Response to reviewer: the original reviewer comments are in italic and dark red, while the authors' replies are in black, with highlights in bold.

Dear Authors,

Thank you for submitting the manuscript. The study addresses an important topic on wind damage modelling and is generally well written, clearly structured, and supported by relevant literature. The integration of field data and modelling approaches provides valuable contributions to improving the understanding of wind risk for individual tree fall along powerlines in Norway using ForestGALES and machine learning.

However, several aspects of the methodology and parameter description require further clarification to ensure transparency, reproducibility, and scientific rigor. Detailed comments and points for clarification are provided in the attached PDF file for your consideration.

Overall, the manuscript has strong potential for publication. Addressing the points raised, particularly those related to methodological clarity and parameter definition, will substantially improve the robustness and reproducibility of the study.

We thank the reviewer for their time reviewing our manuscript. We address the different points raised by the reviewer for clarifying and improving the methodology and parameter description. We thank the reviewer for pointing out these to help us improve the manuscript for publication. The reviewer's original comments are provided in italic, while our replies are provided in normal text. The bold sections in each reply are suggestions for actual manuscript revisions which would be implemented in the revised manuscript at a later stage.

Detail comments and clarification of the manuscript egusphere-2025-6363:

1. L140–141: Simulation approach a. The manuscript mentions 100 simulations using 180 standing trees, but the methodology is not described. Please clarify the sampling approach assumptions and whether resampling techniques were applied.

We clarify the sampling methodology used to sample 180 standing trees in 100 independent simulations: "Considering the large imbalance in the sample sizes between the damaged and standing trees, **we used a repeated random subsampling approach for N = 100 simulations. In each of the simulations, all 180 damaged trees were combined with a randomly selected subset of 180 standing trees drawn without replacement to produce balanced datasets. The differences in the characteristics between the standing and damaged trees were evaluated in each simulation, and the results were summarized across the 100 simulations. This approach assumes independence among trees and treats each random subsample of standing trees as an equally plausible representation of the undamaged**

population. Similar results were obtained when performing the analysis on the complete unbalanced dataset."

2. L153–170: Wind speed and wind condition

a. The use of maximum wind speed at 10 m height to calculate damage probability requires further justification. Consideration of wind speeds at different reference heights could help assess whether model performance (e.g., AUC, accuracy, optimal cut-point) can be improved.

The ForestGALES model can indeed calculate the critical wind speed at different heights. Generally, wind climate data is provided at 10m height from weather stations and common raster products in wind climate datasets. Therefore, it is most common to calculate the critical wind speed at the same height for direct comparison with the climate data. This ensures consistency with standard meteorological wind products (such as the one used here). We agree that considering wind speeds at different reference heights could provide additional insight into which height best explains the observed damage patterns and may further improve model performance metrics such as AUC or classification accuracy. It is important to note that the influence of forest and other ground cover further away from the site of interest increases with the height of the wind data used. Since the objective of the study was to assess individual tree risk along powerlines, keeping the calculations as close as possible to the top of the tree – here 10m height above the zero-plane displacement – is most sensible. We acknowledge this question as a relevant and interesting direction for future research, especially when considering storm events with more complex profiles as highlighted by Zubkov et. al 2026 https://doi.org/10.1016/j.agrformet.2025.110951.

b. The manuscript focuses on maximum wind speed but does not describe the overall wind conditions during the winter 2020–2021 period. A summary of wind speed distribution (minimum, maximum, mean, and percentiles) would provide important context for interpreting the results.

This is a good point – we looked further into the overall wind conditions during the winter 2020-2021 period. **The wind conditions during the winter 2020-2021 period in the regions of interest were relatively mild as seen below in the figure. Across all locations, the mean and median wind speed at 10m during the winter 2020-2021 (all months between September 2020 and April 2021 were taken into account) were around 3 to 4 m.s^{-1}. The maximum wind speed recorded during this period (and subsequently used in the manuscript) was also quite low, just above 10 m.s^{-1}.** We add this information in the revised manuscript in the section 2.2.1. and as a supplementary figure to provide more context as suggested by the reviewer: "**The wind climate during this period (winter 2020-2021) was relatively mild, with a mean wind speed of approximately 3 to 4 m.s^{-1} and a 95th percentile between 4 and 5 m.s^{-1}. The**

maximum observed wind speed itself reflected a mild winter, with values around 10 m.s^{-1} for all locations considered here (see Appendix Figure A 1).”

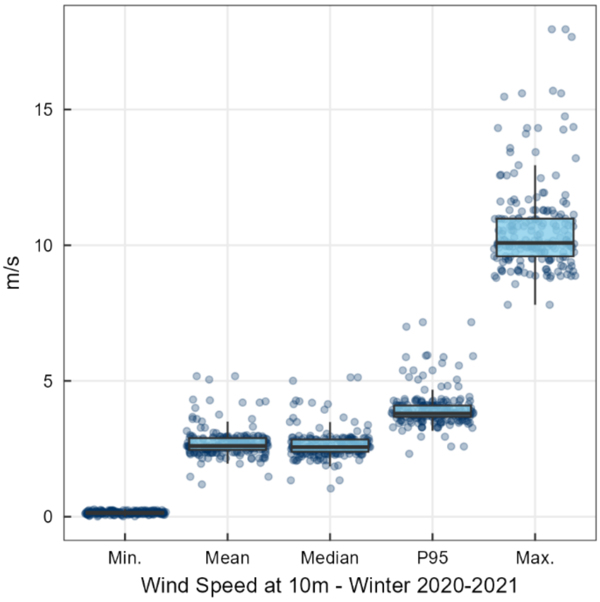


Figure 1. Statistics of the wind speed at 10m during the winter 2020-2021 (Sept. 2020 to April 2021) at the studied locations. The statistics represented are the minimum wind speed (“Min.”), the mean and median, the 95th percentile (“P95”) and the maximum wind speed (“Max.”). Individual locations are shown in the faded points, while the average over all locations is displayed with the boxplots.

> *3. L215–229: Model parameter clarification Several key variables require clearer definition to ensure reproducibility:*
>
> *a. D0 derived from DBH: Clarification is needed on how D0 is derived from DBH, including the underlying equation or assumptions. Please explain why D0 was not directly measured.*

In the ForestGALES model, the diameter at the base of the tree D_0 is derived from the diameter at breast height (DBH) using a model-internal taper relationship. It is computed as follows:

$$D_0 = DBH \times \left(\frac{H_{wa}}{H_{wa} - 1.3}\right)^{1/3}$$

where H_{wa} is the wind action point height defined as:

$$H_{wa} = \begin{cases} H - \frac{cr_{depth}}{2}, & H - \frac{cr_{depth}}{2} > 1.3 \times 2.0 \\ 1.3 \times 2.0, & otherwise \end{cases}$$

With H being total tree height and cr_{depth} is the crown depth. The two formulas assume that the surface strain and stress from wind are constant between a height of 1.3m and the stem base (first equation), and that the wind load acts in the middle of the crown (second equation).

The diameter at the base of the tree was not directly measured as part of the sampling campaign because the campaign was designed prior to the decision to run the ForestGALES was made. Base diameter is not a routinely measured tree attribute when recording tree characteristics, whereas DBH is standard practice. We didn't have any other extensive source of data to adjust the default equation to a Norwegian-specific equation, therefore, D_0 was derived using the ForestGALES default equation. In the manuscript, we would add: **$\boldsymbol{D_0}$: diameter at base (derived from DBH, tree height and crown depth using the ForestGALES default equation; m).**

b. TMC (turning moment coefficient): The definition remains unclear. Please clarify whether TMC_ratio is used and how it is parameterized.

Thank you for highlighting this point. The turning moment coefficient (TMC) is a model-derived parameter in ForestGALES. It quantifies the mechanical leverage of wind loading on an individual tree and incorporates tree size and competitive effects. In our study, we used the standard ForestGALES formulation described in the fgr package (Locatelli et al., 2022):

1. When no competition index is used:

$$T_C = 111.573 \times H \times \left(\frac{DBH}{100}\right)^2$$

2. With the BAL competition index:

$$T_C = 113.54 \times H \times \left(\frac{DBH}{100}\right)^2 - 20.494 \times C_{BAL}$$

3. With the Hegyi competition index:

$$T_C = 3.86 \times C_{HEG} + 124.252 \times H \times \left(\frac{DBH}{100}\right)^2 - 17.282 \times H \times \left(\frac{DBH}{100}\right)^2 \times C_{BAL}$$

If the competition-aware definitions of T_C yield $T_C = 0$, then T_C reverts back to the first definition, where no competition index is used. These equations are well defined in the fgr package, and thus we do not repeat them in the manuscript or the Appendices. The manuscript would however be improved by adding **$\boldsymbol{T_C}$ is the turning moment coefficient as defined in ForestGALES. It is a dimensionless parameter that represents the wind-induced turning moment acting on an individual tree, accounting for tree size and competitive environment. Further details on the calculation of $\boldsymbol{T_C}$ can be found in the fgr R package (Locatelli et al., 2022)**. In our study, no thinning operations were conducted prior to the observed damage, therefore the spacing between trees remained constant, and the TMC_ratio, i.e. the ratio of the turning moment coefficient after and before thinning, was set to 1. The manuscript would then read: **The $\boldsymbol{T_C}$ can further be modified following recent (less than 5 years) thinning operations via the TMC_ratio accounting for differences in the spacing**

between trees before and after thinning operations. Since the model was run at a single point in time with no thinning operations conducted in the 5 years prior, the TMC_ratio was set to 1.0.

c. MOE and MOR moisture condition:

• The moisture condition of the wood is not specified. Indicate whether values correspond to green or air-dried conditions (e.g., 12% MC).

• If dry values are used, clarification is needed on whether conversion to green conditions was applied, as wind damage occurs under green conditions. Reference to established conversion approaches (e.g., Unterwieser and Schickhofer, 2011) would strengthen this section.

We thank the reviewer for pointing out the missing information. The MOE and MOR values used in the study were adapted to the Norwegian conditions in the same was as in Merlin et al. (2025), using values from the Norwegian and FennoScandian literature. In short, **The MOR and MOE values were extracted from (Fischer et al., 2016) and (Høibø and Vestøl, 2010) for spruce and pine growing in Norway and from (Peltola et al., 2000) for birch. The spruce and pine values were obtained from dry boards (spruce) and logs (pine) at 12 % moisture content. The conversion to green wood values used in the ForestGALES model was made following the method of (Unterwieser and Schickhofer, 2011) used by (Locatelli et al., 2016). The new values are summarized in a Supplementary Table, along with the equations for the dry to greenwood conversion.** We present the equations here:

$$MOE_{greenwood} = \frac{MOE_{MCtest}}{1 - 0.00825 \cdot (\, MC_{test} - FSP)}$$

$$MOR_{greenwood} = MOR_{MCtest} - \left(MOR_{MCtest} \frac{FSP - MC_{test}}{100} \right)$$

Table S 1. Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) values used in the Norwegian (NO) parametrization of ForestGALES.

Species	**MOR (kN/mm^2)**		**MOE (N/mm^2)**	
	default	new value	default	new value
Norway spruce	36	41.2 *(Fischer et al., 2016)*	6.3	11.8 *(Fischer et al., 2016)*
Scots pine	46	55.0 *(Høibø and Vestøl, 2010)*	7.3	12.1 *(Høibø and Vestøl, 2010)*
Birch	63	53.6 *(Peltola et al., 2000)*	9.9	11.06 *(Peltola et al., 2000)*

d. f_{knot} parameter: The magnitude and derivation of f_{knot} are not described. Provide typical values or ranges and clarify whether this factor is measured, empirically derived, or sourced from literature.

The parameter f_{knot} is a species-specific factor accounting for the reduction in wood strength due to the presence of knots. This parameter is not measured at the individual tree level. In this study, the f_{knot} values used in this study were the default values from the ForestGALES model and documentation, with no further modifications to the Norwegian conditions. Quantitative data describing knot characteristics of individual trees in Norway and their relationship to wind vulnerability within the ForestGALES framework was not explored in this study and are likely unavailable. Using the default values avoided introducing poorly defined values. The default f_{knot}values are as follows: 0.9 for Norway spruce, 0.85 for Scots pine and 1.0 for birch.

In the manuscript, we would therefore add: **The parameter f_{knot} is a species-specific factor accounting for the reduction in wood strength due to the presence of knots. The default value from the ForestGALES model and fgr for each of the species considered was used here, namely 0.9 for Norway spruce, 0.85 for Scots pine and 1.0 for birch.**

e. W_{stem} definition: The definition of W_{stem} is unclear. Specify whether it represents total stem weight or a defined portion (e.g., merchantable stem). Please clarify whether it is directly measured or estimated using empirical models.

We thank the reviewer for pointing this gap in the variable definition. **The W_{stem} is the total stem weight defined as the total stem volume multiplied by the stem density. The stem volume was estimated using species-specific models defined and routinely used by the Norwegian National Forest Inventory**. The equations are defined in the Appendix of (Merlin et al., 2025) as written in the manuscript line 115, however we consider adding this information in a Supplementary Table. We display the proposed table below:

Table S 2. Norwegian specific allometric and dendrometric equations for estimating mean stem volume and crown depth. Stem volume is calculated following the equations used in the Norwegian National Forest Inventory (Braastad, 1966; Brantseg, 1969; Vestjordet, 1967). The crown depth equations were based on the latest available complete NFI dataset (2016-2020 period). A summarized evaluation of the crown depth models is presented in ***Feil! Fant ikke referansekilden.****.*

Tree variable	Species	Region	DBH class	Equations	Parameter values
Stem volume (m^3)	Norway spruce	West		$V_{stem} = \frac{1}{1000}(a_0 \cdot h^{a_1} \cdot DBH^{a_2} \cdot (h - 1.3)^{a_3} \cdot (DBH + 40)^{pa_4})$	$a_0 = 0.6844; a_1 = 3.0296; a_2 = 2.056; a_3 = -1.7377; a_4 = -0.9756$
		Other	Small (< 10.1 cm in DBH)	$V_{stem} = \frac{1}{1000}(a_0 + a_1 \cdot DBH^2 \cdot h + a_2 \cdot DBH \cdot h^2 + a_3 \cdot h^2 + a_4 \cdot h \cdot DBH)$	$a_0 = 0.52; a_1 = 0.02403; a_2 = 0.01463; a_3 = -0.10983; a_4 = 0.15195$
			Medium	$V_{stem} = \frac{1}{1000}(a_0 + a_1 \cdot DBH \cdot h^2 + a_2 \cdot h^2 + a_3 \cdot DBH \cdot h + a_4 \cdot h + a_5 \cdot DBH)$	$a_0 = -31.57; a_1 = 0.0016; a_2 = 0.0186; a_3 = 0.63; a_4 = -2.34; a_5 = 3.2$
			Large (≥ 12.9 cm in DBH)	$V_{stem} = \frac{1}{1000}(a_0 + a_1 \cdot DBH^2 \cdot h + a_2 \cdot DBH \cdot h^2 + a_3 \cdot h^2 + a_4 \cdot h \cdot DBH)$	$a_0 = 10.14; a_1 = 0.0124; a_2 = 0.03117; a_3 = -0.36381; a_4 = 0.28578$
	Scots pine	West		$V_{stem} = \frac{1}{1000}(a_0 \cdot h^{a_1} \cdot DBH^{a_2} \cdot (h - 1.3)^{a_3} \cdot (DBH + 100)^{a_4})$	$a_0 = 0.1424; a_1 = 2.0786; a_2 = 1.9028; a_3 = -1.0259; a_4 = -0.264$
		Other	Small (< 11.1 cm in DBH)	$V_{stem} = \frac{1}{1000}(a_0 + a_1 \cdot DBH^2 + a_2 \cdot DBH^2 \cdot h + a_3 \cdot DBH \cdot h^2)$	$a_0 = 0.6716; a_1 = 0.075708; a_2 = 0.029679; a_3 = 0.004341;$
			Large (≥ 11.1 cm in DBH)	$V_{stem} = \frac{1}{1000}\left(a_0 + a_1 \cdot DBH^2 + a_2 \cdot DBH^2 \cdot h + a_3 \cdot DBH^2 \cdot \left(3.17935 + 1.0289 \cdot DBH - 0.27023 \cdot \frac{DBH}{h}\right)\right)$	$a_0 = -6.3954; a_1 = 0.178053; a_2 = 0.03317; a_3 = -0.003008;$
	Birch			$V_{stem} = \frac{a_0}{1000}(a_1 + a_2 \cdot DBH^2 + a_3 \cdot DBH^2 \cdot h + a_4 \cdot DBH \cdot h^2 + a_5 \cdot h^2)$	$a_0 = 0.1; a_1 = -18.6827; a_2 = 2.1461; a_3 = 0.1283; a_4 = 0.138; a_5 = -0.6311$

Crown depth (m)	Norway spruce	$l = \frac{1}{10}(b_0 + b_1 \cdot DBH + b_2 \cdot h + b_3 \cdot DBH^2 + b_4 \cdot h^2)^2$ Note that $l = h$ if $\frac{1}{10}(b_0 + b_1 \cdot DBH + b_2 \cdot h + b_3 \cdot DBH^2 + b_4 \cdot h^2)^2 > h$	$b_0 = 6.747673534; b_1 = 0.009887979; b_2 = 0.013019764; b_3 = 0$
	Scots pine		$b_0 = 5.202627248; b_1 = 0.003258464; b_2 = 0.026770534; b_3 = 0; b_4 = -3.27 \cdot 10^{-5}$
	Birch		$b_0 = 3.825279667; b_1 = 0.021639414; b_2 = 0.018076998; b_3 = -2.44 \cdot 10^{-5}$

Braastad, H., 1966. Volumtabeller for bjørk [Volume tables for birch] (No. 21: 23-78), Meddelelser fra Det norske Skogforsøksvesen.

Brantseg, A., 1969. Furu sønnafjells. Kubering av stående skog. Funksjoner og tabeller [Volume functions and tables for Scots Pine. South Norway] (No. 22: 695-739), Meddelelser fra Det norske Skogforsøksvesen. Det norske skogforsøksvesen.

Vestjordet, E., 1967. Funksjoner og tabeller for kubering av stående gran [Functions and tables for volume of standing trees. Norway spruce] (No. 22), Meddelelser fra Det norske Skogforsøksvesen.

4. *L280: Please add a dot between 0.1 and the cut-point.*

We make the change in the manuscript.

5. *L288–289: Model performance assessment*

    a. *The procedure for conducting 100 repetitions of balanced damaged and undamaged samples is not clearly described. Please clarify how datasets were balanced and whether resampling or cross-validation was applied in the AUC assessment.*

As described in the reply to a similar point (see point 1.), we used a repeated random subsampling approach, but no cross-validation. We update the manuscript to use a more consistent terminology of "repeated assessments" rather than "simulations" and add: "**For each of the N = 100 repeated assessments, all 180 damaged trees were combined with a randomly selected subset of 180 standing trees drawn without replacement to produce balanced datasets. The model performance was evaluated in each assessment using ROC analysis, and the results were summarized across the 100 repeated assessments. This approach did not involve cross-validation, instead using a repeated random subsampling (Monte Carlo resampling). It treats each random subsample of standing trees as an equally plausible representation of the undamaged population. Similar results were obtained when performing the analysis on the complete unbalanced dataset.**" We used repeated random subsampling rather than cross-validation because the goal was to assess the robustness of the model discrimination in the study's conditions, under a strong class imbalance.

6. *L359–363 (Table 1): Please include the number of trees for damaged and standing categories for each species.*

We add the number of trees for damaged and standing categories for each of the species:

Variable	Species	Damaged	Standing	U value	p-value	Comment
Number of trees	all	180	18189			
	Birch	48	8106			
	Norway spruce	76	4873			
	Scots pine	56	5210			
Tree height	all	14.05 *(5.09)*	18.36 *(4.79)*	8803.6	***	Damaged trees are smaller
	Birch	13.89 *(5.07)*	18.77 *(4.44)*	844.2	***	
	Norway spruce	15.85 *(5.39)*	18.41 *(4.88)*	1519.4	*	
	Scots pine	12.62 *(4.25)*	17.95 *(5.01)*	580.1	***	
Tree DBH	all	20.93 *(9.96)*	27.23 *(11.56)*	8940.3	*	Damaged trees are thinner
	Birch	20.79 *(13.15)*	31.12 *(17.87)*	792.3	*	
	Norway spruce	18.58 *(5.09)*	21.74 *(4.72)*	1338.7	**	
	Scots pine	23.33 *(6.52)*	31.35 *(7.74)*	579.6	***	

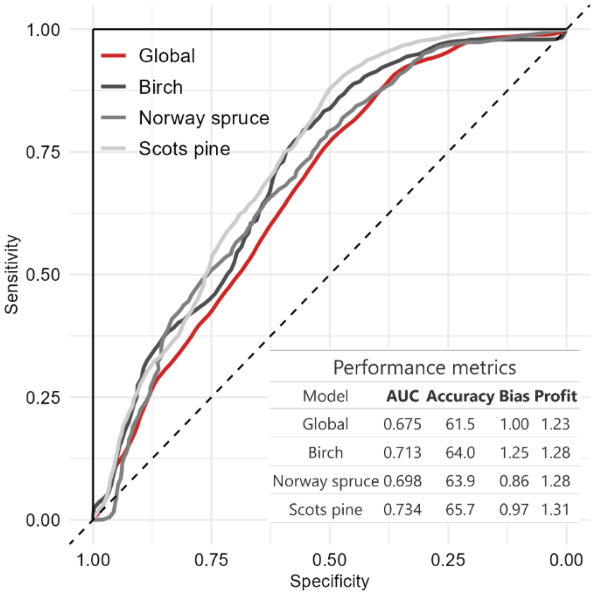
H/d ratio	all	0.71 *(0.17)*	0.69 *(0.16)*	15375	ns	No difference
	Birch	0.66 *(0.12)*	0.69 *(0.15)*	2027.1	ns	
	Norway spruce	0.84 *(0.12)*	0.84 *(0.11)*	1952.6	ns	
	Scots pine	0.58 *(0.11)*	0.54 *(0.09)*	1011.4	ns	

7. *L395–399 (Table 2): Please include the number of samples used for each model and the associated damage threshold.*

The table 2 shows the average of the 100 repeated assessments of the AUC, accuracy and cutpoint of the best global and species-specific models. Each assessment was done on a balanced subsample of $N_{damaged} = 180 = N_{standing}$. Since we worked at the individual tree scale, with a simple binary outcome of Damaged / Undamaged, we did not use a damage threshold (as defined as when working at the stand level where we need to set a damage threshold to decide when the stand is damaged). If the reviewer means the cutpoint; the probability threshold at which Sensitivity and Specificity are equal, it was defined for each of the 100 repeated assessments and the average reported in Table 2. We clarify this in the manuscript, in the table caption, with "**the cutpoint is the probability threshold where model Sensitivity and Specificity are equal**".

8. *L401 (Figure 3): Please provide the total number of samples for each model, including cutpoint and damage threshold, within the performance metrics.*

The figure Figure 3 in the manuscript shows the Receiver Operator Characteristic (ROC) curve and performance metrics for each of the best models (global and species-specific) when considering the entire dataset as described in the figure caption: "All samples were used in this figure ($N_{damaged} = 180; N_{standing} = 18{,}189$). This is slightly different than the results presented in Table 2 where the model performance reported there are the average of the 100 repeated assessments on the balanced subsamples of N = 180 for each of the categories (damaged and standing). It is important to note that the ROC and AUC routines in R are quite robust against unbalanced datasets, so the results using the entire dataset or the 100 repeated assessments of the balanced subsamples are very similar. Nevertheless, to improve the consistency of the methods and results in the manuscript, we update Figure 3 using the averaged results from the 100 repeated assessments. The new figure is shown here:



Performance metrics

Model	**AUC**	**Accuracy**	**Bias**	**Profit**
Global	0.675	61.5	1.00	1.23
Birch	0.713	64.0	1.25	1.28
Norway spruce	0.698	63.9	0.86	1.28
Scots pine	0.734	65.7	0.97	1.31

Figure 2. Receiver Operator Characteristic (ROC) curve and performance metrics for the prediction of the probability of tree damage during the winter 2020-2021 using the best global and species-specific model options (see Feil! Fant ikke referansekilden.). The average of the 100 repeated assessments using balanced sample of $N_{damaged} = N_{undamaged} = 180$ *was used for the figure. The AUC is shown in the table, along with the summary of the average performance metrics (Accuracy in percentage, Bias, and Profit scores) for the cutpoint at which Sensitivity = Specificity.*

References used in the reply to reviewer:

Braastad, H.: Volumtabeller for bjørk, 1966.

Brantseg, A.: Furu sønnafjells. Kubering av stående skog. Funksjoner og tabeller, Det norske skogforsøksvesen, 1969.

Fischer, C., Vestøl, G. I., and Høibø, O.: Modelling the variability of density and bending properties of Norway spruce structural timber, Can. J. For. Res., 46, 978–985, https://doi.org/10.1139/cjfr-2016-0022, 2016.

Høibø, O. and Vestøl, G. I.: Modelling the variation in modulus of elasticity and modulus of rupture of Scots pine round timber, Can. J. For. Res., 40, 668–678, https://doi.org/10.1139/X10-021, 2010.

Locatelli, T., Gardiner, B., Tarantola, S., Nicoll, B., Bonnefond, J.-M., Garrigou, D., Kamimura, K., and Patenaude, G.: Modelling wind risk to Eucalyptus globulus (Labill.) stands, Forest Ecology and Management, 365, 159–173, https://doi.org/10.1016/j.foreco.2015.12.035, 2016.

Locatelli, T., Gardiner, B., Hale, S., and Nicoll, B.: fgr: r Version of the ForestGALES wind risk model. R package version 1.0, 2022.

Merlin, M., Locatelli, T., Gardiner, B., and Astrup, R.: Large-scale modelling wind damage vulnerability through combination of high-resolution forest resources maps and ForestGALES, Forest Ecosystems, 14, 100361, https://doi.org/10.1016/j.fecs.2025.100361, 2025.

Peltola, H., Kellomäki, S., Hassinen, A., and Granander, M.: Mechanical stability of Scots pine, Norway spruce and birch: an analysis of tree-pulling experiments in Finland, Forest Ecol. Manag., 135, 143–153, https://doi.org/10.1016/S0378-1127(00)00306-6, 2000.

Unterwieser, H. and Schickhofer, G.: Influence of moisture content of wood on sound velocity and dynamic MOE of natural frequency- and ultrasonic runtime measurement, Eur. J. Wood Prod., 69, 171–181, https://doi.org/10.1007/s00107-010-0417-y, 2011.

Vestjordet, E.: Funksjoner og tabeller for kubering av stående gran, 1967.