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Mechanical stability of Scots pine across soil conditions and regeneration practices in hemiboreal forests

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The intensification of wind disturbances increases the importance of maintaining tree mechanical stability in Northern European forests. Soil preparation during forest regeneration may influence long-term stability by modifying rooting conditions. We assessed the effects of site conditions, defined as combinations of soil type (*e.g.*, freely draining mineral, waterlogged mineral, and drained peat soils) and site-specific soil preparation methods (disc trenching and mounding), on the mechanical stability of mid-aged Scots pine (*Pinus sylvestris* L.) stands in hemiboreal forests of northeastern Europe (Latvia). A static tree-pulling test was used to quantify resistance to primary and secondary failure, as well as the post-primary-failure stability margin. Trees growing on unprepared freely draining mineral soils exhibited the highest resistance to both primary and secondary failure, whereas trees on waterlogged mineral and peat soils showed reduced stability and a predominance of uprooting. Mounding on waterlogged sites did not consistently enhance long-term mechanical stability. Overall, soil physical properties and their interaction with tree size outweighed the long-term effects of soil preparation alone, highlighting the need for site-specific, climate-smart forest management strategies to enhance wind resistance in hemiboreal forests.

Keywords: Wind Disturbance, Scots Pine, Hemiboreal Forests, Static Tree-pulling Test, Soil Preparation

Introduction

In Northern Europe, forests are increasingly exposed to a range of intensifying climate-driven disturbances, which often interact, leading to long-lasting negative legacy effects (Hanewinkel et al. 2013, Cawley et al. 2014, Csilléry et al. 2017). They might trigger a negative feedback loop, as, for example, wind-weakened trees can become prone to droughts and thus to secondary biotic agents (Seidl et al. 2017), which subsequently reduces mechanical stability, serving as the weak spot in the stand for the next wind disturbance (Cawley et al. 2014, Gardiner et al. 2016, Csilléry et al. 2017). During the late autumn-early spring season (Gardiner et al. 2013), when Northern Europe, including the Eastern Baltic region, experiences most of the annual cyclones (Rutgersson et al. 2022), the likelihood of such effects increases due to insufficient soil frost, as both the duration and frequency of soil freezing in the region decrease (Kellomäki et al. 2010). Under non-frozen, highly water-saturated soil conditions, the strength of tree soil-root anchorage is reduced (Peltola et al. 1999, Nicoll et al. 2006), making trees more prone to uprooting (Gardiner et al. 2008). The amplified impacts of natural disturbances, along with the increase in the total growing stock of forests (Schelhaas et al. 2003, Gregow et al. 2017, Seidl et al. 2017) intensify the socio-economic and ecological impacts (Hanewinkel et al. 2013, Seidl et al. 2017). To sustain the resilience of future forest stands, such effects can be moderated through adaptive (climate-smart) forest management approaches (Nabuurs et al. 2018).

In this regard, one approach could be the restoration of forest stands using material suited to landscape-specific conditions (Johnstone et al. 2010). Trees growing on periodically waterlogged soils can be more prone to windthrow due to shallow rooting systems and reduced strength of root-soil anchorage (Nicoll & Ray 1996, Nicoll et al. 2006, Laapas et al. 2019), especially under non-frozen soil conditions (Telewski & Moore 2017, Laapas et al. 2019, Venäläinen et al. 2020). Hence, matching the site factors (*e.g.*, soil fertility, moisture regime) and the ecological requirements of tree species (Yousefpour et al. 2010) is becoming increasingly important (Martín et al. 2010, Lindner et al. 2014, Suvanto et al. 2019). In the Eastern Baltic region, stands of species with greater morphological plasticity (Danjon et al. 2005, Yang et al. 2018, Matisons et al. 2021), such as Scots pine (*Pinus sylvestris* L.), are found on soils ranging from freely draining mineral to constantly waterlogged organic (Korhonen et al. 2021, Seipulis et al. 2024). This species can adapt mechanically to different wind climates, yet the risk of wind damage increases when grown under inappropriate soil conditions (Seipulis et al. 2024). For instance, under conditions of constantly high groundwater levels, pine cannot develop a deep root system to ensure mechanical stability (Nicoll et al. 2006), increasing the risk of wind damage (Gardiner 2021).

The coupling of site factors with forest regeneration material can be further enhanced through soil preparation (Orlander et al. 1990). Under the periodically waterlogged conditions, the restoration of forest stands on the mounding can enhance root distribution (Celma et al. 2019, Duminš et al. 2025), hence the strength of soil-root anchorage for both the individual trees and the stand could be increased accordingly (Díaz-Yáñez et al. 2016, Nicoll & Ray 1996,

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Ray & Nicoll 1998). However, quantitative information on the long-term effects of forest restoration through mounding on the mechanical stability of trees in periodically waterlogged sites is not available (Duminš et al. 2025).

Tree mechanical stability can be effectively characterized by the static tree-pulling test, which provides reliable information on the maximum resistive turning moment, indicating the susceptibility of trees to uprooting or stem breakage, depending on which component (root anchorage or stem integrity) is the weakest (Peltola et al. 1999, Nicoll et al. 2006). Thus, under sufficient soil-root anchorage, tree mechanical stability is determined by stem strength; however, in either mode of failure, the fatal collapse of a tree occurs in two distinct phases (Detter et al. 2015). The initial phase is a primary failure (PF), when internal wood damage occurs (Detter et al. 2015). PF is an early, hidden structural failure that is not visible during stem bending; when the tree's hydraulic system is disrupted, it can trigger physiological drought stress and long-term legacy effects for windthrow survivors (Mitchell 2013). The final stage of tree collapse is the secondary failure (SF), which occurs at peak loading and results in either uprooting or stem breakage (Peltola et al. 1999).

The aim of this study was to assess how the mechanical stability (loading resistance) of mid-aged Scots pine varies across contrasting site conditions, defined as combinations of soil type (*e.g.*, freely draining mineral, waterlogged mineral, and drained peat soils) and site-specific soil preparation methods (disc trenching and mounding), in the hemiboreal forests of the Eastern Baltic region in Latvia. Accordingly, two research questions were addressed: (1) How does the mechanical stability of mid-aged Scots pine vary across contrasting site conditions? (2) How do the characteristics of primary (PF) and secondary failure (SF), as well as the post-failure stability margin, differ among these conditions? We hypothesize that: (i) tree stability is higher on freely draining mineral soils due to stronger soil-root anchorage; and (ii) mounding improves mechanical stability in waterlogged conditions compared to unprepared sites. This study advances current knowledge by evaluating the mechanical stability of trees across contrasting soil conditions and site-specific soil preparation approaches in mid-aged Scots pine stands. Integrating primary and secondary failure (PF/SF) metrics with stability margin enables a more comprehensive assessment of both internal damage and fatal failure, providing new insights into the mechanisms governing tree stability under different site conditions.

Materials and methods

Study area

The study area is in the hemiboreal forest zone in Latvia, where approximately 51% of the territory is covered by forests (NFI 2026). About 25% of these forests consist of pine-dominated stands (NFI 2026). Across all forests, approximately 12%, 2%, and 3% of pine-dominated stands are situated on freely draining mineral soils, periodically waterlogged mineral soils, and drained peat soils, respectively, with corresponding total growing stocks of 115, 20, and 29 million cubic meters (NFI 2026). The climate in Latvia is largely influenced by westerlies from the North Atlantic, with local conditions varying with distance from the Baltic Sea (Krauklis & Draveniece 2004). This corresponds to an eastward increase in continentality (Krauklis & Draveniece 2004), resulting in local differences in air temperature and precipitation (LEGMC 2026). The mean annual precipitation in Latvia is 685 mm, with the highest mean monthly total (76 mm) occurring in August (LEGMC 2026). The warmest month is July (+17.8 °C) while the coldest is February (-3.1 °C). Mean annual air temperature and wind speed are higher in western and central parts of Latvia, reaching +8.0 °C (in Riga) and 4.3 m s^{-1} (Ventspils; coastal area), respectively, while in the uplands eastwards, those values are reduced to +5.7 °C (Aluksne) and 2.5 m s^{-1} (Aluksne), respectively (LEGMC 2026).

Study sites and sample trees

The study was conducted in forest stands managed by the Forest Research Stations near Jelgava (56° 44′ 24″ N, 23° 44′ 32″ E) and Kalsnava (56° 40′ 48″ N, 25° 54′ 43″ E), and by Riga Forests Ltd. (Daugava Forest District) near Ogre (56° 53′ 14″ N, 24° 40′ 27″ E), respectively. The studied 40-50-year-old pine stands were situated on flat terrain under lowland conditions, with elevations ranging from 5 m (Jelgava) to 45 m (Ogre) and 90 m (Kalsnava) a.s.l. The studied stands represented freely draining and waterlogged mineral soils (fine sand) and drained deep peat soils (organic – Tab. 1). On freely draining mineral soils, stands without initial soil preparation (Control) and stands established after disc trenching (Trench) were studied. On waterlogged mineral soils, undrained stands were sampled with (Mounding) and without initial soil preparation (Wet). For comparison, similarly aged Scots pine stands established after drainage on organic soils without initial preparation, namely drained deep peat (Peat), were also included (Tab. 1). The studied stands have been managed conventionally according to the forestry guidelines of the time (1970s-1980s), assuming initial planting densities and promoting natural regeneration, with 5,000 Scots pine saplings per hectare on dry mineral soils and 4,000 saplings per hectare on drained deep peat and waterlogged mineral soils. At that time, pre-commercial thinning was not prescribed, and the first commercial thinning for the studied stands was carried out at ages 20-30 years. None of the selected stands exhibited recorded windthrow damage or any biotic or fire disturbance prior to sampling.

For testing, the main selection criteria were that trees were co-dominant and had no visible signs of pathogen infection, pest damage, stem defects, or mechanical injuries. Furthermore, the selected trees had to represent the stand's mean diameter at breast height (DBH), which was measured with a manual caliper. The distance between the sample tree and neighboring trees corresponded to the mean stand spacing, and closely spaced trees were avoided to minimize the potential effects of increased root contacts. Stands were further screened to ensure the possibility

Tab. 1 - The number of studied stands and sampled trees, and mean (± 95% confidence interval) stand age, stem diameter at breast height (DBH), total height (H), stemwood volume (V), gravimetric moisture content (θ_g), soil bulk density (ρ_{Soil}), and stand basal area (G) of each studied type of soil preparation of Scots pine stands. Control - stands on dry mineral soils without initial preparation; Trench - stands on dry mineral soils established after disc trenching; Mounding - stands on waterlogged mineral soils with mounding; Wet - stands on waterlogged mineral soils without initial soil preparation; Peat - drained deep peat (organic) soils without initial preparation.

Sample group	Stand (n)	Tree (n)	Stand age (years)	DBH (cm)	H (m)	V (m^3)	θ_g (%)	ρ_{Soil} (kg m^{-3})	G (m^2 ha^{-1})
Control	4	20	45.7 ± 11.9	24.7 ± 1.9	23.5 ± 1.3	0.55 ± 0.11	13.9 ± 2.1	1198 ± 56	21.51 ± 2.17
Mounding	6	36	42.4 ± 7.4	20.4 ± 1.1	17.8 ± 0.6	0.29 ± 0.04	33.3 ± 2.2	1012 ± 45	24.94 ± 1.07
Peat	9	33	54.2 ± 7.7	26.1 ± 1.4	23.2 ± 0.8	0.59 ± 0.07	70.2 ± 3.3	364 ± 61	24.70 ± 2.41
Trench	4	23	38.5 ± 8.1	22.7 ± 1.6	19.3 ± 0.5	0.38 ± 0.06	26.8 ± 4.2	1108 ± 65	26.43 ± 2.01
Wet	7	46	39.2 ± 6.4	20.5 ± 1.1	17.8 ± 0.6	0.30 ± 0.04	37.5 ± 1.9	990 ± 39	25.46 ± 0.96

of clearing a ≥25° pulling sector toward the anchor tree at a distance at least equal to the height of the sample tree. To characterize the microsite growing conditions of the sample tree (stand basal area, G), all trees ≥6 cm DBH within a radius of 12.62 m around each sample tree were measured for DBH (Tab. 1).

Static pulling test protocol

Tree pulling was conducted during frost-free periods without precipitation and under calm or comparably light wind conditions across the tested stands. Prior to testing, all sample trees were topped to minimize the effects of wind and crown mass on force measurements (Fig. 1). Pulling was performed by applying continuous loading using a 2-stroke motorised winch (1800 Capstan Cable Winch, Nordforest, Germany) positioned at 30-40 m from the sample tree and fixed to the secondary anchor point (tree) (AP2 – Fig. 1). A pulley-block system (PB – Fig. 1), made of two double pulleys and an 11-mm polyester rope as the pulling line (PL – Fig. 1), was installed between the winch and the sample tree. The attachment point of the pulling line on the sample tree (AP1 – Fig. 1) was set at half of its original height (Fig. 1). To prevent the slippage of the attachment, point during loading, the topping height of the trees was 1 m above the original height (TH – Fig. 1). Trees were pulled until they either uprooted or broke at the stem. The parameters of mechanical stability were measured and recorded using the TreeQinetic® system (Argus Electronic GmbH, Rostock, Germany). A dynamometer (DI – Fig. 1) positioned between the pulley system and the sample tree measured pulling force and the angle between the pulley line and the air-line linking the sample and anchor tree (α – Fig. 1). Stem inclination was measured at the base (IM0 – Fig. 1) and at 5 m height (IM5 – Fig. 1) using inclinometers.

Soil-root plate measurements, soil sampling, and laboratory analyses

For uprooted trees, the maximum depth of the soil-root plate was measured by inserting a steel rod near the stem base, and five radii (at 0°, 45°, 90°, 135°, and 180°) of the soil-root plate surface were assessed to calculate the relative soil-root plate depth (RPD, m m^{-3}) and width (RPW, m m^{-3}) in relation to stem volume. Following each static pulling test, pits were excavated at each sample tree. Soil samples were extracted from pit walls at depths of 0-10, 10-20, 20-40, and 40-80 cm using a 100 ml core sampler. Samples were sealed in airtight bags and transported to the Forest Environment Laboratory of the Latvian State Forest Research Institute "Silava". Soil bulk density (ρ_{Soil}, kg m^{-3}) and gravimetric moisture content (θ_g, %) were determined for the samples after oven drying at 105 °C for 48 h, and the mean value across all sampled depths was calculated for each tree (Tab. 1).

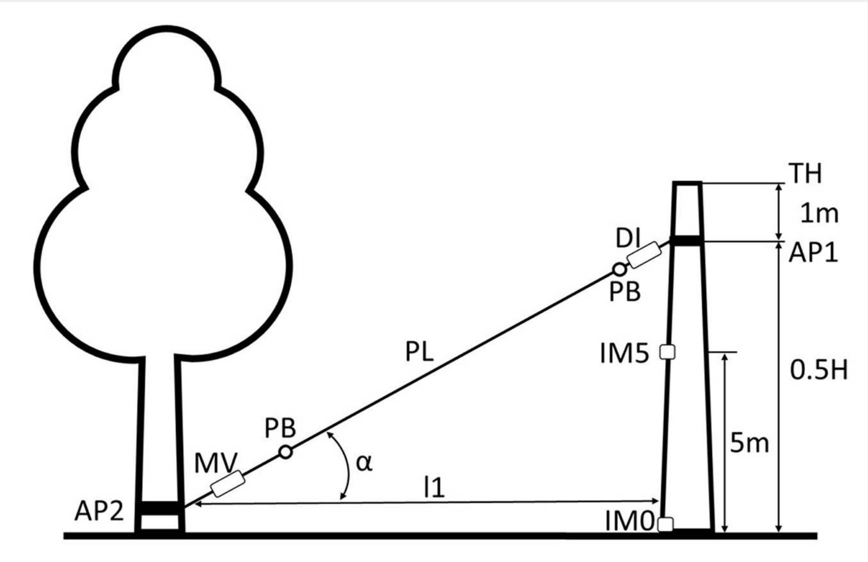

Fig. 1 - Scheme of the destructive static pulling test setup. AP1 and AP2 anchor points; PB - pulley block; PL - pulling line; DI - dynamometer; α - the slope angle of the pulling line; l1 - the distance between the sample tree and the anchoring tree; IM0 and IM5 - inclinometers at the height of 0 and 5 m, respectively; H - tree height; TH - topping height; MV - motor winch.

Calculations of indicators of mechanical stability

The bending moment at the stem base (BM, kNm) for each sample tree was calculated following Krišans et al. (2022a – eqn. 1):

$$BM = F \cdot h_{AP1} \cdot \cos(Me_\alpha) \tag{1}$$

where *F* is the pulling force (kN), h_{AP1} is the attachment height of the pulling line at half of tree height (m), and Me_α is the median of the angle between the pulling line and the air-line between the sample and anchor tree (°).

Stem curvature (N_Δ, °) was expressed as the difference between simultaneous tilt measurements at the base and at the height of 5 m on the stem:

$$N_\Delta = N_{5m} - N_0 \tag{2}$$

where N_Δ and N_{5m} are inclinations at the stem base and at 5 m height, respectively. An increase in N_Δ with a proportional rise in BM indicates elastic deformation, whereas a sudden increase in N_Δ without a corresponding increase in BM implies structural failure of wood fibers, such as the PF (Detter et al. 2015). Under continued loading, trees ultimately experience SF either as uprooting or as stem breakage, indicating the maximum load resistance or the limit of mechanical stability (Detter & Rust 2013). The difference (BM_{DIF}) between the bending moment at SF (BM_{SF}) and PF (BM_{PF}) indicates the remaining stability margin after initial damage.

Tree volume estimation

To account for loading resistance relative to tree size, stemwood volume (*V*, m^3), an integrative parameter of tree growth success (Zeide 1993), was used as a tree-size covariate. *V* is a robust proxy for overall tree size, as indicated by Peltola et al. (2000), Krišans et al. (2022a), Seipulis et al. (2024), and others. *V* was calculated using a locally developed volume equation after Liepa (2018 – eqn. 2):

$$V = 0.00016541 \cdot H^{0.56582} \cdot DBH^{0.25924 \cdot 0.4343 \cdot \ln(H) + 1.59689} \tag{3}$$

where *DBH* is the stem diameter at the height of 1.3 m (cm), and *H* is the tree height (m).

Statistical analysis

Prior to the statistical analysis, the normality of the data was assessed diagnostically using histograms, which indicated that the data were normally distributed. The effects of soil preparation and SF mode (uprooting or stem breakage) on BM_{PF}, BM_{SF}, and BM_{DIF}, as well as the differences in soil parameters (θ_g and ρ_{Soil}) and RPD and RPW of the sampled trees, were evaluated using a zero-intercept linear mixed-effects model fitted in R v. 4.5.2 (R Core Team 2025), using the package "lme4" (Bates et al. 2015 – eqn. 4):

$$y_{ij} = V_{ij} : sc_{ij} + (V_{ij} : stand_j) + \varepsilon \tag{4}$$

where V_{ij} is the tree stem volume; sc_i represents the site conditions; $V_{ij} : sc_i$ is the interaction. To account for the unequal sample sizes and potential intercorrelation among the trees, the studied stand was included as the random slope ($V_{ij} : stand_j$) in the model. A zero-intercept model was applied to reflect the biological constraint that the response variable equals zero when the predictor is zero, thereby ensuring biologi-

Tab. 2 - Estimated marginal means (EMM), their standard error (SE), degrees of freedom (df), lower and upper levels of 0.95% confidence interval (CI) of the stand basal area (G, $m^2\ ha^{-1}$) gravimetric moisture content (θ_g, %), soil bulk density (ρ_{Soil}, kg m^{-3}), stem diameter at breast height (DBH, cm), total height (H, m), and the stemwood volume (V, m^3) for each studied type of soil preparation of Scots pine stands. Grouping (common letters) indicates results of Tukey's HSD *post-hoc* test, where identical letters denote no significant differences among treatments. Control - stands on dry mineral soils without initial preparation; Trench - stands on dry mineral soils established after disc trenching; Mounding - stands on waterlogged mineral soils with mounding; Wet - stands on waterlogged mineral soils without initial soil preparation; Peat - drained deep peat (organic) soils without initial preparation.

Parameter	Soil	EMM	SE	df	Lower CI	Upper CI	Group
G	Control	24.30	1.91	52.5	20.50	28.10	a
	Mounding	24.90	2.03	23.8	20.70	29.10	a
	Peat	25.60	1.69	25.4	22.10	29.10	a
	Trench	25.50	1.49	30.6	22.50	28.60	a
	Wet	25.90	1.68	41.9	22.50	29.20	a
θ_g	Control	14.4	6.55	16.4	0.541	28.3	a
	Mounding	34.7	2.01	35.6	30.641	38.8	ab
	Peat	74	6.69	21.8	60.119	87.9	c
	Trench	28.2	2.47	71.6	23.252	33.1	a
	Wet	36.4	1.75	45.6	32.848	39.9	b
ρ_{Soil}	Control	1179	116.1	16.1	932.9	1425	b
	Mounding	1002	36	34	929.1	1076	b
	Peat	301	119.2	21.8	53.7	548	a
	Trench	1096	44.8	67.8	1007	1186	b
	Wet	1005	31.6	44.2	940.9	1068	b
DBH	Control	12.8	0.498	127	11.8	13.7	ab
	Mounding	11.6	0.378	128	10.9	12.4	a
	Peat	13.6	0.561	129	12.5	14.8	b
	Trench	12.2	0.361	126	11.5	12.9	ab
	Wet	12.4	0.288	128	11.9	13	ab
H	Control	20.5	0.640	151	19.2	21.7	b
	Mounding	15.3	0.458	148	14.4	16.2	a
	Peat	20.5	0.666	143	19.2	21.9	b
	Trench	16.7	0.468	148	15.7	17.6	a
	Wet	16.4	0.356	152	15.7	17.1	a
V	Control	0.51	0.06	34.9	0.38	0.64	ab
	Mounding	0.29	0.05	21.1	0.19	0.39	a
	Peat	0.59	0.04	28.7	0.51	0.68	b
	Trench	0.38	0.05	38.2	0.27	0.49	a
	Wet	0.31	0.04	29.1	0.22	0.40	a

cal realism and preventing implausible predictions. Fixed-effect significance was evaluated using Wald's χ^2 test. Several alternative combinations of fixed effects and their interactions were tested for each response variable; however, only the final models selected through model comparison, which retain the maximum number of statistically significant fixed effects, are presented. *Post-hoc* pairwise comparisons among significant factor levels were conducted using Tukey's honestly significant difference (HSD) test. Multiple comparisons were controlled using Tukey-adjusted familywise error rate correction, as implemented in the "emmeans" package in R (Lenth & Piaskowski 2026). The normality of the analyzed data was assessed diagnostically using histograms, which indicated that the data were normally distributed.

Results

Stand and soil characteristics

The analyzed dataset represents Scots pine stands established under different site conditions, among which the variations in the size of stems and roots of sampled trees, soil physical properties, and stand structure were observed (Tab. 1, Tab. 2, Tab. 3, Tab. 4). Site conditions created clear gradients in soil moisture and tree size, from dry mineral to waterlogged and Peat soils, with the largest trees in Peat and the smallest in Mounded and Wet sites. The number of studied stands ranged from four to nine per site conditions, with 20 to 46 trees sampled per group (Tab. 1). Larger trees by DBH and V were observed in Peat stands, while their height was similar to that of trees in Control (Tab. 1, Tab. 2). Smaller trees in terms of DBH and height were tested in Mounding, Trench, and Wet stands (Tab. 1, Tab. 2). Despite variations in tree size, G did not differ significantly ($p > 0.05$) among site conditions (Tab. 1, Tab. 2). This indicates that variation in tree dimensions was largely offset by changes in stand density.

Among the studied groups, differences were also observed in soil physical properties, as θ_g differed significantly ($p < 0.05$), with the Control and Trench stands having

Tab. 3 - The frequency of stem breakage and the mean (±95% confidence interval) bending moment at the stem base, expressed per stemwood volume, at both primary (BM_{PF}) and secondary failures (BM_{SF}), as well as the difference between them (BM_{DIF}), together with the depth (RPD) and width (RPW) of the soil root plate attributed to stem volume for each studied type of soil preparation of Scots pine stands. Control - stands on dry mineral soils without initial preparation; Trench - stands on dry mineral soils established after disc trenching; Mounding - stands on waterlogged mineral soils with mounding; Wet - stands on waterlogged mineral soils without initial soil preparation; Peat - drained deep peat (organic) soils without initial preparation.

Sample group	Stem breakage (%)	BM_{PF} (kNm m^{-3})	BM_{SF} (kNm m^{-3})	BM_{DIF} (%)	RPD (m m^{-3})	RPW (m m^{-3})
Control	35	74.75 ± 7.44	101.78 ± 9.70	26.5 ± 3.0	0.68 ± 0.15	0.51 ± 0.07
Mounding	44	63.23 ± 3.52	97.79 ± 5.03	34.7 ± 3.4	0.52 ± 0.15	0.26 ± 0.04
Peat	42	65.58 ± 3.69	94.85 ± 4.19	30.9 ± 2.2	0.66 ± 0.09	0.28 ± 0.04
Trench	52	67.20 ± 5.87	96.31 ± 7.70	30.1 ± 3.1	0.71 ± 0.13	0.33 ± 0.04
Wet	26	66.28 ± 3.85	85.17 ± 3.72	22.4 ± 2.5	0.45 ± 0.05	0.24 ± 0.03

Tab. 4 - Estimated mean trends (EMT), their standard error (SE), degrees of freedom (df), lower and upper levels of 0.95% confidence interval (CI) of the depth (RPD, $m\ m^{-3}$) and width (RPW, $m\ m^{-3}$) of the soil root plate, expressed per stemwood volume for each studied type of soil preparation of Scots pine stands. Grouping (common letters) indicates results of Tukey's HSD *post-hoc* test, where identical letters denote no significant differences among treatments. Control - stands on dry mineral soils without initial preparation; Trench - stands on dry mineral soils established after disc trenching; Mounding - stands on waterlogged mineral soils with mounding; Wet - stands on waterlogged mineral soils without initial soil preparation; Peat - drained deep peat (organic) soils without initial preparation.

Parameter	Soil	EMT	SE	df	Lower CI	Upper CI	Group
RPD	Control	1.24	0.32	61.6	0.59	1.88	a
	Mounding	-0.28	0.51	86.7	-1.29	0.74	a
	Peat	0.26	0.31	74.6	-0.35	0.88	a
	Trench	1.35	0.86	67.9	-0.37	3.07	a
	Wet	0.66	0.31	73.0	0.04	1.27	a
RPW	Control	0.63	0.49	38.9	-0.36	1.62	a
	Mounding	1.17	0.83	87.0	-0.49	2.83	a
	Peat	0.64	0.49	73.1	-0.33	1.60	a
	Trench	0.15	1.36	48.0	-2.58	2.88	a
	Wet	1.35	0.48	35.7	0.38	2.33	a

the driest soils (Tab. 1, Tab. 2), while the highest soil saturation levels were observed in Peat and Wet stands (Tab. 1, Tab. 2). Mounding stands exhibited intermediate moisture levels, being similar to Control, Trench, and Wet (Tab. 1, Tab. 2). ρ_{Soil} also varied significantly among soil types ($p < 0.05$), being lowest in Peat and substantially higher for mineral soils, irrespective of hydrological regime and site conditions (Tab. 1, Tab. 2).

Root plate metrics

RPD and RPW showed a considerable variability but did not differ significantly among site conditions ($p > 0.05$ – Tab. 4). Estimated mean trends indicated overlapping confidence intervals for both parame-

Tab. 5 - Estimated mean trends (EMT), their standard error (SE), degrees of freedom (df), lower and upper levels of 0.95% confidence interval (CI) of bending moment at the stem base, expressed per stemwood volume, at both primary (BM_{PF}, $kNm\ m^{-3}$) and secondary failures (BM_{SF}, $kNm\ m^{-3}$), as well as the difference between them (BM_{DIF}, %) for each studied type of soil preparation of Scots pine stands. Results are also shown separately for the frequency of mode of secondary failure (SF mode; uprooting or stem breakage). Grouping (common letters) indicates results of Tukey's HSD post-hoc test, where identical letters denote no significant differences among treatments. Control - stands on dry mineral soils without initial preparation; Trench - stands on dry mineral soils established after disc trenching; Mounding - stands on waterlogged mineral soils with mounding; Wet - stands on waterlogged mineral soils without initial soil preparation; Peat - drained deep peat (organic) soils without initial preparation.

Parameter	Soil / SF mode	EMT	SE	df	Lower CI	Upper CI	Group
BM_{PF}	Control	100.8	7.27	34.3	86.1	115.6	b
	Mounding	70.6	8.49	137.2	53.8	87.4	ab
	Peat	72.9	5.57	61.1	61.8	84	a
	Trench	74.4	8.17	142.9	58.2	90.5	ab
	Wet	67.7	6.97	49.5	53.7	81.7	a
BM_{SF}	Control	142	7.52	23.9	126.5	158	b
	Mounding	101.7	9.63	139.4	82.6	121	a
	Peat	103.9	5.99	53.1	91.9	116	a
	Trench	101.4	9.33	146.8	83	120	a
	Wet	86.5	7.34	34.2	71.6	101	a
BM_{DIF}	Control	39.7	5.07	32.9	29.35	50	b
	Mounding	31.8	5.98	137.5	19.92	43.6	ab
	Peat	30.8	3.9	60.1	22.97	38.6	ab
	Trench	27.8	5.76	143.6	16.38	39.2	ab
	Wet	17.3	4.87	47.1	7.48	27.1	a
BM_{PF}	Uprooting	73.8	4.03	43.6	65.7	81.9	a
	Stem breakage	75.3	5.27	34.2	64.6	86	a
BM_{SF}	Uprooting	102	4.79	43.1	92.4	112	a
	Stem breakage	109	6.33	34.6	96.4	122	a
BM_{DIF}	Uprooting	28.9	2.76	33.3	23.3	34.5	a
	Stem breakage	34.5	3.31	20.9	27.6	41.4	a

Tab. 6 - Estimates (Est.), strength (Wald's χ^2), and significance of the fixed effects from linear mixed-effects models (model ANOVA) for the mode of secondary failure (SF mode; uprooting or stem breakage), stemwood volume (V), and their interaction on the bending moment at the stem base, for both primary (BM_{PF}, kNm m^{-3}) and secondary failures (BM_{SF}, kNm m^{-3}), and their difference (BM_{DIF}, %) across the studied site conditions in Scots pine stands. σ^2 - total variance of the response; τ_{11} - variance associated with the random effect/slope (stand); ICC - intraclass correlation coefficient; R^2_M - marginal coefficient of determination; R^2_C - conditional coefficient of determination. Control - stands on dry mineral soils without initial preparation; Trench - stands on dry mineral soils established after disc trenching; Mounding - stands on waterlogged mineral soils with mounding; Wet - stands on waterlogged mineral soils without initial soil preparation; Peat -drained deep peat (organic) soils without initial preparation. (***): $p<0.001$; (**): $p<0.01$; (*): $p<0.05$.

Effect	Parameter	BM_{PF}		BM_{SF}		BM_{DIF}	
		Est.	χ^2	Est.	χ^2	Est.	χ^2
Fixed effects	SF mode	-	6.68*	-	8.25*	-	2.46
	break	-2.88	-	-4.19*	-	-1.54	-
	uproot	-2.96*	-	-3.57*	-	-0.87	-
	V	75.33***	228.34***	109.30***	333.09***	34.47***	131.29***
	SF mode: V	-1.52	0.06	7.27	1.06	-5.59	2.42
Random Effects	σ^2	22.80	-	32.36	-	13.74	-
	$\tau_{11\ site.vol:break}$	94.94	-	133.73	-	18.11	-
	$\tau_{11\ site.vol:uproot}$	93.96	-	87.14	-	20.74	-
	ICC	0.28	-	0.27	-	0.29	-
	N_{stand}	30	-	30	-	30	-
	N_{tree}	158	-	158	-	158	-
	R^2_M	0.89	-	0.92	-	0.70	-
	R^2_C	0.92	-	0.94	-	0.77	-

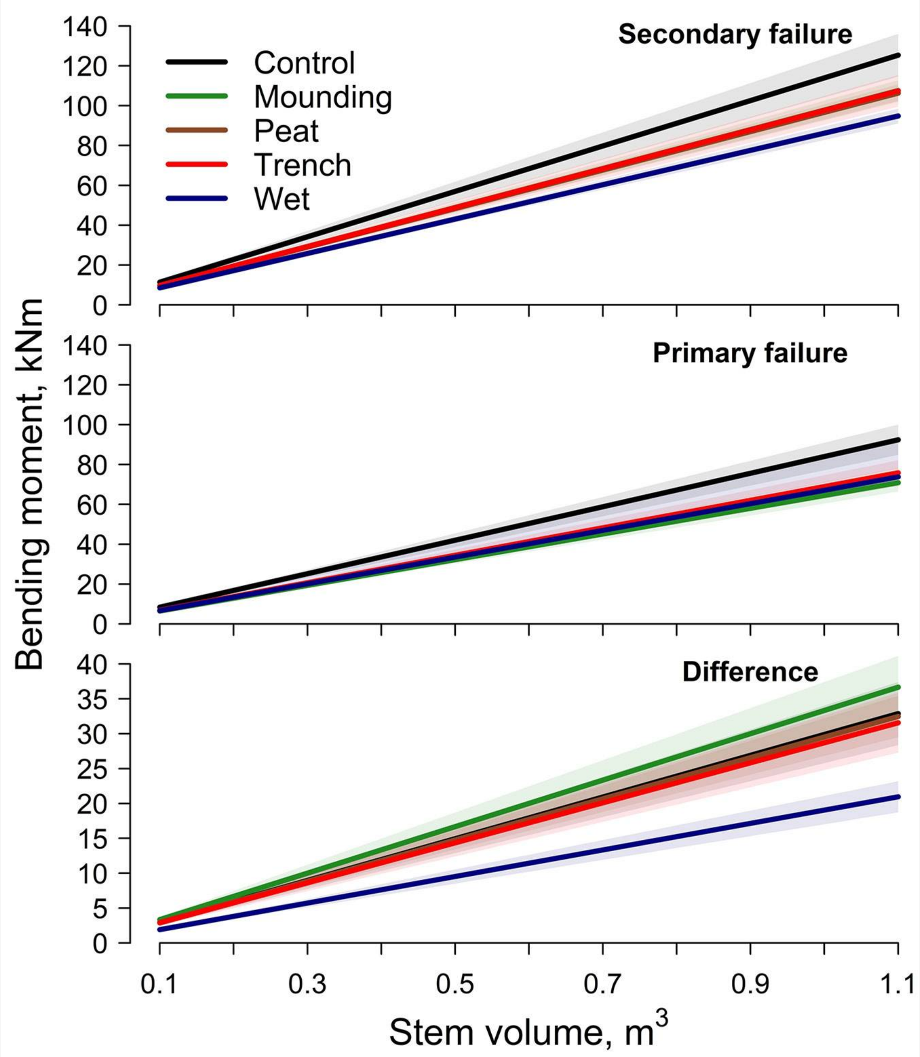

Fig. 2 - The bending moment at the stem base of Scots pine at the moment of primary and secondary failure, and the difference among the studied site conditions. The coloured area represents the 95% confidence interval. Control - stands on dry mineral soils without initial preparation; Trench - stands on dry mineral soils established after disc trenching; Mounding - stands on waterlogged mineral soils with mounding; Wet - stands on waterlogged mineral soils without initial soil preparation; Peat - drained deep peat (organic) soils without initial preparation.

Tab. 7 - Estimates (Est.), strength (Wald's χ^2), and significance of the fixed effects from linear mixed-effects models (model ANOVA) for stemwood volume (V, m^{-3}), type of soil preparation in Scots pine stands, and their interaction on the bending moment at the stem base, expressed per stemwood volume, for both primary (BM_{PF}, kNm m^{-3}) and secondary failures (BM_{SF}, kNm m^{-3}), and their difference (BM_{DIF}, %). The table also includes the random-effect variances for site and model performance metrics (R^2) for Scots pine under the studied site conditions. σ^2 - total variance of the response; τ_{11} - variance associated with the random effect/slope (stand); ICC - intraclass correlation coefficient; R^2_M - marginal coefficient of determination; R^2_C - conditional coefficient of determination. Control - stands on dry mineral soils without initial preparation; Trench - stands on dry mineral soils established after disc trenching; Mounding - stands on waterlogged mineral soils with mounding; Wet - stands on waterlogged mineral soils without initial soil preparation; Peat - drained deep peat (organic) soils without initial preparation. (***): p<0.001; (**): p<0.01; (*): p<0.05.

Effects	Predictors	BM_{PF}		BM_{SF}		BM_{DIF}	
		Est.	χ^2	Est.	χ^2	Est.	χ^2
Fixed effects	V	100.83***	204.78***	142.02***	390.94***	39.65***	65.48***
	Soil	-	16.52**	-	26.32***	-	5.16
	Control	-12.09***	-	-17.92***	-	-5.05	-
	Mounding	-1.89	-	-1.20	-	0.52	-
	Peat	-4.01	-	-4.85	-	-0.72	-
	Trench	-2.38	-	-1.54	-	0.67	-
	Wet	-0.72	-	-0.54	-	0.41	-
	V : Soil	-	14.58**	-	33.20***	-	11.40*
	Mounding	-30.22**	-	-40.36**	-	-7.90	-
	Peat	-27.95**	-	-38.16***	-	-8.88	-
	Trench	-26.46*	-	-40.60***	-	-11.89	-
	Wet	-33.10**	-	-55.51***	-	-22.38**	-
Random effects	σ^2	25.66	-	35.85	-	12.91	-
	$\tau_{11\ stand:vol}$	28.09	-	16.87	-	12.77	-
	ICC	0.18	-	0.09	-	0.17	-
	N_{stand}	30	-	30	-	30	-
	N_{tree}	158	-	158	-	158	-
	R^2_M	0.90	-	0.93	-	0.76	-
	R^2_C	0.92	-	0.94	-	0.80	-

ters across all tested groups, suggesting that differences in mechanical stability were not primarily driven by systematic variation in root plate dimensions. Nevertheless, descriptive values indicated wider soil-root plates for Control and Trench (dry mineral soils), whereas for relatively waterlogged conditions (Mounding, Peat, Wet), they were smaller (Tab. 3). Also, larger relative depths were observed for Control, Trench, and Peat (Tab. 3).

Failure modes and loading resistance

To address Research Questions (1) and (2), differences in loading resistance and failure characteristics were analyzed across contrasting site conditions that represent combinations of soil type and site-specific soil preparation methods. We found that mechanical stability was highest for Control, whereas pines in Wet and Peat stands exhibited reduced stability; Mounding did not provide a clear long-term stability advantage over unprepared waterlogged sites (Wet), resulting in a greater prevalence of uprooting.

The frequency of stem breakage as a mode of SF ranged from 26% in Wet to 52% in Trench stands, respectively (Tab. 3). Control and Peat stands exhibited intermediate stem-breakage frequencies (35% and 42%, respectively), indicating notable variation in modes of fatal failure among the studied groups. Trees that experienced stem breakage tended to exhibit higher BM_{PF}, BM_{SF}, and BM_{DIF} values than uprooted trees; however, these differences were not statistically significant (p > 0.05 – Tab. 5). Consistently, the mode of SF had no significant effect on BM_{DIF} in the linear mixed-effects models (Tab. 6), indicating that uprooting and stem breakage are associated with similar post-yield resistance. V was the strongest tree-size covariate explaining variation in BM_{PF} and BM_{SF}, as well as BM_{PDIF} in relation to the mode of SF (p < 0.001 – Tab. 6). In contrast, the interaction between failure mode and V was not significant for any response variable (p > 0.05 – Tab. 6). The random effect (stand) level accounted for approximately 27-29% of the total variance (ICC), highlighting the relatively high importance of local conditions in determining failure mode and mechanical stability. The model's explanatory power was high, with marginal R^2 values ranging from 0.70 to 0.92 and conditional R^2 values up to 0.94 (Tab. 6).

Mechanical stability differed among the tested site conditions, as the BM at the stem base, expressed per stemwood volume, varied (Tab. 3, Tab. 5, Fig. 2). Site conditions had a significant effect on BM_{PF} and BM_{SF}, but not on BM_{DIF} (Tab. 7), indicating that while the onset of internal damage and the resistance to PF and SF varied, the post-failure stability margin remained relatively consistent. For BM_{PF}, the highest resistance was observed in Control, which differed significantly (p < 0.05) from Peat and Wet trees (Tab. 5). Similarly, BM_{SF} were highest in Control, while all other site conditions altogether formed a homogeneous group with significantly lower resistance (Tab. 5). The BM_{DIF}, representing the remaining mechanical capacity after PF, was also highest in Control and lowest in Wet stands, as they differed significantly (p < 0.05) from each other (Tab. 5). In linear mixed-effects models, V was the best tree-size covariate for explaining variation in both BM_{PF} and BM_{SF}, as well as BM_{DIF} (p < 0.001 – Tab. 7, Fig. 2). Meanwhile, significant interactions between V and site conditions were observed for all tested parameters of loading resistance (p < 0.001 – Tab. 7). Random effect (stand) accounted for 9-18% of the total variance (ICC), while model explanatory power was high, with marginal R^2 values ranging from 0.76 to 0.93 and conditional R^2 values up to 0.94 (Tab. 7).

Discussion

Our results show that the mechanical stability of mid-aged Scots pine varies across site conditions, addressing Research Question (1) and suggesting that these differences might have important implications under the increasingly disturbance-prone climate of Northern Europe (Hanewinkel et al. 2013, Seidl et al. 2014). Scots pine stands of Control (unprepared freely draining mineral soils) consistently exhibited the highest mechanical stability characterised by resistance to both PF (primary failure), SF (secondary failure), as well as the largest post-primary failure stability margin quantified by BM_{DIF} (Tab. 3, Tab. 5, Tab. 7, Fig. 2). These stands also showed the lowest risk of uprooting, indicating higher potential of resistance to wind disturbances. In contrast, Wet (unprepared, waterlogged mineral soils) and Peat (drained peat soils) showed consistently reduced stability and greater susceptibility to uprooting, indicating an increased risk of damage under amplified storminess. Soil preparation by mounding did not provide a clear long-term improvement in stability compared with unprepared Wet sites, suggesting limited effectiveness in mitigating windthrow risk under such site conditions. From a management perspective, regeneration strategies should prioritize selecting site-adapted species and consider the inherent limitations of wetter soils, where alternative species, *e.g.*, birch (Krišans et al. 2020a), may provide greater long-term stability.

As no single dominant explanatory factor was identified in the models (Tab. 7), we speculate that the superior mechanical performance of Control trees reflects the combined effects of several factors, including larger RPW and RPD and lower G associated with larger stems (Helmisaari et al. 2007). Generally, larger trees, especially in terms of V, are reported to have increased resistance to both PF and SF because higher BM is required to initiate structural failure, as loading resistance generally increases with tree size (Krišans et al. 2022a, Krišans et al. 2023). Lower θ_g and higher ρ_{Soil} (Tab. 1, Tab. 2, Tab. 3) might have also contributed to the superior mechanical performance of Control trees (Peltola et al. 1999, Gardiner et al. 2016), as higher ρ_{Soil} increases the mechanical strength of the soil matrix by improving particle contact and interlocking, which enhances soil shear strength and root-soil friction (Nicoll et al. 2006, Coutts 1986), particularly under relatively dry to moderately moist conditions (Peltola et al. 1999). A similar but inverse combination of factors likely explains the significantly lower BM_{DIF} observed in Wet stands (Tab. 1, Tab. 2, Tab. 3).

A comparable limitation in mechanical stability may also explain the relatively low loading resistance observed in Peat stands, despite the relatively larger stem dimensions (Nicoll et al. 2006, Gardiner et al. 2008 – Tab. 1, Tab. 2). Moreover, no specific root adaptations were observed in these stands, contrary to expectations based on studies of older Scots pine or other species of similar size (Seipulis et al. 2024) as well as in other species of similar age and size (Krišans et al. 2020a, 2020b, 2022a). As stands mature and structural competition stabilizes, mechanical stability shifts from being primarily collective (stand-level) to increasingly determined by individual tree characteristics (Nicoll & Ray 1996, Pukkala et al. 2016, Telewski & Moore 2017).

The studied Peat stands represent relatively recent growing conditions in northeastern Europe, emerging from forest drainage and melioration since the 1960s (Peltomaa 2007). Accordingly, genotypes adapted to mineral soils may be insufficiently acclimated to deep peat conditions (Krišans et al. 2022b). The origin of the forest regeneration material used to establish the studied stands is unknown; yet, considering conventional forestry practices, generic sources were likely used, which would minimize differences in adaptation to local site conditions of the studied stands (Stanturf et al. 2014). Such interpretation is supported by the relatively low influence of microsite conditions on loading resistance, as indicated by the ICC (Tab. 7). Accordingly, trees from all tested groups may have tended to behave similarly while maintaining traits crucial for mechanical stability (Nicoll & Ray 1996, Telewski & Moore 2017, Krišans et al. 2020a, 2020b, Gardiner 2021, Seipulis et al. 2024), with some groups showing higher success (*e.g.*, Control) and others lower success (*e.g.*, Peat, Wet). The absence of site-specific acclimation might also explain the lack of differences in loading resistance observed between Wet and Mounding stands. Although mounding improves early establishment by elevating seedlings above the water table (Orlander et al. 1990, Celma et al. 2019, Duminš et al. 2025), its long-term effect on mechanical stability appears to be limited, as developing root systems ultimately depend on the surrounding soil conditions. Therefore, the establishment of Scots pine stands on mounds should be considered a supportive, rather than a decisive, measure in managing windthrow risk. In contrast, trees in Trench stands exhibited a higher frequency of stem breakage (Tab. 3), suggesting that root anchorage may have been sufficient and thus that the stems were mechanically better developed relative to stem strength (Moore et al. 2018).

Trees typically adjust growth between below- and aboveground parts in response to local conditions, balancing soil-root anchorage and height growth, supported by surrounding canopies, to maintain mechanical stability while remaining competitive for light (Telewski & Moore 2017). The relatively low frequency of stem breakage in Control trees, compared to the unexpectedly high frequency in Peat stands, can be explained by the combination of large stems that exceed root strength, thereby requiring higher loads to cause breakage, and the damping effects of peat soils (Moore et al. 2018). Under loose soil conditions, trees are likely subjected to higher wind-induced swaying frequencies (Quine & Gardiner 2007), thus specific root adaptations might take place (Nicoll & Ray 1996, Krišans et al. 2020a, 2020b), which, however, were visually apparent through the soil-root plate dimensions in this study. The dimensions of the soil-root plate are constrained by the adaptive growth of roots in response to wind and site conditions, as evidenced by the T- and I-shaped cross-sections of structural roots. Such adaptations efficiently resist vertical flexing on the tree's leeward and windward sides, respectively (Nicoll & Ray 1996). Unfortunately, we did not examine the roots in this manner in this study.

The prevailing uprooting indicated roots as the weak part in "the chain" of mechanical stability (Peltola 2006, Gardiner et al. 2016), particularly for trees in Wet stands. Weaker soil-root anchorage apparently led to significantly lower BM_{DIF} and increased likelihood of rapid failure following primary damage. Accordingly, addressing Research Question (2), the joint analysis of PF and SF, along with the BM_{DIF}, further revealed that trees in wetter soils had reduced stability after initial damage, indicating a higher likelihood of rapid collapse following PF. Trees with lower BM_{DIF} (*e.g.*, Wet trees) failed soon after the occurrence of PF, primarily due to weak soil-root anchorage rather than stem weakness, implying that trees experiencing stem breakage tend to "survive" primary failure longer, with the limiting factor shifting from roots to the stem. The relatively high ICC (Tab. 6) suggests that the mode of SF is strongly influenced by microsite conditions, highlighting the importance of individual tree resistance to loading for overall stand-level stability (Zeng et al. 2004). Nevertheless, it should be acknowledged that the observed predominance of uprooting may partly result from the methodological approach of the static pulling test, in which the pulling line is attached at half the stem height, as stems with greater basal swelling are more resistant to breakage (Peltola et al. 2000, Gardiner 2021).

In summary, the mechanical stability of Scots pine is strongly shaped by the interaction between tree size and soil conditions. Trees in dense mineral soils are better anchored but may face higher drought risk and thus greater negative impacts from secondary agents, such as pests (Seidl et al. 2017), whereas trees in wet soils are more prone to uprooting. Still, lower loading resistance can expose trees growing in relatively better-watered soils to the negative impacts of storms (Gardiner et al. 2013). Accordingly, our results highlight the need to balance such trade-offs. This could be addressed by using Scots pine planting material suited to site conditions (preferably on freely draining mineral soils), lowering initial planting density to allow young saplings to develop wind resistance, and carefully applying thinning, either avoiding it or performing it at low intensity. The productivity gains from Scots pine cultivation on drained peat soils should be considered against increased windthrow risk and broader environmental costs, including carbon losses and altered hydrological functioning, as well as the use of alternative species or mixed stands.

Limitations and future research

Although the sample size was sufficient to detect general patterns, the number of stands per site conditions was relatively limited, which may constrain the generalization of the results across the region. The applied static tree-pulling test protocol introduces methodological limitations, as the de-topping of trees and the fixed attachment height at half of the tree height may influence force distribution and the mode of SF. However, the calculation of the bending moment accounts for the missing tree top, and thus the results are expected to be comparable to those obtained using established approaches (Nicoll et al. 2006). Moreover, a previous study by Seipulis et al. (2024) has demonstrated the comparability of such approaches. The analysis of root systems was limited to generalized soil-root plate dimensions, without a detailed assessment of root architecture or structural root properties. As a result, important aspects of belowground adaptation, such as root distribution patterns and biomechanical properties, could not be fully evaluated. Future research should therefore focus on integrating high-resolution assessments of root system architecture (*e.g.*, three-dimensional root mapping), extending analyses to older stands, where long-term acclimation might be more pronounced, and comparing responses across tree species while accounting for genotypic differences. This would improve understanding of the mechanisms underlying tree stability and enhance the transferability of results for forest management under changing environmental conditions.

Conclusions

This study demonstrated that the mechanical stability of mid-aged Scots pine varies significantly across site conditions, with the highest stability observed on freely draining mineral soils, confirming the first hypothesis (1). However, the hypothesis that mounding on waterlogged sites increases individual tree stability through improved root development (2) was not supported, as no significant long-term differences were observed compared to unprepared sites. While mounding may facilitate early establishment, it did not result in advanced root development and mechanical stability compared to unprepared waterlogged sites. Instead, long-term stability of Scots pine appeared to be driven primarily by tree size and, likely, by the combined effects of multiple site factors, highlighting that soil preparation alone is insufficient to fully compensate for unfavorable soil conditions. The integration of primary and secondary failure metrics revealed that trees on wetter soils not only exhibit lower resistance but also reduced stability margins after initial damage, increasing their vulnerability to failure. Accordingly, adaptive forest management that integrates site-specific soil considerations and assessments of mechanical stability is critical to sustaining forest resilience under climate change and enhancing long-term forest stand stability in the Eastern Baltic region.

List of abbreviations

The following abbreviations are used throughout the text:

- PF - primary failure;
- SF - secondary failure;
- Control - stands on dry mineral soils without initial preparation;
- Trench - stands on dry mineral soils established after disc trenching;
- Mounding - stands on waterlogged mineral soils with mounding;
- Wet - stands on waterlogged mineral soils without initial soil preparation;
- Peat -drained deep peat (organic) soils without initial preparation.
- V - stemwood volume;
- BM - bending moment at the stem base;
- BM_{PF} - bending moment at the stem primary failure;
- BM_{SF} - bending moment at the stem secondary failure;
- BM_{DIF} - difference between BM_{PF} and BM_{SF};
- DBH - diameter at breast height;
- ρ_{Soil} - soil bulk density;
- θ_g - soil gravimetric moisture content;
- N_{Δ} - stem curvature;
- H - tree height;
- RPD - relative soil-root plate depth (attributed to the stem volume);
- RPW - relative soil-root plate width (attributed to the stem volume);
- ICC - intraclass correlation coefficient;
- N_0 - stem inclinations at the base;
- N_{5m} - stem inclination at 5 m height;
- F - pulling force;
- h_{AP1} - attachment height of the pulling line at half of tree height;
- Me_{α} - median of the angle between the pulling line and the air-line between the sample and the anchor tree.

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