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Brief Report

In the Northeasternmost Stands in Europe, Beech Shows Similar Wind Resistance to Birch

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Abstract: The ongoing shifts in natural vegetation zones predict the expansion of European beech (*Fagus sylvatica* L.) into the Eastern Baltic region, suggesting it will become a potential alternative to birch (*Betula pendula* Roth. and *Betula pubescens* Ehrh.) in forest regeneration. For a successful application of alternative forest regeneration material, an evaluation of susceptibility to natural disturbances (e.g., wind) is necessary for reliable projections of timber yield in the long term. This study compared the loading resistance of beech growing in the northeasternmost stands in Europe to local birch by applying the static tree-pulling test. Relationships between dimensions of aboveground parts and resistance against intrinsic wood damages (primary failure) and fatal (secondary) failure were similar between species. However, birch, which is more drought sensitive compared to beech, is suggested to have a higher susceptibility to post-storm legacy effects, supporting beech as a potential alternative to birch in terms of wind resistance.

Keywords: pulling test; wind damage; European beech; birch; root anchorage

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1. Introduction

Under changing climate, diversification of forest regeneration material with transferred genotypes or species is considered among the most effective means for sustaining productivity and reducing environmental risks [1,2]. European beech (*Fagus sylvatica* L.), which is economically important in Central Europe [3], is predicted to expand into the Eastern Baltic region [4–7], becoming a potential alternative for forest regeneration, as suggested by high productivity and self-regeneration [7]. There is also evidence of rapid adaptation to local weather conditions [8]. Considering comparable forestry applications (as stand-forming or admixture species) and wood properties [9,10], in the Eastern Baltic region, beech appears as an alternative to birch (*Betula pendula* Roth. and *Betula pubescens* Ehrh.), which is susceptible to snow loading [11] and is weather sensitive [12]. Still, information on the susceptibility of alternative forest reproductive material to natural disturbances (e.g., storms) is crucial for reliable projections of timber yield in the long term [13,14].

In Northern European forests, wind is a major disturbance, which causes most of the damage to growing stock [15,16] and leads to severe economic consequences [17], particularly resulting from the post-storm legacy effects such as pests, diseases, and increased susceptibility to water shortage [18,19]. Accordingly, information about tree wind resistance, which is crucial for sustainable management and the accuracy of long-term projections, can be efficiently obtained using the static tree-pulling test [20–22]. In addition to the resistance to fatal (secondary) failure, the static tree-pulling test can estimate the occurrence of primary failure, which is internal structural wood damage [23–25], hinting at the expectancy of post-storm legacy effects [18,19,26]. Under intensifying effects of storms in the Eastern Baltic region [15,16,27,28], the forestry potential of beech is supported by its evolutionary adaptation to wind loading [29].

The aim of the study was to assess the loading resistance of beech growing in the northeasternmost stand in Europe and compare it with that of local birch. Considering differing stem and crown architecture [30], we hypothesized beech to have higher loading resistance compared to birch.

2. Materials and Methods

2.1. Study Sites and Sample Trees

The northeasternmost beech stands of Europe, located in the northwestern part of Latvia (hemiboreal forest zone of the Eastern Baltic region; N 57°14′20″, E 22°40′06″), were studied. In total, 18 beech trees were sampled in 3 stands, which represented the first (established using the planting material of unidentified provenance) and second (progenies of the first transferred trees) generations of trees with the ages of 138 and 48–72 years, respectively (Table 1). These stands have been established as regular plantations (planted in a 2 × 3 m grid), and no stand thinning has been performed, except the removal of dead trees, thus the stand structures have only changed under natural conditions. The distribution of tree stem diameters at breast height among the stands was similar, yet the older stand was less dense, and thus had a lower stand basal area (according to inventory in 2021) (Table 1). Trees in the youngest stand were smaller in height than in the older stand and hence had smaller stem–wood volumes (Table 1).

Table 1. Age, basal area (G), soil density (ρ_{soil}), and gravimetric water content (θ_g) of the studied stands, and the number (N), mean (±standard error) diameter at breast height (DBH), height (H), stem–wood volume (V_s), depth of soil–root plate (DP_r), and the volume of soil–root plate (V_r) of the sample trees of European beech (*Fagus sylvatica* L.) and birch (*Betula pendula* Roth. and *Betula pubescens* Ehrh.).

Site	Age	N	DBH (cm)	H (m)	V_s (m^3)	DP_r (m)	V_r (m^3)	G (m^2 ha^{-1})	ρ_{soil} (kg m^{-3})	θ_g (%)
Beech										
1	72	6	34.7 ± 4.6	30.6 ± 2.1	1.59 ± 0.43	1.01 ± 0.11	2.93 ± 0.49	44.2 ± 3.2	1362 ± 60	15.6 ± 0.6
2	138	6	33.4 ± 4.9	30.0 ± 1.4	1.46 ± 0.38	0.66 ± 0.14	2.57 ± 0.98	33.6 ± 7.3	1324 ± 88	18.7 ± 1.1
3	48	6	32.7 ± 5.3	26.6 ± 0.5	1.23 ± 0.36	1.04 ± 0.18	3.23 ± 1.44	38.8 ± 2.3	1348 ± 59	15.7 ± 1.5
Birch										
4	73	9	27.0 ± 1.4	29.0 ± 1.7	0.75 ± 0.09	0.83 ± 0.09	1.71 ± 0.40	48.9 ± 6.0	1233 ± 36	7.3 ± 1.8
5	104	16	34.8 ± 3.7	32.9 ± 1.4	1.42 ± 0.30	0.86 ± 0.05	3.71 ± 1.06	38.1 ± 5.0	1268 ± 50	9.2 ± 1.0
6	46	6	30.0 ± 4.4	30.1 ± 1.0	0.99 ± 0.33	0.86 ± 0.06	1.84 ± 0.69	60.8 ± 3.6	1273 ± 39	10.0 ± 1.8
7	46	6	28.1 ± 3.0	30.6 ± 1.5	0.87 ± 0.21	0.77 ± 0.12	1.60 ± 0.70	69.9 ± 4.7	1260 ± 51	9.0 ± 4.1
8	53	6	29.4 ± 2.6	29.7 ± 1.1	0.92 ± 0.18	0.79 ± 0.12	2.20 ± 0.71	26.3 ± 0.3	1258 ± 10	26.2 ± 3.6

The study area is situated on flat terrain in lowland (<110 m a.s.l.) with freely draining mesotrophic loamy deep soils (Table 1). The climate of the study area (western part of Latvia) is humid continental [31], which is influenced by air masses from the North Atlantic [32]. The mean annual sum of precipitation is 673.3 mm, and the highest and lowest monthly mean air temperature is in July (17.6 °C) and February (−2.7 °C), respectively [33]. The mean annual wind speed is 3.1 m s^{-1} [33], and the mean maximum wind speed at the elevation of 10 m is 16.2 m s^{-1} [34].

In each stand, six canopy trees without visual signs of mechanical damage, pathogen infection, or pest infestation were selected for sampling according to the stem diameter at breast height distribution of the stand. Trees growing close together, as well as edge trees, were avoided to minimize edge effects on the loading resistance. To characterize the differences in loading resistance with local species, previously published data on 43 birch trees from 8 stands [35,36] with similar dimensions and ages were used (Table 1). The birch stands, which represented an area (N 56°40′ to N 57°13′ and E 22°51′ to E 23°53′) with comparable meteorological and site conditions, have been managed conventionally, presuming one to two thinnings during a 70-year rotation cycle.

Soil parameters, such as density and gravimetric water content (Table 1), were determined from the 100 mL volume samples. They were obtained near each soil–root plate at the depths of 0–0.1, 0.1–0.2, 0.2–0.4, and 0.4–0.8 m and stored in sealed bags. Samples were brought to a laboratory and dried for 24 h at 105 °C temperature. The gravimetric water content of the soil was expressed as the difference in weight between the original and dried samples. Soil density was expressed for dried samples.

2.2. Static Tree-Pulling Tests

The loading resistance of beech and birch was estimated using the destructive static tree-pulling tests performed under non-frozen soil conditions during 2019–2022 corresponding to previously applied methodology [22]. Under this approach, a pulling line (rope/cable) on the sample tree was placed on height, which corresponded to 50% of the total height. Prior to pulling, selected sample trees were detopped and pruned to reduce the possible underestimation of the loading resistance caused by the effects of canopy mass above the half height of the sample tree, as well as wind. Sample tree detopping was performed one meter above half of the total height (anchoring point) to prevent the slipping-off of a polyester loop sling Aro Bull (Kong, Monte Marenzo, Italy; static loading limit of 35 kN) used to fix the puling line on the sample tree.

The pulling line was made as a pulley block system, consisting of oppositely placed two double pulleys from Roll Double (Edelrid, Germany; static loading limit of 50 kN), and a 12 mm rope (Capstan Winch Cable, Nordforest, Germany; static loading limit of 17 kN) was used to make the pulling line, which was extended by adding a static polyester rope (Tenex Tec 12; diameter 12 mm; static loading limit of 53 kN; Samson Rope Technologies Inc., Ferndale, WA, USA). All connections of the pulling line were secured using steel carabiners from Big Dan Arborist (ISC, Bangor, Wales, UK; static loading limit of 50 kN).

Tree pulling was performed using a motor winch (1800 Capstan Cable Winch, Nordforest, Germany; static loading limit of 17 kN), anchored at the base of an oppositely located tree at a distance of 30–40 m. Trees were pulled until the occurrence of uprooting or stem breakage (fatal failure). The pulling force and the angle of the pulling line (dynamometer placed between the pulley block system and the extension rope anchored at the sample tree) and stem tilting (inclinometers placed on the stem at the base and at 5 m height) were recorded using the TreeQinetic System (Argus Electronic GmbH, Rostock, Germany).

For each uprooted tree, the dimensions of the soil–root plate were determined. The maximum depth was approximated by penetrating through a measuring rod at the central (thicker) part of the soil–root plate. The height and width of the soil–root plate were determined by measuring five radii (at 0°, 45°, 90°, 135°, and 180°) on the surface from the tree stem base until the edge of the soil–root plate. The length of individual roots, which stretched out from the main body of soil–root plate, was not counted as the edge.

2.3. Data Processing and Analysis

The obtained data on the pulling force and the angle of the pulling line were used to estimate the loading resistance of trees as the bending moment at stem base (BBM, in kNm) as follows:

$$\mathrm{BBM} = \mathrm{F} \cdot \mathrm{h}_{\mathrm{anchor}} \cdot \cos(\mathrm{median}(\alpha_{\mathrm{line}})) \quad (1)$$

where the recorded force of pulling is F, h_{anchor} is the attachment height of the pulling line on the sample tree (half of the initial tree height), and the angle between the pulling line and the surface of the ground is α_{line}.

The inclinometer data on the recorded stem tilting at the base and at 5 m height were used to calculate the deflection of the stem (N_Δ, °) as the difference between them:

$$\mathrm{N}_\Delta = \mathrm{N}_{5\mathrm{m}} - \mathrm{N}_{\mathrm{base}}, \quad (2)$$

The occurrence of primary (PF) and secondary (SF) failures was estimated according to BBM and N_Δ [22]. As a result of tree bending, the PF occurs under the compression as a structural damage of wood either in roots or stem [23–25]. PF was estimated graphically as the end of the proportional increase of BBM and N_{Δ} [22]. The SF was estimated as the maximum BBM, as the fatal failure either by uprooting or stem breakage occurred.

The volume of the soil–root plate, which is a proxy for tree anchorage [37,38], was approximated as half of an elliptical paraboloid:

$$V = \left(\frac{1}{2}\right) \cdot \pi \cdot h \cdot a \cdot b, \tag{3}$$

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

The stem–wood volume was calculated for each of the species according to the local equations by Liepa [39] as follows:

$$V_{beech} = \left(\frac{0.785 \cdot DBH^2 \cdot H}{10000}\right) \cdot \left(0.99 \cdot \left(\frac{750}{1500 + DBH}\right) + \frac{2.3}{DBH^2} - \frac{DBH}{2000}\right), \tag{4}$$

$$V_{birch} = 0.0000909 \cdot H^{0.71677} \cdot DBH^{0.16692 \cdot 0.4343 \cdot \ln(H) + 1.7570}, \tag{5}$$

where H and DBH is tree height (m) and the stem diameter at breast height (cm), respectively.

The differences in the volume of the soil–root plate, as well as in BBM at both the PF and SF between the species were evaluated using the analysis of covariance (linear mixed-effects models) relating to stand and tree dimensions. The models in general form were as:

$$y_{ijk} = \mu + V_{ij} + sp_k + V_{ij} : sp_k + (stand_j) + \varepsilon_{ij}, \tag{6}$$

where V_{ij} is the tree size covariate (stem–wood volume) [22,35,36], sp_k is the fixed effect of species, and $V_{ij} : sp_k$ is the interaction between the covariate and species. In the models, the stand was included as the random effect ($stand_j$) to account for local specifics, pseudoreplication, as well as unbalanced sample groups. The models were fit with the maximum likelihood approach. The significance of the fixed effects was estimated using Type II Wald's χ^2 test. Data analysis was conducted in R (v. 4.2.2) [40] using the package "lme4" [41].

3. Results and Discussion

The resistance against static loading for both species was dependent on the soil–root anchorage, as most of the trees uprooted during the test (except two beeches in the older stand), indicating that stem resistance exceeds the strength of the soil–root anchorage. The prevailing uprooting suggests that a higher volume of quality timber could be retracted using salvage logging, as stems are less likely to be cracked [42]. Still, the occurrence of stem breakage of beech could be related to a more dynamic and adaptive root system [3,43,44], suggesting the capability of stronger root anchoring compared to birch, given that the size and volume of the soil–root plate were similar (Table 1). Accordingly, differences in stem breakage suggested the relevance of root architecture [3,43,44], even though the soil–root plate dimensions are considered a tree stability proxy [37,38]. The prevailing uprooting also suggested that the root system is the main location of PF.

Tree stability is tightly linked to the dimensions of the aboveground parts [45], hence significant ($p < 0.001$) relationships between the PF and SF and the stem–wood volume were observed for both sampled species (Figure 1, Table 2). Still, these relationships were weaker compared to the other native tree species, such as Norway spruce (*Picea abies* (L.) Karst.) [46] and common aspen (*Populus tremula* L.) [22], as suggested by the lower marginal R^2 (Table 2). Apparently, beech might be more sensitive to microsite conditions, suggesting higher uncertainty in estimating the relationship between tree size and loading resistance against both PF and SF. However, the relationships between tree size and loading resistance for beech appeared to be less influenced by site compared to aspen and spruce [22,46], as indicated by a lower variance in the stand (intraclass correlation; Table 2).

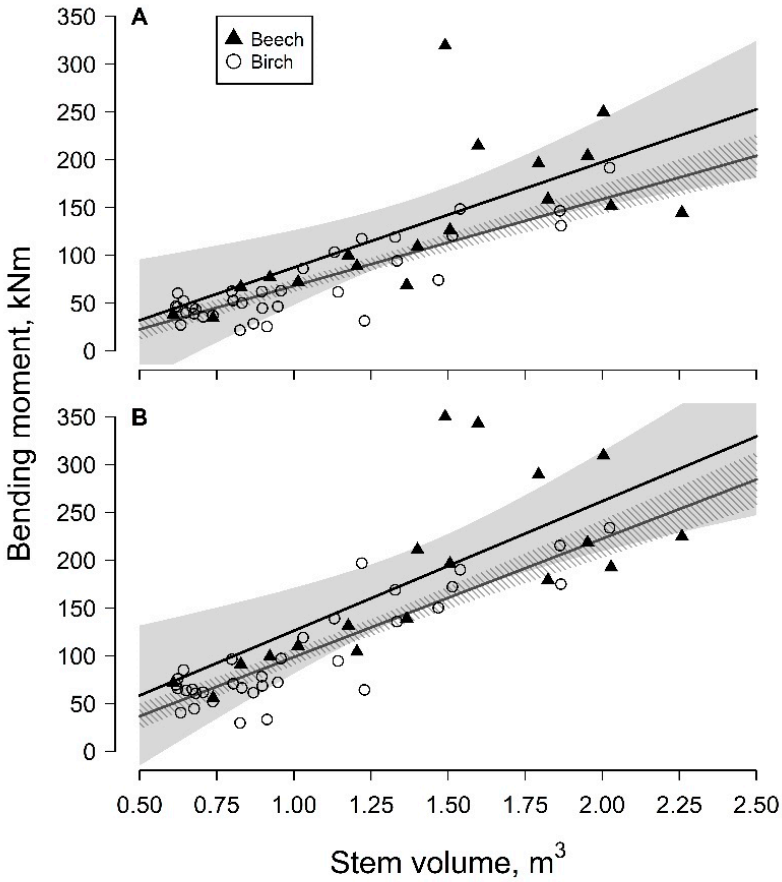

Figure 1. The relationships between the stem–wood volume and the basal bending moment of European beech (*Fagus sylvatica* L.) and birch (*Betula pendula* Roth. and *Betula pubescens* Ehrh.) at the (**A**) primary (BBM_{PF}) and the (**B**) secondary (BBM_{SF}) failures. The coloured area indicates a 95% confidence interval.

Table 2. Strength (Wald's χ^2) and significance of the fixed effects (model ANOVA) of the stem–wood volume (V_{stem}) and species on the basal bending moment at primary (BBM_{PF}) and secondary failures (BBM_{SF}), as well as the volume of the soil–root plate (V_{roots}), model performance (R^2), and random variances in site for European beech (*Fagus sylvatica* L.) and birch (*Betula pendula* Roth. and *Betula pubescens* Ehrh.) on freely draining mineral soil in the Eastern Baltic region. σ^2—total variance in the response; τ_{00}—variance associated with random effects (site); ICC—intraclass correlation coefficient.

	BBM_{PF}	BBM_{SF}	V_{ROOTS}
Predictors (χ^2)	χ^2	χ^2	χ^2
(Intercept)	1.57	0.29	0.11
V_{stem}	47.71 ***	52.71 ***	19.33 ***
species [birch]	0.23	0.01	0.03
V_{stem}:species [birch]	1.95	0.90	0.15
Random Effects			
σ^2	1111.71	1424.36	0.71
τ_{00}	176.50_{site}	423.33_{site}	0.16_{site}
ICC	0.14	0.23	0.19
N	8_{site}	8_{site}	7_{site}
Observations	61	61	53
Marginal R^2	0.67	0.69	0.52
Conditional R^2	0.71	0.76	0.61

Level of significance: *** $p < 0.001$

Contrary to the study hypothesis, beech and birch showed similar loading resistance against PF and SF, as indicated by uniform ($p > 0.05$) relationships between BBM and the stem–wood volume Figure 1, Table 2). This suggests a comparable adaptability of both species to local wind climates, supporting beech as a potential alternative to birch in terms of wind resistance. Under such circumstances, susceptibility to post-storm effects appears as the main concern regarding the selection of species [19]. Trees weakened by wind are more prone to droughts [18,47], as internal structural wood damage disrupts tree hydraulics [24,25], thus increasing the physiological water deficit [48]. This, in turn, can enhance the negative post-storm legacy effects [19] and increase the susceptibility of trees/stands to wind damage [18,26], thus forming a negative feedback loop [48]. In this regard, birch, which is more drought sensitive compared to beech [12,49], appears to increase the forest susceptibility to post-storm legacy effects [18,19], supporting the greater forestry potential of beech under projected climate changes in the Eastern Baltic region [15,28].

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