Variance	SD	Variance	SD	Variance	SD	Variance	SD
Site	2.61	0.98	2.88	0.71	7.12	2.67	0.31	0.02
Residual	35.01	5.92	43.79	6.61	12.22	3.49	24.11	0.15
Fixed effects	χ^2 -value	p -value	χ^2 -value	p -value	χ^2 -value	p -value	χ^2 -value	p -value
V_{stem} (covariate)	134.64	<0.001	285.13	<0.001	49.15	<0.001	31.07	<0.001
Site type	0.55	0.81	0.03	0.869	0.06	0.798	2.02	0.154
V_{stem} by site type	5.04	0.025	4.89	0.041	4.55	0.042	3.19	0.07
Marginal R^2	0.69		0.82		0.56		0.44	
Model p -value	<0.001		<0.001		<0.001		<0.001	

4. Conclusions

The results of this study support the notion of high resistance and plasticity of the eastern Baltic population of silver birch to wind damage, particularly in periodically waterlogged sites, suggesting its ability to cope with the synergic effects of intensifying natural disturbances. The hypothesis of the study was confirmed partially, as the periodically waterlogged conditions reduced resistance of silver birch to SF (collapse), but for PF the opposite was observed. In contrast to hypothesis, waterlogged conditions also facilitated stem breakage, indicating high resistance and plastic adaptability of root system of eastern Baltic silver birch. Accordingly, more extensive application of the species for planning climate-smart landscapes by matching ecological plasticity of species with environmental constraints with respect to wind and water deficit within the region could be suggested. Still in periodically waterlogged sites, susceptibility of birch to a repeated wind damage appeared age/size dependent, suggesting necessity for different rotation length. The quantified wind resistance of birch should be used to improve the accuracy of wind damage models aiding more efficient decision making regarding the adaptive management.

Supplementary Materials: The following are available online at <https://www.mdpi.com/1999-4907/12/1/21/s1>, Figure S1: A scheme of the destructive pulling test setup. AP1 and AP2—anchor points; DI—dynamometer; MW—manual winch; I1 and I2—inclinometers; H—tree height; TH—topping height; SC—steel cable; PE—polyester extension line. Figure S2: Preparation of sample tree to destructive sampling. Technical worker is limbing and topping a tree. In a periodically waterlogged site.

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