

Estimation of the static modulus of elasticity of wood from the dynamic modulus of elasticity

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Abstract

Aim of study: Analyze the behavior and predictive capacity of different non-destructive testing (NDT) methods—ultrasound, longitudinal and transverse vibrations, and static bending—for estimating the MOEGTO in two species of great forestry interest in Europe: *Pinus sylvestris* and *Populus × euramericana*. Additionally, this study focuses on developing global prediction models for MOEGTO using the NDT modulus of elasticity from both species, and on improving the reliability of prediction through the cross-validation process.

Area of study: Provenance Region 8 (Northern Iberian System, Spain) and Ribera del Carrión (Palencia, Spain).

Material and methods: A total 75 sawn lumber samples (45 of *Pinus sylvestris* and 30 of *Populus × euramericana*) with dimensions of 60 × 40 × 1200 mm were analyzed using ultrasonic testing, longitudinal and transverse vibration methods, and both destructive and non-destructive static bending tests performed with a universal testing machine. Regression models were developed to predict the static modulus of elasticity (MOEGTO).

Main results: The prediction model using the NDT method of longitudinal vibrations with Fast Fourier Transform (FFT) software for *Pinus sylvestris* showed the highest coefficient of determination with $R^2=0.56$, while for *Populus × euramericana*, the ultrasound method with the Sylvatest 4 device yielded $R^2=0.67$. For both species, the best-fit global prediction model was obtained with the ultrasound method using the Sylvatest Trio device, achieving $R^2=0.60$. Additionally, the application of cross-validation improved the predictive performance of the global models, particularly for the three ultrasound methods and the longitudinal vibration method, all of which attained R^2 values above 0.6.

Research highlights: This study confirms the reliability of ultrasound and longitudinal vibration techniques for estimating MOEGTO and contributes new insights by comparing multiple NDT methods across two species and developing robust cross-validated global prediction models.

Keywords: longitudinal vibrations; non-destructive testing; *Pinus-sylvestris*; *Populus × euramericana*; static bending; transversal vibrations; ultrasound.

Estimación del módulo de elasticidad estático de la madera a partir del módulo de elasticidad dinámico

Resumen

Objetivo del estudio: Analizar el comportamiento y la capacidad predictiva de diferentes métodos de ensayos no destructivos (END)—ultrasonidos, vibraciones longitudinales y transversales, y flexión estática—

para la estimación del módulo de elasticidad estático (MOEGTO) en dos especies de gran interés forestal en Europa: *Pinus sylvestris* y *Populus × euramericana*. Además, este estudio se centra en el desarrollo de modelos de predicción global del MOEGTO utilizando el módulo de elasticidad NDT de ambas especies, y en la mejora de la fiabilidad de la predicción mediante el proceso de validación cruzada.

Área del estudio: Región de procedencia 8 (Sistema Ibérico Septentrional, España) y Ribera del Carrión (Palencia, España).

Material y métodos: Se analizaron 75 muestras de madera aserrada (45 de *Pinus sylvestris* y 30 de *Populus × euramericana*) con dimensiones de 60 × 40 × 1200 mm mediante ensayos de ultrasonido, vibración longitudinal y transversal, y ensayos de flexión estática, tanto destructivos como no destructivos, realizados con una máquina de ensayos universal. Se desarrollaron modelos de regresión para predecir el módulo de elasticidad estático (MOEGTO).

Resultados principales: El modelo de predicción mediante el método END de vibraciones longitudinales con el software de Transformada Rápida de Fourier (FFT) para *Pinus sylvestris* mostró el mayor coeficiente de determinación con $R^2 = 0.56$, mientras que para *Populus × euramericana*, el método de ultrasonido con el dispositivo Sylvatest 4 arrojó un $R^2 = 0.67$. Para ambas especies, el modelo de predicción global con mejor ajuste se obtuvo con el método de ultrasonido utilizando el dispositivo Sylvatest Trio, logrando un $R^2 = 0.60$. Además, la aplicación de la validación cruzada mejoró el rendimiento predictivo de los modelos globales, en particular para los tres métodos de ultrasonido y el método de vibración longitudinal, los cuales alcanzaron valores de R^2 superiores a 0.6

Aspectos destacados de la investigación: Este estudio confirma la fiabilidad de las técnicas de ultrasonido y vibración longitudinal para estimar MOEGTO y aporta nuevos conocimientos al comparar múltiples métodos NDT en dos especies y desarrollar modelos de predicción global sólidos y validados de forma cruzada.

Palabras clave: ensayos no destructivos; flexión estática; *Pinus sylvestris*; *Populus × euramericana*; ultrasonido; vibraciones longitudinales; vibraciones transversales.

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Introduction

Non-Destructive Testing (NDT) dedicated to the study of wood encompasses a set of techniques and tools that allow for the estimation of the physical-mechanical properties of the materials under study, as well as the determination of the quality and suitability of the pieces for structural applications. Essentially, NDT is based on the premise of using non-invasive techniques to examine materials without affecting their structure or compromising their final use capacity (Uzcategui et al., 2023).

Among the main non-destructive techniques and methods focused on evaluating the characteristics and technological properties of wood, ultrasound, induced transverse and longitudinal vibrations, as well as non-destructive static bending tests, stand out (Schimleck et al., 2019).

Ultrasound testing is one of the most commonly used methods due to its high sensitivity and versatility in applications across various fluids and materials (Wang et al., 2022). Specifically, for wood, this procedure involves the use of devices equipped with piezoelectric transducers that measure the time of flight (ToF) of ultrasound through the material, which, in conjunction with the sample length, allows for the determination of ultrasonic velocity, used to assess the modulus of elasticity (Bucur, 2006).

Ultrasound technology initially found practical applications in wood studies for detecting and locating internal defects in sawn timber (McDonald et al., 1969). The most significant increase in the use of ultrasound technology occurred from the 2000s onward, driven by the development of portable, user-friendly devices,

among which equipment such as Sylvatest® and Fakopp Microsecond Timer® became widely adopted due to their frequent use across various sectors dedicated to the evaluation of structural wood. This widespread adoption led to numerous studies, initially focusing on detecting decay or damage in standing trees (Kazemi-Najafi et al., 2009), and later expanding to the evaluation of the mechanical properties of sawn lumber, particularly for the determination and prediction of the modulus of elasticity (Van Duong & Hasegawa, 2021).

Another important method in the non-destructive evaluation of wood is the technique of induced transverse and longitudinal vibrations. These involve measuring the natural frequencies of vibration, where the direction of wave propagation can be either perpendicular (transverse vibration) or parallel (longitudinal vibration) to the fiber direction (Bube, 1992).

Similar to ultrasound testing, the most significant advancements in vibration testing took place during the 1990s, driven by the development and implementation of computer programs based on Fast Fourier Transform (FFT) technique. Consequently, these improvements facilitated the widespread adoption of these methods, particularly the use of induced longitudinal waves, for evaluating the strength and stiffness properties of wood (Arriaga et al., 2005). In more recent studies, transverse and longitudinal vibration tests have been used to evaluate the modulus of elasticity in sawn lumber from various *Pinus* species (Acuña et al., 2023; Uzcategui et al., 2023).

On the other hand, among NDT techniques, non-destructive static bending tests are also included. These tests utilize the deflection behavior of a simply supported beam under a center-point loading configuration or a cantilever beam, all without causing piece failure, preserving the structural integrity and allowing for their subsequent use.

Non-destructive static bending, along with ultrasound and transverse vibration tests, has been employed to assess the mechanical properties of sawn wood from *Pseudotsuga menziesii* (Mirb.) Franco and *Cryptomeria japonica* (L.f.) D. Don (Yang et al., 2008). Additionally, other studies have focused on the application of static bending to cantilever beams for measuring the static flexural modulus and comparing it with the dynamic modulus of solid wood (Guo et al., 2009).

The wide variety of NDT methodologies currently available has played a significant role in the analysis and characterization of the technological properties of wood. However, despite the extensive research in the field of NDT, some studies have focused on applying NDT methods for predicting the mechanical properties of timber pieces from existing structures (Arriaga et al., 2022; Osuna-Sequera et al., 2023). Other examples include studies on the effect of cross-section (Osuna-Sequera et al., 2020), piece length (Osuna-Sequera et al., 2021) and the influence of wood moisture content on the modulus of elasticity (Carreira et al., 2022). Similarly, research has focused on comparing two or even three NDT methods with conventional static bending tests in accordance with EN 408 standards (Pošta et al., 2016; Hodoušek et al., 2017).

Currently, there is a need to compare the most widely used non-destructive testing techniques to assess their reliability relative to traditional static bending tests. Based on this, the main objective of this article is to analyze the behavior and predictive capacity of different NDT methods—ultrasound, longitudinal and transverse vibrations, and static bending—for estimating the static modulus of elasticity (MOEGTO) in two species of great forestry interest in Europe: *Pinus sylvestris* L. and *Populus × euramericana* (Dode) Guinier, clone I-214. Additionally, this study focuses on developing global prediction models for MOEGTO using the NDT modulus of elasticity from both species, and on improving the reliability of prediction through the cross-validation process.

Material and methods

Test materials

The tests were conducted on two species: *Pinus sylvestris* L. from Provenance Region 8 (Northern Iberian System, Spain) and *Populus × euramericana* (Dode) Guinier, clone I-214 from Ribera del Carrión (Palencia, Spain). The study material consisted of 75 lumber pieces (45 of *P.s sylvestris* and 30 of *P. × euramericana*) with dimensions of 60 × 40 × 1200 mm, in accordance with the dimensional requirements established by the EN 408:2011 standard (AENOR, 2011). The pieces were conditioned in the Wood Laboratory of the University of Valladolid, Palencia Campus, Spain, at 65 ± 5% relative humidity (RH) and 20 ± 2 °C until reaching constant mass according to the UNE 408:2011 standard (AENOR, 2011). All samples were measured and weighed to determine their density at 12% moisture content (MC), in accordance with the EN 384:2016

standard (AENOR, 2016). The moisture content of the samples was calculated on a slice taken from them in accordance with Standard EN 13183-1:2002 (AENOR, 2002).

Ultrasonic tests

The propagation velocity of ultrasonic waves was measured using three devices: the Fakopp Microsecond Timer ($E_{\text{dyn_Ultra1}}$) - Fakopp, Sopron, Hungary, equipped with 23 kHz pin sensors; the Sylvatest Trio ($E_{\text{dyn_Ultra2}}$); and the Sylvatest 4 ($E_{\text{dyn_Ultra3}}$) - CBS-CBT, Lausanne, Switzerland, equipped with 22 kHz conical sensors. The test configuration followed the direct transmission method, with the transducers placed at the ends of the pieces (Figure 1).

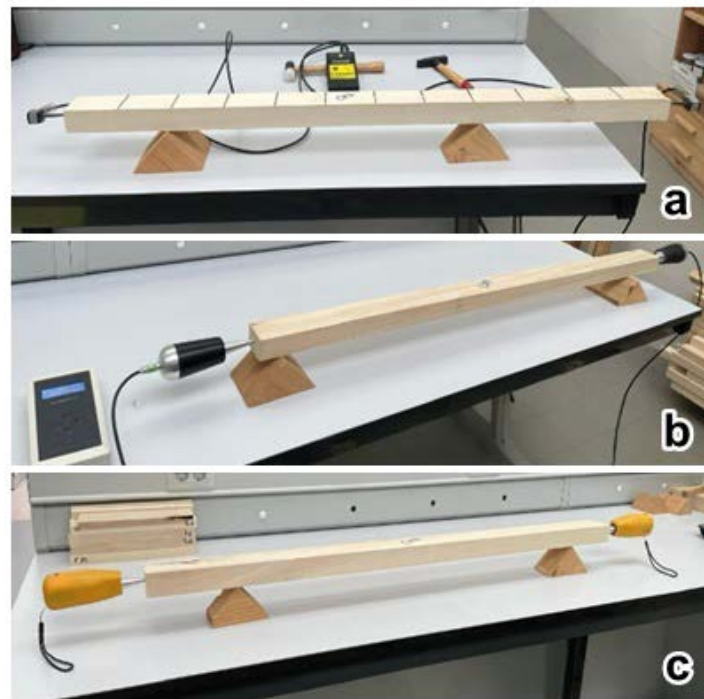


Figure 1. Ultrasonic testing devices: a. Fakopp Microsecond Timer (Ultra1), b. Sylvatest Trio (Ultra2), c. Sylvatest 4 (Ultra3).

The dynamic modulus of elasticity for the ultrasonic methods ($E_{\text{dyn_Ultra1}}$, $E_{\text{dyn_Ultra2}}$ and $E_{\text{dyn_Ultra3}}$) was calculated using Equation (1).

$$E_{\text{dyn_Ultra1,2,3}} = V^2 \cdot \rho \quad (1)$$

Where V is the ultrasound velocity (m/s), ρ is the density (kg/m^3) of each piece at 12% MC and $E_{\text{dyn_Ultra1,2,3}}$ is the dynamic modulus of elasticity for the ultrasonic methods (N/mm^2).

Induced longitudinal vibrations

In this test, each piece was placed on two support stands. Longitudinal vibrations were induced by applying an impulse to one end of the specimen using a 100 g steel hammer. The response was recorded at the opposite end using a unidirectional microphone (frequency range: 100 to 15,000 Hz; sensitivity: -56 dB) connected to a data acquisition system with a sampling rate of 44.1 kHz. The signal was processed using Fast Fourier Transform (FFT) with a Hann window (Figure 2).



Figure 2. Longitudinal vibration testing.

The wave velocity was calculated using Equation (2).

$$V = 2 * L * f \quad (2)$$

Where L is the length of the pieces (m), f is the fundamental vibration frequency (Hz) and V is the wave velocity (m/s).

The dynamic modulus of elasticity for longitudinal vibrations ($E_{\text{dyn_Long_vibra}}$) was determined using the same Equation (3).

$$E_{\text{dyn_Long_vibra}} = (2 * L * f)^2 * \rho \quad (3)$$

Where L is the length of the pieces (m), f is the fundamental vibration frequency (Hz), ρ is the density (kg/m^3) of each piece at 12%-MC and $E_{\text{dyn_Long_vibra}}$ is the dynamic modulus of elasticity for longitudinal vibrations (N/mm^2).

Transverse vibrations – cantilever beam

The vibration frequency for each sample was estimated by placing it in a cantilever beam configuration. One end was fixed to a support with a metal plate and secured with two tightening screws to ensure uniform pressure. The vibration of each cantilever piece was induced by striking the top surface of the beam with a 100 g steel hammer. The vibration was recorded using a microphone and a Fast Fourier Transform (FFT) analyzer software- Fakopp, Sopron, Hungary- (Figure 3).



Figure 3. Transverse vibration testing of a cantilever beam.

Four free span lengths (L) were tested: 1.1, 1.0, 0.9, and 0.8 m. For each configuration, only the first vibration mode (fundamental frequency) was used to estimate the dynamic modulus of elasticity. Higher-

order modes were not considered, as the first mode provides a more stable and representative measurement for cantilever configurations (Arriaga et al., 2014; Guo et al., 2009).

The natural frequencies of the transverse vibrations of the cantilever beam was calculated based on the principles established in Euler-Bernoulli beam theory using Equation (4).

$$f_n = C_n \sqrt{\frac{E_{dyn} * I}{\rho * S * L^4}} \quad (4)$$

Where: f_n is the natural frequency (Hz), C_n is the constant that depends on the vibration mode, with the following values: mode 1 = 0.562 (the natural frequency, used in this study), mode 2 = 5.5014, mode 3 = 9.8198; E_{dyn} is the dynamic modulus of elasticity (Pa); I is the moment of inertia of the cross-sectional area (m^4); ρ is the apparent density (kg/m^3); S is the cross-sectional area (m^2); and L is the free length of the cantilever piece (m).

Equation (4) was rewritten as shown in Equation (5).

$$f_n^2 = C_n^2 * \frac{E_{dyn_Trans_vibra} * I}{\rho * S} * \frac{1}{L^4} \quad (5)$$

That is a general linear model: $y = ax + b$

Where: $y = f_n^2$,

$$x = \frac{1}{L^4},$$

$$a = \frac{C_n^2 * (E_{dyn_Trans_vibra} * I)}{\rho * S},$$

and $b = 0$, in order to calculate the frequency for each free length of the pieces (L). Therefore, the dynamic modulus of elasticity for transverse vibrations ($E_{dyn_Trans_vibra}$) was calculated using Equation (6).

$$E_{dyn_Trans_vibra} = a * \frac{\rho * S}{C_n^2 * I} \quad (6)$$

Where a is the slope of the regression line with $x = 1/L^4$ and $y = f^2$.

Non-destructive static center-point bending test

The static bending test was conducted in a three-point bending configuration using a universal testing machine (Figure 4).



Figure 4. Non-destructive static center-point bending test.

The modulus of elasticity was obtained from the deformation measurements recorded using a linear variable differential transformer (LVDT) positioned at the bottom center of each piece. The test speed was 10 mm/min, with a programmed force limit of 2.5 kN. Subsequently, the specimens were removed without sustaining any damage. The static modulus of elasticity for non-destructive static center-point bending test ($E_{static_Centr_bend}$) was calculated using Equation (7).

$$E_{static_Centr_bend} = a_1 * \frac{L^3}{48 * I} \quad (7)$$

Where: a_1 is the slope of the force-deformation curve, L is the distance between beam supports (m), and I is the moment of inertia of the cross-sectional area (m⁴).

Non-destructive static bending – cantilever beam

The bending deformation was measured for each piece. The specimens were placed in a cantilever configuration in the universal testing machine, with one end fixed to a support using a metal plate and two tightening screws to ensure uniform pressure, leaving the other end free (Figure 5).



Figure 5. Non-destructive static bending of a cantilever beam.

A LVDT positioned at the bottom end of each piece was used to record the deformation. The testing speed was set at 10 mm/min. When a deformation of 16 mm was reached, the specimens were removed without sustaining damage. The dynamic modulus of elasticity for non-destructive static bending of the cantilever beam ($E_{static_Cant_bend}$) was calculated using Equation (8).

$$E_{static_Cant_bend} = a_2 \frac{L^3}{3 * I} \quad (8)$$

Where: a_2 is the slope of the force-deformation curve, L is the free length of the piece (m), and I is the moment of inertia of the cross-sectional area (m⁴).

Destructive static bending – four-point configuration

The static bending test to failure was conducted on each specimen using a four-point bending configuration in accordance with the EN 408:2011 standard (AENOR, 2011) (Figure 6).



Figure 6. Four-point static bending test according to EN 408:2011.

The global bending modulus of elasticity (MOEGTO) was obtained from the deformation measurements recorded using a LVDT positioned at the bottom center of each piece. The test speed was 10 mm/min until a programmed force limit of 2.5 kN was reached. Afterward, the LVDT was removed, and the test continued at a speed of 15 mm/min until the specimens failed. The *MOEGTO* was determined following Equation (9).

$$MOEGTO = \frac{3 \cdot a \cdot L^2 - 4 \cdot a^3}{2 \cdot b \cdot h^3 \cdot \left(2 \cdot \frac{w_1 - w_2}{F_1 - F_2} - \frac{6 \cdot a}{5 \cdot G \cdot b \cdot h} \right)} \quad (9)$$

Where: a is the distance between a load point and the nearest support (mm), L is the distance between supports (mm), b is the width of the cross-section (mm), h is the height of the cross-section (mm), w is the deformation (mm), F is the force (N), and G is the shear modulus (MPa), which was considered infinite in this case according to the UNE 408:2011 standard (AENOR, 2011).

Statistical analysis

The statistical analysis of the data was performed using R software (v.4.3.1:2023) (R Core Team, 2023). The assumptions of normality (Shapiro-Wilk test, Kolmogorov-Smirnov test) and homoscedasticity (Levene's test) were verified for the density of both species and different modulus of elasticity ($E_{\text{dyn_Ultra1}}$, $E_{\text{dyn_Ultra2}}$, $E_{\text{dyn_Ultra3}}$, $E_{\text{dyn_Long_vibra}}$, $E_{\text{dyn_Trans_vibra}}$, $E_{\text{static_Centr_bend}}$, $E_{\text{static_Cant_bend}}$ and MOEGTO). The statistical relationship between the different NDT methods and MOEGTO was assessed using Pearson's correlation analysis.

The detection of statistically significant differences in density between both species and between the NDT methods and MOEGTO was performed, based on the normality and homoscedasticity results, using the Kruskal-Wallis test, adjusted with the Bonferroni correction.

In addition to classical descriptive statistics (mean, standard deviation, coefficient of variation), we included robust estimators to account for potential outliers and distribution asymmetries. These included the trimmed mean (T. mean 0.1), which excludes the highest and lowest 10% of values; the Winsorized mean (W. mean 0.1), which replaces extreme values with the closest remaining values; the Huber estimator, a robust central tendency measure; and the robust confidence intervals (R. upper CI, R. lower CI). The standard errors of these measures (SE, W. mean SE, Median SE) were also computed. Homogeneous groups were identified

through robust grouping analysis (R. groups). These metrics were included to better interpret the variability and distribution of MOE values and are discussed in the Results section.

Linear regression models to predict MOEGTO from the different dynamic and static modulus of elasticity obtained through NDT methods for each species and Lin's correlation coefficient were developed using Equation (10).

$$y = \beta_0 * x + \beta_1 \quad (10)$$

Where: y = MOEGTO prediction, β_1 = intercept, β_0 = slope, and x = NDT dynamic modulus.

Cross-validation was used to estimate the error rate efficiently and in an unbiased manner. Its goal (Larson, 1931) is to test the model's ability to predict new data that were not used in its estimation.

This study used this technique for each predicted variable, splitting the total data (75 beams) into a training set of 60 beams (80% of total) and a test set of 15 beams (20% of total). These percentages were selected in order to combine a good accuracy (better with high training percentage) and a low overfitting (better with low training percentage) across all models. K-fold cross-validation (k-fold= 10) is used and the method is repeated $n = 5$ times, yielding 5 different random partitions of the original sample. The algorithm was iterated 50 times, each time randomly selecting training and test sets, resulting in 5×50 models whose results were averaged to obtain a single estimation (Figure 7). Two MAPE values were computed in each iteration: MAPE.model, calculated from the training folds (80% of the data), and MAPE.test, from the validation fold (20%). These values were then averaged across the 250 iterations to evaluate generalization accuracy. Slight differences between MAPE.model and MAPE.test are expected due to random fold composition. In this way, the statistical performance values for each global model were ensured to be robust, and their variability and stability around the mean value could be analyzed.

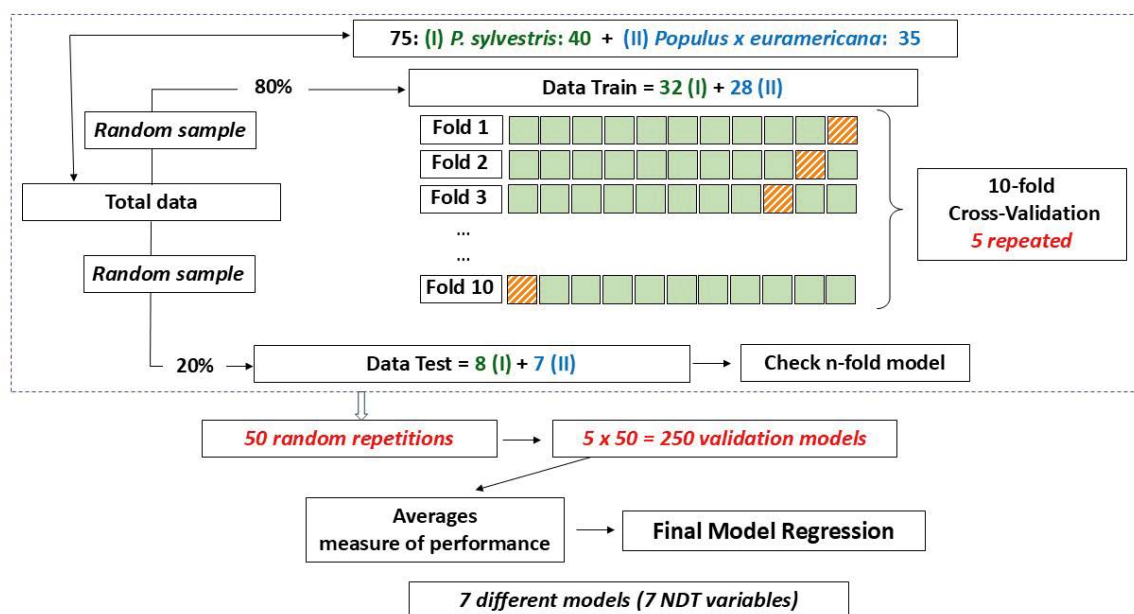


Figure 7. Cross validation process - 50 iterations over 5 repeated 10-folds validation.

The following statistical values were obtained from these models:

β_0 = slope

β_1 = intercept

R^2 = a measure of the model's goodness of fit, indicating the proportion of the total variance of the dependent variable explained by the model.

MSE = a measure of the model's error, representing the standard deviation of the model's errors. MSE is the arithmetic mean of the squared differences between the predicted and actual values, calculated using Equation (11).

$$MSE = \frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2 \quad (11)$$

$RMSE$ = the square root of the MSE and is used to obtain the average error in the same units as the dependent variable. These values were obtained using Equation (12).

$$RMSE = \sqrt{\sum_{i=1}^n \frac{(\hat{y}_i - y_i)^2}{n}} = \sqrt{MSE} \quad (12)$$

MAE = the arithmetic means of the absolute differences between the predicted and actual values. This metric indicates the average size of the errors in the model's predictions and is expressed in the same units as the dependent variable (see Equation 13).

$$MAE = \frac{1}{n} \sum_{i=1}^n |y_i - \hat{y}_i| \quad (13)$$

RSE = Residual Standard Error is an estimator of σ^2 (variance of the errors) and is given by Equation (14).

$$RSE = \sqrt{\frac{RSS}{n-2}} \quad (14)$$

Where RSS is the Residual Sum of Squares.

$MAPE$ = is a measure of the percentage error and is expressed as a percentage. This metric indicates the average size of the errors in the model's predictions as a percentage of the actual value. The values were obtained using Equation (15).

$$MAPE = \frac{1}{n} \sum_{i=1}^n 100 \frac{|X_i - Y_i|}{X_i} \quad (15)$$

In Equation (14), X_i denotes the predicted MOEGTO value from the regression model, and Y_i is the corresponding observed MOEGTO value for the same specimen.

Results

The evaluation of the modulus of elasticity for the lumber of *P. sylvestris* and *P. × euramericana* using ultrasound techniques, induced transverse and longitudinal vibrations, and non-destructive static bending with center-point and cantilever loading, in comparison to the static bending test, yielded the following results:

Density

Normality and homoscedasticity tests indicated that the density data for *P. sylvestris* samples followed a normal distribution, whereas *P. × euramericana* exhibited a non-normal distribution. Furthermore, the variances were found to be statistically different between both species (Table 1).

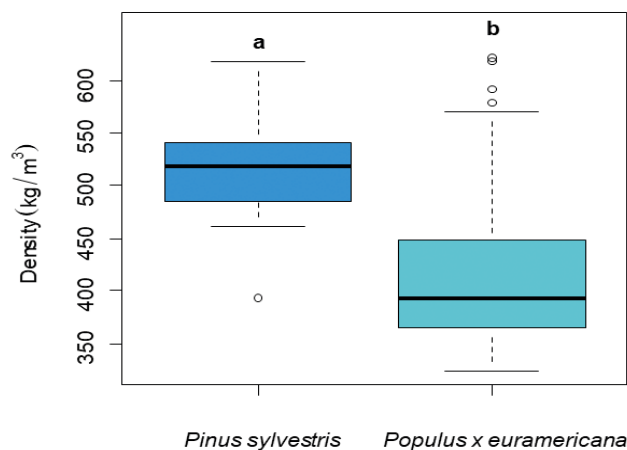
The Kruskal-Wallis test confirmed the presence of statistically significant differences between the two species (Figure 8).

Table 1. Descriptive analysis: wood density of *Pinus sylvestris* and *Populus × euramericana*.

Specie	Density (kg/m³) Mean ± IC*	CV (%)	Normality test				Homoscedasticity Levene's Test
			Shapiro-Wilk		LKS**		
			W	p- value	D	p-value	p-value
<i>Pinus sylvestris</i>	519.09 ± 16.42	8.84	0.972	0.622	0.098	0.656	0.049
<i>Populus</i> × <i>euramericana</i>	423.55 ± 23.85	19.27	0.856	5.4e-05	0.200	9.6e-05	

*IC 95% Interval of Confidence.

** Kolmogorov-Smirnov test with Lilliefors correction.

**Figure 8.** Density box plot of each species tested.

Dynamic and static modulus of elasticity with non-destructive testing (NDT) and destructive static bending (MOEGTO)

The descriptive statistics for the modulus of elasticity of *P. sylvestris*, obtained through NDT methods and MOEGTO, are presented in Table 2, while those for *P. × euramericana* are shown in Table 3. The comparative analysis and the statistically significant differences of the modulus of elasticity obtained with the NDT methods and MOEGTO for both species are presented in Figure 9.

Table 2. Descriptive analyses: NDT MOEs and MOEGTO of *Pinus sylvestris*.

Statistics	E _{dyn_Ultra1}	E _{dyn_Ultra2}	E _{dyn_Ultra3}	E _{dyn_Long_vibra}	E _{dyn_Trans_vibra}	E _{static_Centr_bend}	E _{static_Cant_bend}	MOEGTO
n	45	45	45	45	45	45	45	45
Mean	11206.7	14281.2	13874.6	11414.4	9882.7	18390.9	7914.4	15596.5
Median	10790.8	13959.9	14357.0	10438.2	9818.0	17717.4	7715.2	15376.3
St. dev	2779.1	3632.3	3127.3	3337.0	2228.7	5318.6	2050.5	2896.2
CV	24.8	25.4	22.5	29.2	22.6	28.9	25.9	18.6
Lilliefors								
KS	0.161	0.087	0.745	0.165	0.820	0.250	0.307	0.020
SE	507.4	663.2	571.0	609.2	406.9	971.0	374.4	528.8
T. mean 0.1	587.4	756.3	634.7	707.7	420.7	1028.0	432.6	631.8

Statistics	E _{dyn_Ultra1}	E _{dyn_Ultra2}	E _{dyn_Ultra3}	E _{dyn_Long_vibra}	E _{dyn_Trans_vibra}	E _{static_Centr_bend}	E _{static_Cant_bend}	MOEGTO
W. mean 0.1	11216.8	14241.8	13814.5	11368.6	9749.6	18220.7	7956.1	15601.0
W. mean SE	592.5	762.8	640.3	713.8	424.4	1037.0	436.4	637.3
Median SE	974.4	1272.6	921.8	1075.7	652.1	1713.9	721.8	1012.7
Huber est.	11181.1	14262.5	13829.3	11312.4	9790.0	18222.6	7917.0	15596.5
Rob. upper CI	12279.1	15684.8	15029.5	12709.7	10761.4	20392.6	8686.6	16731.4
Rob. lower CI	10226.4	13007.7	12745.0	10260.3	9094.6	16431.0	7172.0	14557.4
Rob. groups	<i>cd</i>	<i>ab</i>	<i>bc</i>	<i>cd</i>	<i>de</i>	<i>a</i>	<i>e</i>	<i>a</i>

St. dev= Standard deviation, CV=coefficient of variation (%), Lilliefors KS =Kolmogorov-Smirnov test with Lilliefors correction, SE= Standard Error, T. mean 0.1= 0.1 Trimmed Mean, W. mean 0.1= 0.1 Winsorized mean, W. mean SE= standard error of the winsorized mean, Median SE= Standard error of the median, Huber est.=Huber estimator, Rob. upper CI= Robust upper confidence intervals, Rob. lower CI= Robust lower confidence intervals, Rob. groups= Robust homogeneous groups.

Table 3. Descriptive analyses: NDT MOEs and MOEGTO of *Populus × euramericana*.

Statistics	E _{dyn_Ultra1}	E _{dyn_Ultra2}	E _{dyn_Ultra3}	E _{dyn_Long_vibra}	E _{dyn_Trans_vibra}	E _{static_Centr_bend}	E _{static_Cant_bend}	MOEGTO
n	30	30	30	30	30	30	30	30
Mean	10043.7	13017.4	12904.2	10784.6	9919.9	15182.8	6786.0	14943.6
Median	9715.8	12713.8	12747.0	10462.4	9700.0	14656.0	6659.5	15110.7
St. dev	2062.5	2790.0	2822.4	2328.7	2024.1	3872.1	1300.8	1853.4
CV	20.5	21.4	21.9	21.6	20.4	25.5	19.2	12.4
Lilliefors KS	0.098	0.080	0.203	0.237	0.001	0.000	0.059	0.661
SE	307.5	415.9	420.7	347.1	301.7	577.2	193.9	276.3
T. mean 0.1	279.9	376.5	388.5	318.7	306.5	489.3	202.0	294.9
W. mean 0.1	9836.2	12748.8	12642.3	10589.0	9824.0	14901.0	6726.2	14934.4
W. mean SE	273.7	368.2	379.8	311.6	299.7	478.4	197.6	288.3
Median SE	322.4	385.0	528.8	376.5	198.5	497.4	184.8	425.4
Huber est.	9823.6	12715.0	12622.1	10529.7	9762.4	14617.8	6655.2	14890.4
Rob. upper CI	10748.0	13993.3	13875.7	11584.6	10564.8	16561.3	7207.8	15496.2
Rob. lower CI	9505.7	12300.7	12163.7	10179.4	9350.5	14210.2	6413.3	14394.4
Rob. groups	<i>c</i>	<i>b</i>	<i>b</i>	<i>c</i>	<i>c</i>	<i>a</i>	<i>d</i>	<i>a</i>

St. dev= Standard deviation, CV=coefficient of variation (%), Lilliefors KS =Kolmogorov-Smirnov test with Lilliefors correction, SE= Standard error, T. mean 0.1= 0.1 Trimmed Mean, W. mean 0.1= 0.1 Winsorized mean, W. mean SE= standard error of the winsorized mean, Median SE= Standard error of the median, Huber est.=Huber estimator, Rob. upper CI= Robust upper confidence intervals, Rob. lower CI= Robust lower confidence intervals, Rob. groups= Robust homogeneous groups.

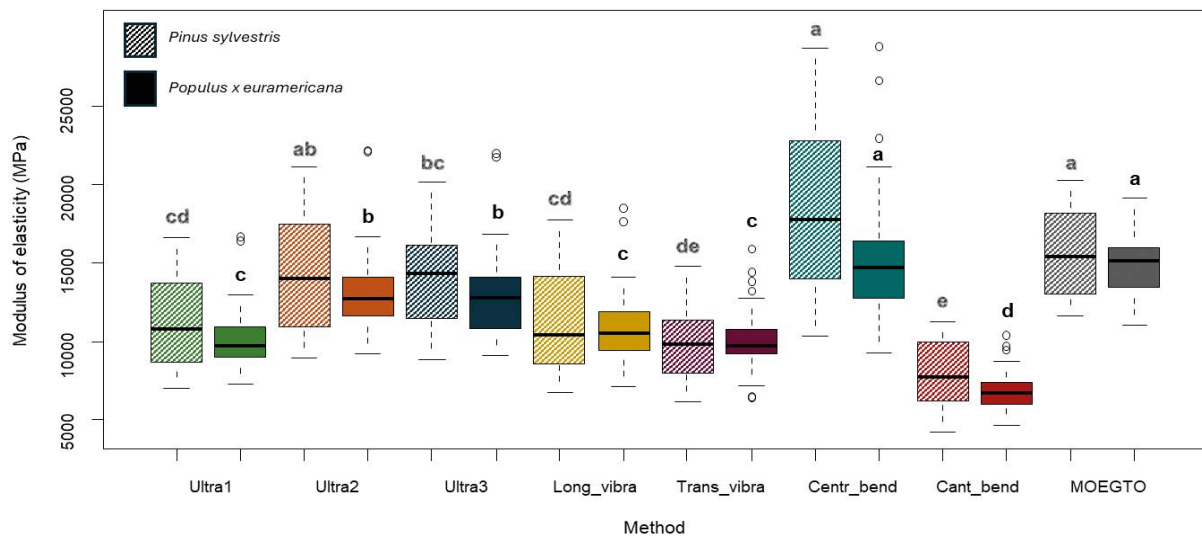


Figure 9. Box plots showing the distribution of modulus of elasticity values obtained from different NDT methods and MOEGTO. Letters indicate statistically homogeneous groups ($p < 0.05$) according to Kruskal-Wallis test with Bonferroni correction.

The non-destructive static bending method in a cantilever beam configuration ($E_{\text{static_Cant_bend}}$) showed the lowest modulus of elasticity values, with a mean of 7,914.4 MPa for *P. sylvestris* and 6,786 MPa for *P. x euramericana*. In contrast, the highest average values were obtained using the non-destructive static bending method with center-point loading ($E_{\text{static_Centr_bend}}$), reaching 18,390.9 MPa for *P. sylvestris* and 15,182.8 MPa for *P. x euramericana*.

The correlation analysis between NDT and MOEGTO revealed strong correlations among the three ultrasonic methods for both species (Figure 10).

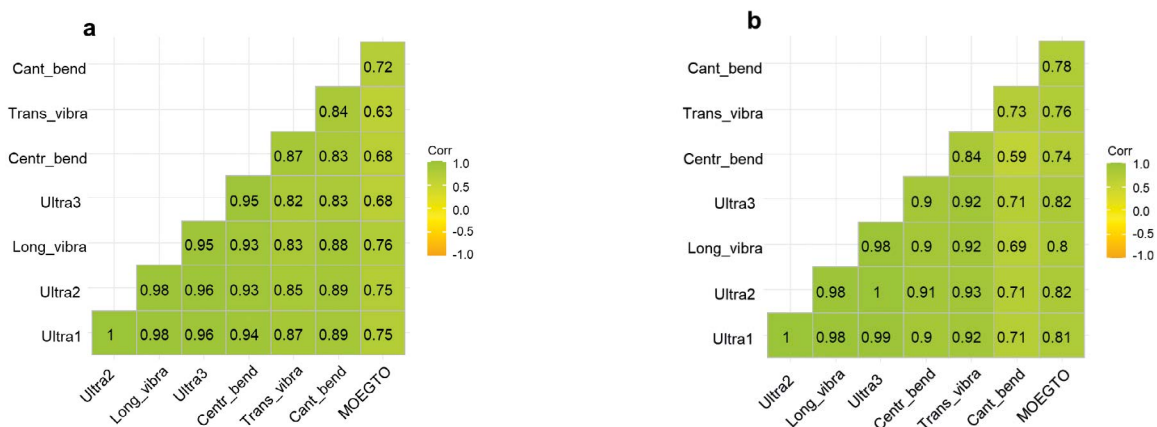


Figure 10. Pearson correlation coefficients (r) between dynamic MOE obtained from NDT methods and MOEGTO for a) *Pinus sylvestris* and b) *Populus x euramericana*.

Prediction of MOEGTO using the NDT modulus of elasticity

The values of the main statistical indicators for the regression models of the predictor variables (E_{NDT}) with respect to MOEGTO are summarized for *P. sylvestris* (Table 4) and *P. x euramericana* (Table 5).

Table 4. MOEGTO prediction based on *Pinus sylvestris* NDT modulus of elasticity.

<i>NDT MOE</i>	β_1	β_0	$R^2 \text{ adj.}$	<i>RSE</i>	<i>p-value</i>	<i>Coef. Corr. Lin</i>
$E_{\text{dyn_Ultra1}}$	6892.2	0.777	0.540	1965	2.302e-06	0.333 (0.170, 0.478)
$E_{\text{dyn_Ultra2}}$	7098.0	0.595	0.541	1962	2.189e-06	0.672 (0.451, 0.815)
$E_{\text{dyn_Ultra3}}$	6915.7	0.626	0.437	2173	4.197e-05	0.576 (0.325, 0.751)
$E_{\text{dyn_Long_vibra}}$	8093.0	0.657	0.558	1925	1.264e-06	0.389 (0.211, 0.543)
$E_{\text{dyn_Trans_vibra}}$	7553.5	0.814	0.371	2298	0.0002138	0.172 (0.062, 0.276)
$E_{\text{static_Centr_bend}}$	8809.0	0.369	0.440	2167	3.884e-05	0.467 (0.254, 0.636)
$E_{\text{static_Cant_bend}}$	7600.2	1.010	0.494	2060	8.892e-06	0.115 (0.047, 0.182)

β_1 =intercept, β_0 =slope, $R^2 \text{ adj.}$ = adjusted R-squared, *RSE*= residual standard error, *Coef. Corr. Lin*= Lin's correlation coefficient.

Table 5. MOEGTO prediction based on *Populus × euramericana* NDT modulus of elasticity.

<i>NDT MOE</i>	β_1	B_0	$R^2 \text{ adj.}$	<i>RSE</i>	<i>p-value</i>	<i>Coef. Corr. Lin</i>
$E_{\text{dyn_Ultra1}}$	7591.9	0.732	0.656	1088	9.953e-12	0.193 (0.115, 0.269)
$E_{\text{dyn_Ultra2}}$	7874.4	0.543	0.660	1080	7.303e-12	0.563 (0.412, 0.684)
$E_{\text{dyn_Ultra3}}$	7966.6	0.541	0.670	1064	3.845e-12	0.550 (0.401, 0.671)
$E_{\text{dyn_Long_vibra}}$	8113.5	0.633	0.625	1136	6.501e-11	0.259 (0.158, 0.354)
$E_{\text{dyn_Trans_vibra}}$	8037.2	0.696	0.568	1218	1.371e-09	0.171 (0.097, 0.244)
$E_{\text{static_Centr_bend}}$	9599.8	0.352	0.530	1271	8.793e-09	0.571 (0.427, 0.687)
$E_{\text{static_Cant_bend}}$	7434.0	1.1066	0.594	1181	3.589e-10	0.051 (0.027, 0.075)

β_1 =intercept, β_0 =slope, $R^2 \text{ adj.}$ = adjusted R-squared, *RSE*= residual standard error, *Coef. Corr. Lin*= Lin's correlation coefficient.

The regression performance of each NDT method for predicting MOEGTO is summarized in Table 6 and visualized in Figure 11. This figure combines data from both species and shows the global regression models, confirming that both *P. sylvestris* and *P. × euramericana* exhibit similar trends across all methods. It also highlights that the three-point bending method ($E_{\text{static_Centr_bend}}$) and cantilever bending method ($E_{\text{static_Cant_bend}}$) produce the steepest regression slopes, while the other NDT techniques (ultrasound and vibrations) show comparable and more moderate linear behavior. These patterns reinforce the consistency of predictive relationships across species and validate the global approach.

Table 6. MOEGTO global prediction for *Pinus sylvestris* and *Populus × euramericana* based on two species NDT modulus of elasticity.

<i>NDT MOE</i>	β_1	B_0	$R^2 \text{ adj.}$	<i>RSE</i>	<i>p-value</i>	<i>Coef. Corr. Lin</i>
$E_{\text{dyn_Ultra1}}$	7370.9	0.745	0.596	1481	2.995e-16	0.261 (0.181, 0.337)
$E_{\text{dyn_Ultra2}}$	7517.6	0.569	0.601	1483	2.200e-16	0.622 (0.505, 0.724)
$E_{\text{dyn_Ultra3}}$	7480.1	0.581	0.541	1580	3.532e-14	0.570 (0.439, 0.677)
$E_{\text{dyn_Long_vibra}}$	8008.5	0.652	0.596	1482	3.157e-16	0.326 (0.232, 0.414)
$E_{\text{dyn_Trans_vibra}}$	7805.1	0.747	0.443	1740	4.497e-11	0.171 (0.108, 0.233)
$E_{\text{static_Centr_bend}}$	9542.7	0.344	0.483	1676	2.838e-12	0.524 (0.404, 0.626)
$E_{\text{static_Cant_bend}}$	7982.4	0.998	0.537	1586	4.766e-14	0.081 (0.052, 0.111)

β_1 =intercept, β_0 =slope, $R^2 \text{ adj.}$ = adjusted R-squared, *RSE*= residual standard error, *Coef. Corr. Lin*= Lin's correlation coefficient.

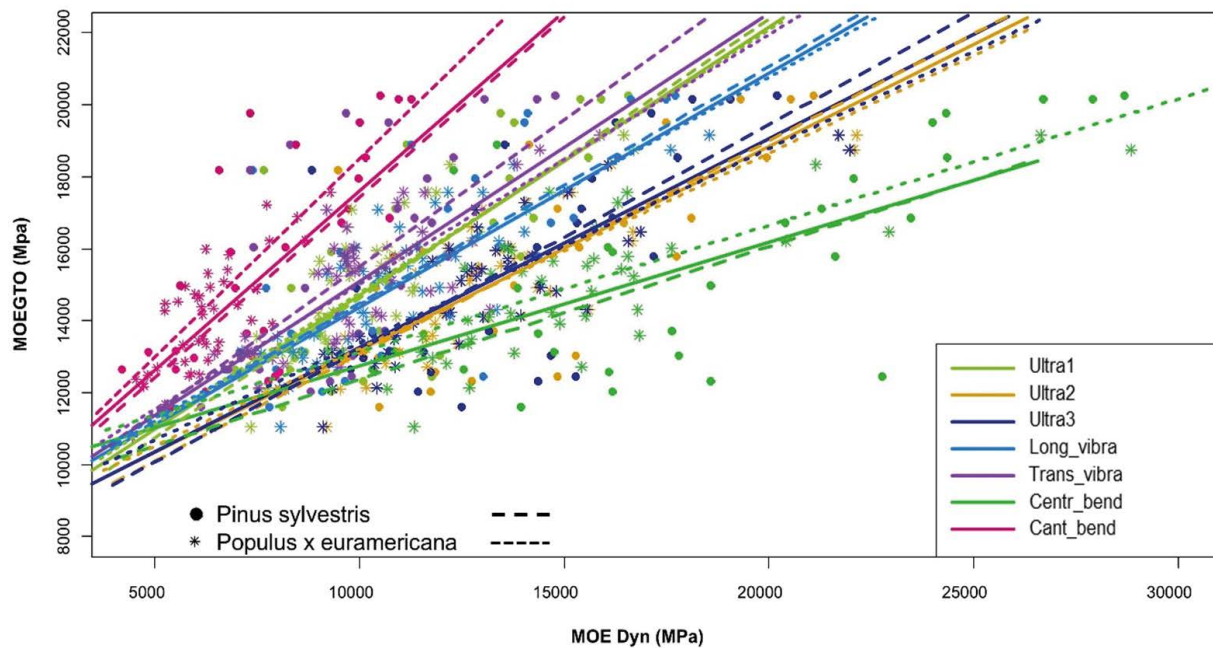


Figure 11. Global regression models between MOEGTO and the dynamic modulus of elasticity obtained from each NDT method. The plot shows both species: *Pinus sylvestris* (dashed lines) and *Populus × euramericana* (dotted lines). The solid lines represent the combined regression models using data from both species.

The individual regression analysis for *P. sylvestris* and *P. × euramericana*, as well as the global regressions for both species, revealed that the highest values for the NDT modulus of elasticity and MOEGTO predictions were obtained with the $E_{static_Centr_bend}$ method. It was also found that the modulus of elasticity values obtained through ultrasound using the Sylvatest Trio and Sylvatest 4 devices (E_{dyn_Ultra2} and E_{dyn_Ultra3}) were higher than those obtained with Fakopp (E_{dyn_Ultra1}).

The global prediction models for MOEGTO using the NDT modulus of elasticity of both species together showed no significant loss of predictive accuracy compared to the individual regressions. This indicates that the data obtained for the NDT modulus of elasticity for *P. sylvestris* and *P. × euramericana* showed the same level of fit in the global prediction models.

Although the R^2 values in global regressions were slightly higher than in species-specific models, this increase is partly explained by the broader range of input values when combining both species. However, RMSE values obtained from cross-validation (Table 7) confirm that model accuracy did not decrease, supporting the validity of the global prediction models.

Table 7. Regression metrics for 10-fold cross-validation repeated 5 × 50 iterations.

NDT Method	Intercept Mean (sd)	Slope Mean (sd)	RMSE Mean (sd)	Rsquared Mean (sd)	MAE Mean (sd)	RSE Mean (sd)	MAPE. Model Mean (sd)	MAPE. Test Mean (sd)
E_{dyn_Ultra1}	7358.9 (246.5)	0.747 (0.022)	1432.9 (51.0)	0.65 (0.031)	1171.9 (35.9)	1486.2 (50.7)	7.6 (0.217)	7.5 (1.4)
E_{dyn_Ultra2}	7507.3 (250.3)	0.569 (0.017)	1419.3 (49.8)	0.66 (0.032)	1148.5 (38.9)	1477.6 (55.0)	7.4 (0.234)	7.4 (1.4)

NDT Method	Intercept Mean (sd)	Slope Mean (sd)	RMSE Mean (sd)	Rsquared Mean (sd)	MAE Mean (sd)	RSE Mean (sd)	MAPE. Model Mean (sd)	MAPE. Test Mean (sd)
$E_{\text{dyn_Ultra3}}$	7478.8 (295.8)	0.581 (0.021)	1525.7 (48.9)	0.62 (0.031)	1212.0 (37.4)	1585.9 (54.8)	7.8 (0.251)	7.7 (1.6)
$E_{\text{dyn_Long_vibra}}$	7995.6 (267.0)	0.653 (0.022)	1428.0 (48.9)	0.66 (0.031)	1173.7 (34.4)	1487.6 (57.8)	7.6 (0.208)	7.5 (1.2)
$E_{\text{dyn_Trans_vibra}}$	7820.5 (372.8)	0.745 (0.034)	1678.3 (63.4)	0.52 (0.035)	1354.0 (44.9)	1744.5 (66.0)	8.7 (0.292)	8.8 (1.6)
$E_{\text{static_Centr_bend}}$	9544.6 (259.0)	0.343 (0.014)	1609.2 (65.0)	0.55 (0.036)	1283.9 (49.9)	1681.3 (65.3)	8.5 (0.326)	8.3 (1.9)
$E_{\text{static_Cant_bend}}$	7988.9 (311.5)	0.996 (0.044)	1542.1 (42.3)	0.59 (0.030)	1268.0 (38.3)	1590.6 (44.4)	8.3 (0.238)	8.2 (1.6)

RMSE= root mean squared error, MAE= mean absolute error, RSE= relative standard error, MAPE.model= mean absolute percentage error model, MAPE.test= mean absolute percentage error test.

Additionally, the global prediction models showed that the $E_{\text{dyn_Ultra2}}$ method had the highest correlation with MOEGTO, followed by the $E_{\text{dyn_Ultra1}}$ and $E_{\text{dyn_Long_vibra}}$ methods.

Cross-validation of MOEGTO predictive models

The cross-validation results for generating MOEGTO prediction models using the combined NDT modulus of elasticity data for *P. sylvestris* and *P. × euramericana* are presented in Table 7.

The cross-validation statistics regression metrics provide a mean value for each globally cross-validated model generated with an NDT variable. These mean values are derived from the 250 partial models generated, allowing for the analysis of their homogeneity and stability. Figure 12 displays the statistical behavior of the main regression metrics (slope, RMSE, and MAPE for both training and test sets) across 250 iterations of the cross-validation process for each NDT method. Each green dot represents one iteration, and the horizontal lines indicate the mean and ± 3 standard deviations (σ). The consistent grouping of values within the $\pm 3\sigma$ interval (above 97.5% in all cases) confirms the statistical stability of the models. All models were developed using the combined dataset of *P. sylvestris* and *P. × euramericana*, as no significant species–method interaction was detected. These results demonstrate the robustness and reliability of the cross-validation methodology used in this study.

The results revealed that the three ultrasound methods, namely, the Fakopp Microsecond Timer, Sylvatest Trio, and Sylvatest 4 devices, provided highly similar results, with an R^2 greater than 0.6 for predicting the MOEGTO. Regarding the vibration methods, the best fits were obtained using the longitudinal vibration method compared to the transverse vibration method, with the former being simpler and more reproducible for estimating the dynamic modulus of elasticity.

Moreover, Figure 13 presents the final cross-validation model for the Ultra1 method, along with the representation of the test points from the 5-fold cross-validation that were randomly selected.

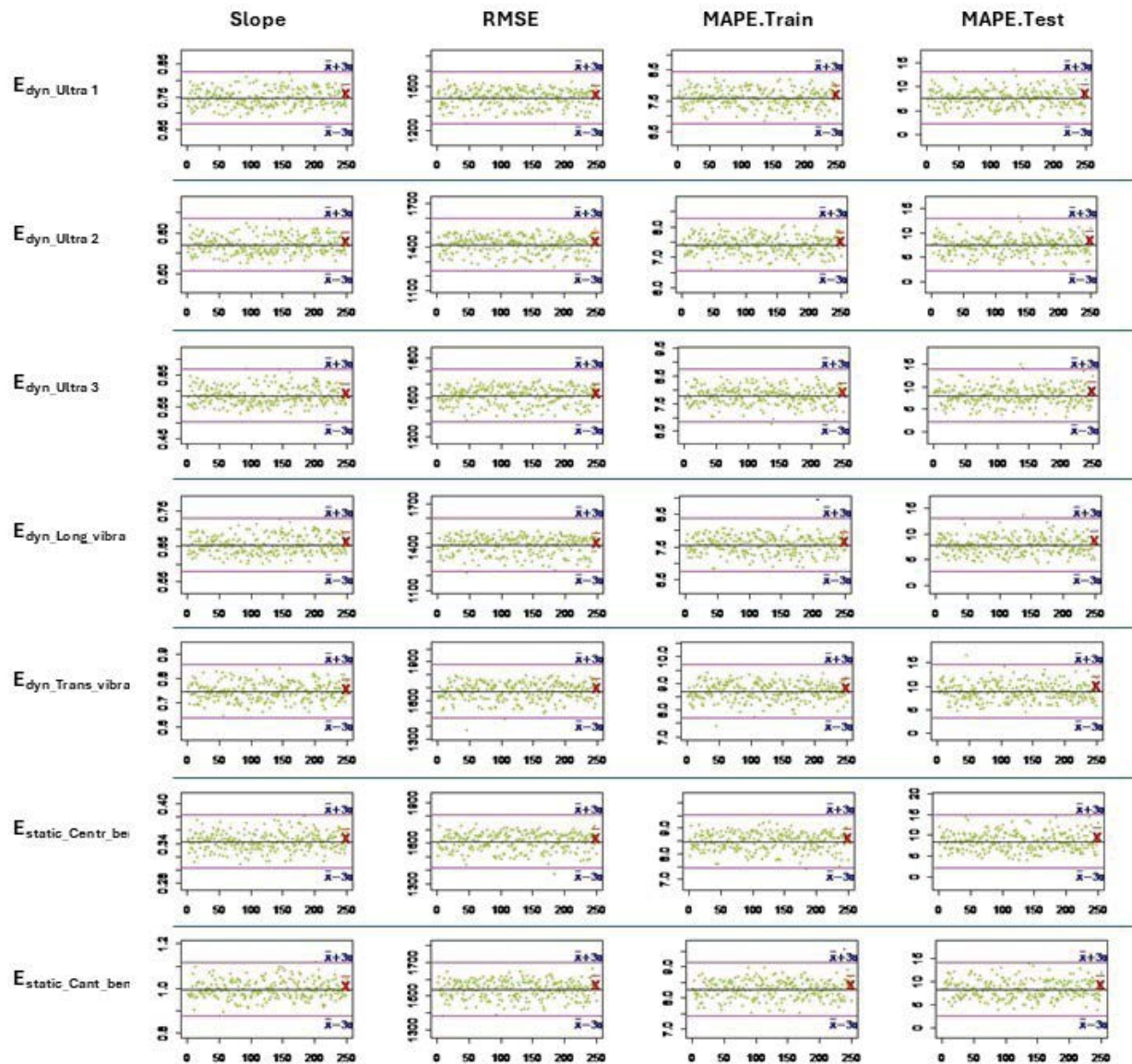


Figure 12. Dispersion plots of regression metrics (slope, RMSE, MAPE.model, and MAPE.test) across 250 cross-validation iterations per NDT method. MAPE.model refers to the error within the training folds; MAPE.test to the error on the validation fold in each iteration. The horizontal lines show the mean and $\pm 3\sigma$ bounds.

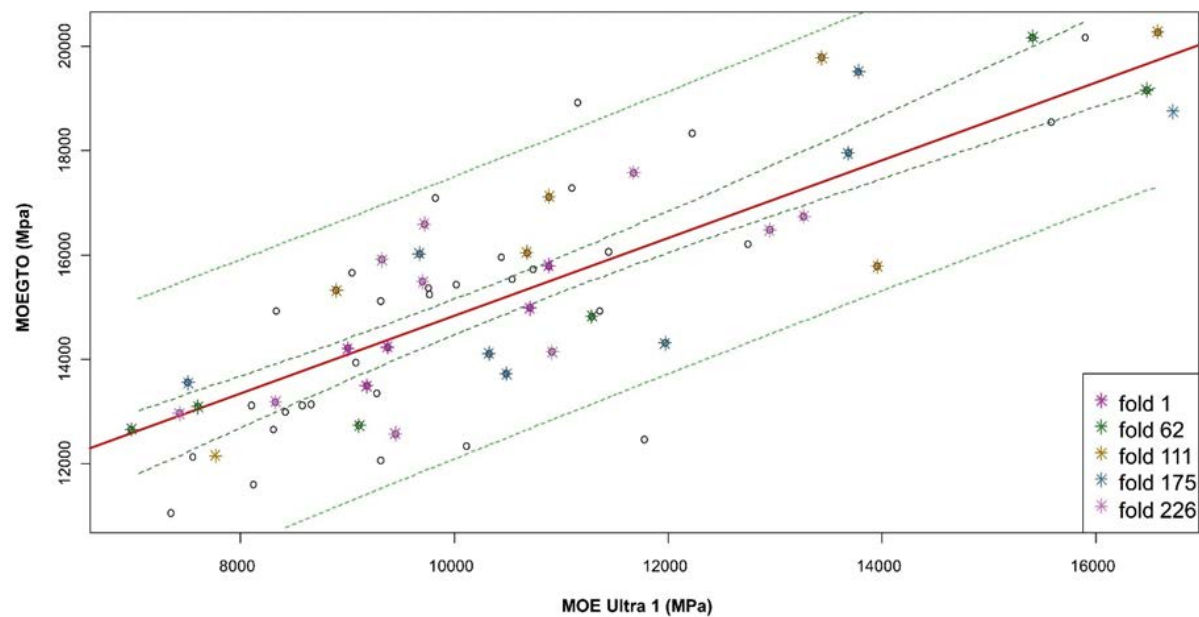


Figure 13. Final regression model for the Ultra1 method using cross-validation. The figure displays the predicted versus observed MOEGTO values for five representative test folds randomly selected from the full cross-validation process. The dashed green lines indicate the 95% confidence interval of the regression.

Discussion

Density

The mean density of *P. sylvestris* was 519.09 kg/m³, similar to the average densities of 514 kg/m³ (Konofalska et al., 2021) and 520 kg/m³ (Güntekin, 2023). This value is consistent with those reported for *P. sylvestris* in previous studies (Auty et al., 2016).

Populus × euramericana exhibited a mean density of 423.55 kg/m³, similar to the 423 kg/m³ reported by Cabrera et al. (2022) and the 420.4 kg/m³ reported by Casado et al. (2009), but relatively higher than the 361.29 kg/m³ reported by Casado et al. (2012), whose samples originated from younger, fast-growing plantation material, likely resulting in lower wood density compared to the more mature timber used in this study.

Dynamic modulus of elasticity with NDT and static bending (MOEGTO)

Statistically significant differences between the $E_{\text{dyn_Ultra1}}$ and $E_{\text{dyn_Ultra2}}$ methods for both species align with those reported by Arriaga et al. (2022) for *Pinus nigra* Arnold ssp. *salzmannii* (Dunal) Franco, where the highest average modulus of elasticity values (12,880 MPa) were obtained with the Sylvatest Trio device, while the Fakopp device yielded an average value of 11,420 MPa. Similar differences were found between the $E_{\text{dyn_Ultra2}}$ and $E_{\text{dyn_Trans_vibra}}$ methods, consistent with findings by Yang et al. (2008) for *Pseudotsuga menziesii* (Mirb.) Franco, where a 12.6% increase in the modulus of elasticity was reported when measured with Sylvatest Trio compared to that obtained via transverse vibrations.

For *P. sylvestris*, no statistically significant differences were found between the $E_{\text{static_Centr_bend}}$ (18,390.9 MPa) and MOEGTO (15,596.5 MPa) tests. Similarly, for *P. × euramericana*, $E_{\text{static_Centr_bend}}$ (15,182.8 MPa) and MOEGTO (14,943.6 MPa) showed no significant differences. The results obtained are consistent with those reported by Yoshihara (2013), who observed no statistically significant differences in the modulus of elasticity values derived from three-point and four-point bending tests in *Tsuga heterophylla*. Nevertheless, other authors have documented discrepancies between both configurations, particularly in relation to shear

deformation effects inherent to three-point bending (Brancheriau et al., 2002). In the present study, the absence of significant differences between $E_{\text{static_Centr_bend}}$ and MOEGTO may be attributed to the high span-to-depth ratio of the specimens and the low applied load levels during testing, conditions under which the influence of shear deformation is expected to be negligible.

The $E_{\text{dyn_Ultra1}}$ for *P. sylvestris* (11,206.7 MPa) was similar to the values of 12,969 MPa reported by Osuna-Sequera et al. (2020) and 11,805 MPa reported by Hassan et al. (2013). This value also aligns with those obtained for other species, such as *P. nigra* subsp. *salzmannii* (11,420 MPa) (Arriaga et al., 2022).

The E_{dyn} for *Ultra2* (14,281.2 MPa) and *Ultra3* (13,874.6 MPa) in *P. sylvestris* was similar to the mean of 13,633 MPa reported by Arriaga et al. (2017), while higher values (16,780.3 MPa) were reported by Acuña et al. (2023). Species such as *Pseudotsuga menziesii* (Mirb.) Franco have also shown similar mean values to those of *P. sylvestris* (14,028 MPa) (Yang et al., 2008). These comparisons confirm that the values measured in this study fall within expected ranges reported in the literature. However, rather than focusing on absolute MOE values, the aim of the present work is to contribute to current efforts in evaluating the predictive capability and reliability of different NDT methods through a comparative approach and robust cross-validation procedures.

Regarding the mean value of the modulus of elasticity obtained by longitudinal vibrations ($E_{\text{dyn_Long_vibra}}$) for *P. sylvestris* (11,414.4 MPa), it was similar to the means of 11,026 MPa (Hassan et al., 2013) and 10,860 MPa (Arriaga et al., 2012), but exceeded the value (8,887 MPa) reported by Fernández-Serrano & Villasante (2022).

For *P. sylvestris*, the modulus of elasticity obtained from transverse vibrations ($E_{\text{dyn_Trans_vibra}}$) was 9,882.7 MPa, with similar values reported for *Pinus radiata* D. Don, which had a mean of 10,010 MPa (Arriaga et al., 2014). Greater values (13,155.14 MPa) for *P. sylvestris* were reported by Acuña et al. (2023). The MOEGTO obtained for this species (15,596.5 MPa) aligns with the value (15,161 MPa) published by Vestøl & Høibø (2010). Other studies report lower values for this species, such as 13,740 MPa (Krzosek et al., 2021) and 11,500 MPa (Stöd et al., 2024).

Populus × euramericana showed a mean E_{dyn} with *Ultra1* of 10,043.7 MPa, which was above the value reported by Casado et al. (2013). The averages obtained with $E_{\text{dyn_Ultra2}}$ and $E_{\text{dyn_Ultra3}}$ were 13,017.4 MPa and 12,904.2 MPa, respectively, similar to the mean value of 12,570.5 MPa obtained by Acuña et al. (2023). Reduced mean values (10,181.6 MPa) obtained with Sylvatest were reported for this species by Casado et al. (2012).

For *Populus × euramericana*, the mean modulus of elasticity obtained with the longitudinal vibration method ($E_{\text{dyn_Long_vibra}}$) (10,784.6 MPa) was greater than that reported by Casado et al. (2012), who obtained a value of 7,363 MPa. Meanwhile, the modulus obtained with the transverse vibration method ($E_{\text{dyn_Trans_vibra}}$) (9,919.9 MPa) was similar to the mean of 9,354.9 MPa reported by Acuña et al. (2023).

Correlation analysis between non-destructive testing (NDT) and static bending (MOEGTO)

A perfect Pearson correlation ($r = 1.00$) was observed between the $E_{\text{dyn_Ultra1}}$ and $E_{\text{dyn_Ultra2}}$ methods, indicating complete linear association between the values measured by both ultrasonic devices, in line with results reported for glued laminated wood of *Picea abies* (L.) H. Karst. using the Fakopp and Sylvatest devices (Nowak et al., 2015).

High correlation coefficients were also observed between the $E_{\text{dyn_Ultra2}}$ method and $E_{\text{dyn_Long_vibra}}$ for both species. Although similar correlations (0.81) between ultrasonic and longitudinal vibration methods have been documented in tropical hardwood species (Baar et al., 2012), this trend is also consistent with results reported in temperate conifers such as *Picea abies* and *P. radiata*, where both methods showed comparable predictive capacity for MOE (Arriaga et al., 2014; Hassan et al., 2013).

MOEGTO prediction using the NDT E_{dyn} and cross-validation

The individual and global regression plots showed that the three ultrasound methods yielded higher values than those obtained with the transverse and longitudinal vibration methods ($E_{\text{dyn_Trans_vibra}}$ and $E_{\text{dyn_Long_vibra}}$). This behavior is consistent with previous studies comparing ultrasound with vibration-based NDT methods (Casado et al., 2012; Hassan et al., 2013; Oberhofnerová et al., 2016; Acuña et al., 2023).

In the case of *P. sylvestris*, the R^2 value obtained between $E_{\text{dyn_Ultra1}}$ and MOEGTO (0.54) was lower than those reported in previous studies 0.66 in Osuna-Sequera et al. (2020), 0.73 in Hassan et al. (2013), and 0.81 in Arriaga et al. (2017). This difference may be explained by the use of ungraded sawn timber with natural variability and small cross-section (60×40 mm), in contrast to previous studies using defect-free specimens under controlled conditions. While this may reduce R^2 values, it enhances the practical relevance of the results by reflecting real structural timber behavior. It was also comparable to values reported for other species, such as *P. pinaster* (0.57) (Morales-Conde & Machado, 2017).

For *P. sylvestris*, the R^2 values obtained in this study for $E_{\text{dyn_Ultra2}}$ (0.54) and $E_{\text{dyn_Long_vibra}}$ (0.56) were clearly lower than those reported by Hassan et al. (2013) and Arriaga et al. (2017), who found R^2 values between 0.73 and 0.86. These differences likely reflect greater material variability and differences in testing conditions. Similar R^2 values to ours have been reported for other species, such as *P. nigra* subsp. *Salzmannii* (Arriaga et al., 2022; $R^2 = 0.54$).

The adjusted determination coefficient between $E_{\text{dyn_Long_vibra}}$ and MOEGTO for *P. sylvestris* (0.55) was lower than the value of 0.86 reported by Hassan et al. (2013). Similarly, the adjusted R^2 between the $E_{\text{dyn_Ultra2}}$ and MOEGTO variables (0.54) was lower than the value of 0.70 reported by Osuna-Sequera et al. (2020).

For *P. × euramericana*, the adjusted determination coefficients between the ultrasonic method $E_{\text{dyn_Ultra1}}$ and MOEGTO (0.65) were similar to the value of 0.50 obtained for the same species by Casado et al. (2013). The coefficient for $E_{\text{dyn_Ultra2}}$ and MOEGTO (0.66) matched the value of 0.68 reported by Casado et al. (2012). Likewise, the adjusted R^2 for $E_{\text{dyn_Long_vibra}}$ and MOEGTO (0.62) aligned with the values (0.64 and 0.70) reported by Casado et al. (2009; 2012).

The best correlations for predicting the MOEGTO in *P. sylvestris* were obtained from the NDT ultrasonic tests using the Fakopp and Sylvatest Trio devices ($E_{\text{dyn_Ultra1}}$ and $E_{\text{dyn_Ultra2}}$), as well as the longitudinal vibration method ($E_{\text{dyn_Long_vibra}}$). In *P. × euramericana*, all three ultrasonic tests ($E_{\text{dyn_Ultra1}}$, $E_{\text{dyn_Ultra2}}$, and $E_{\text{dyn_Ultra3}}$) and the longitudinal vibration method ($E_{\text{dyn_Long_vibra}}$) showed higher correlations with the MOEGTO. These results align with previous studies where the dynamic modulus of elasticity obtained through ultrasonics proved to be the method with the highest linear relationship and the best predictor of the static modulus (Horáček et al., 2012; Oberhofnerová et al., 2016; Morales-Conde & Machado, 2017).

The cross-validated global regression models showed that the $E_{\text{dyn_Ultra2}}$ method (Sylvatest Trio) exhibited the best fit for MOEGTO prediction ($R^2 = 0.60$), followed closely by $E_{\text{dyn_Ultra1}}$ (Fakopp) and $E_{\text{dyn_Long_vibra}}$ (both $R^2 = 0.59$). These global regression models are presented in Table 6, while their predictive accuracy based on repeated cross-validation is summarized in Table 7 and Figures 11 and 12. These results suggest that the models for both species are statistically consistent, demonstrating improvements in MOEGTO prediction.

Additionally, the models obtained from cross-validation demonstrated an increase in both reliability and fit for MOEGTO prediction. It was also found that the accuracy of these new predictions is very high, as the errors reported -specifically the MAPE.test- showed an average value lower than 9% in all cases.

Conclusions

This article provides comparative evidence on the predictive capacity of different non-destructive testing (NDT) techniques —ultrasound, longitudinal vibration, and static bending— for estimating the MOEGTO in structural sawn timber. It also demonstrates the feasibility of applying repeated cross-validation to evaluate model robustness across two species with similar mechanical behavior: *P. sylvestris* and *P. × euramericana*.

The global prediction models for MOEGTO, built using NDT modulus of elasticity data from both species combined, show no significant loss of predictive accuracy compared to models developed for each species individually. This indicates a consistent level of model fit across both species and supports the use of generalized models when species exhibit similar mechanical trends.

Cross-validation notably improved the predictive accuracy of the models, particularly for the three ultrasound devices ($E_{\text{dyn_Ultra1}}$, $E_{\text{dyn_Ultra2}}$, and $E_{\text{dyn_Ultra3}}$) and the longitudinal vibration method ($E_{\text{dyn_Long_vibra}}$), all of which achieved R^2 values above 0.6. These results underscore the robustness and reliability of the cross-validation approach.

In contrast, static bending methods —three-point bending ($E_{\text{static_Centr_bend}}$) and cantilever bending ($E_{\text{static_Cant_bend}}$)— were found to be less effective for predicting MOEGTO in these species. The other NDT techniques, especially ultrasound and vibration methods, produced the most accurate and consistent prediction models, with a more stable and linear behavior.

These findings contribute to improving the reliability of MOE prediction using NDT techniques under practical conditions, particularly for heterogeneous and ungraded timber.

Data availability: Data will be available upon request from the corresponding author.

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