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Stiffness of wood from two hyperdominant species in Central Amazon evaluated by different nondestructive methodologies

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ABSTRACT

This study evaluated nondestructive testing (NDT) to estimate the stiffness of *Protium puncticulatum* (Breu-vermelho) and *Micrandropsis scleroxylon* (Piãozinho) wood. A total of 100 test samples (20×20×300 mm) were manufactured from the wood of three trees of each species, with the final dimension aligned longitudinally. NIR spectroscopy, a stress wave timer and a regression equation were used to estimate stiffness, with the traditional methodology used as a standard. The destructive methodology resulted in average stiffness values of 9890 MPa for *P. puncticulatum* wood and 15002 MPa for *M. scleroxylon*. Pearson correlation results indicate that the regression equation (r=0.83; 0.72) and NIR spectroscopy (r=0.79) presented the strongest correlations with the standard method for predicting stiffness. When nondestructive testing was evaluated without distinguishing between species, statistical analysis revealed no significant differences between methods. The evaluated methods estimated stiffness satisfactorily, albeit with variations. NDT 1 overestimated stiffness across species, NDT 2 provided better distribution, and NDT 3 estimated stiffness well for *M. scleroxylon* but underestimated stiffness when applied to multiple species. These findings demonstrate that NDT methods offer an alternative to traditional destructive testing for wood characterization, but highlights the importance of selecting an appropriate nondestructive method for each wood species.

KEYWORDS: tropical wood; modulus of elasticity; NDT; mechanical waves, near infrared

Rigidez da madeira de duas espécies hiperdominantes na Amazônia Central avaliadas por diferentes metodologias não destrutivas

RESUMO

O estudo avaliou as metodologias não destrutivas (NDT) para estimar a rigidez da madeira de *Protium puncticulatum* (Breu-vermelho) e *Micrandropsis scleroxylon* (Piãozinho). Um total de 100 corpos-de-prova (20×20×300 mm) foram preparados a partir da madeira de três árvores de cada espécie, com as dimensões na direção longitudinal. Uma equação de regressão, um temporizador de ondas de estresse e a espectroscopia NIR foram usados para estimar a rigidez e compará-los com a metodologia tradicional. O método destrutivo produziu valores médios de rigidez de 9.890 MPa para *P. puncticulatum* e 15.002 MPa para *M. scleroxylon*. Os resultados da correlação de Pearson indicam que a equação de regressão (r=0,83; 0,72) e a espectroscopia NIR (r=0,79) apresentaram as correlações mais fortes com o método padrão para predição de rigidez. Quando testes não destrutivos foram avaliados sem distinguir entre espécies, a análise estatística não revelou diferenças significativas entre os métodos. Os métodos avaliados estimaram a rigidez satisfatoriamente, embora com variações. O NDT 1 superestimou a rigidez entre as espécies, o NDT 2 forneceu melhor distribuição e o NDT 3 estimou a rigidez bem para *M. scleroxylon*, mas subestimou a rigidez quando aplicado a várias espécies. Este estudo demonstrou que os métodos NDT oferecem uma alternativa aos testes destrutivos tradicionais para caracterização da madeira, mas destaca a importância de selecionar um método não destrutivo apropriado para cada espécie de madeira.

PALAVRAS-CHAVE: madeiras tropicais; modulo de elasticidade; NDT; ondas mecânicas; infravermelho próximo

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The study of the technological properties of lesser-known native species is essential for sustainable management on the Amazon. While many commercial woods have been researched, numerous species remain unstudied due to vast biodiversity (Almeida et al. 2020).

Wood characterization follows standards from the Brazilian Association of Technical Standards, the American Society for Testing and Materials, the Pan-American Standards Commission, and European Standards, among others. Methods for determining wood properties are evolving to become faster, more accurate, and cost-effective. Recently, nondestructive testing methods (NDTs) have gained prominence for estimating wood's physical-mechanical properties without structural alterations. Examples include regression equations based on basic density, stress wave propagation, impulse tomography, and NIR spectroscopy (Araújo 2007; Mancini et al. 2019; Araújo et al. 2022).

Flexural stiffness is mathematically expressed as the product of the modulus of elasticity (MOE) and the cross-section's moment of inertia, reflecting wood's ability to maintain shape under load. Higher values indicate lower deformation. Stiffness is crucial in structural applications like beams, columns, and floors, where minimizing bending and vibration ensures safety and durability (Kollmann & Coté Jr. 1968; Ross 2015). In this context, this study aimed to evaluate different non-destructive methods for estimating the stiffness of wood from two Amazonian species.

The woods used in the study were collected at the Experimental Station of Tropical Silviculture of the National Institute for Amazonian Research, located at the ZF-2 site, Manaus, Amazonas (2°37' to 2°38' S, 60°09' to 60°11' W). The samples were obtained from an inventoried plot (subplots of 100×4.25 m) established within the proposal of the INCT Madeiras da Amazônia – MCTIC/CNPq/FAPEAM. The selection criterion for *Protium puncticulatum* J.F.Macbr., Burseraceae (Breu-vermelho) and *Micrandropsis scleroxylon* W.Rodr., Euphorbiaceae (Piãozinho) was their high abundance in the plots. In addition to their high occurrence in the study area, the selected species possess significant economic potential. Species of the genus *Protium* are traditionally valued for their production of aromatic resins, which are widely used by indigenous and local communities. Although its wood is not extensively exploited commercially, it exhibits favorable physical and mechanical properties that could support its use in construction and furniture manufacturing (Freitas and Vasconcellos 2019). *M. scleroxylon* is recognized for its dense and durable wood, making it a promising candidate for demanding structural applications, such as beams, flooring, and high-end furniture (Rodrigues 1973). In the context of sustainable forest management, the technological characterization of these species can expand their potential applications, enhance the value of lesser-known woods, and reduce harvesting pressure on traditionally exploited commercial species.

Individuals were randomly selected for harvesting (three individuals per species), considering characteristics such as diameter at breast height and commercial height, as well as the proximity between individuals of the same species. In the Wood Engineering and Artifacts laboratory/COTEI/INPA the logs were processed into planks and the test specimens were cut with their largest dimension in the longitudinal direction. For the stiffness test, specimens measured 20×20×300 mm, while for wood density determination, they measured 20×20×50 mm. For the destructive test, 20 samples were used, and for the nondestructive determinations, 30 samples were used, totaling 50 samples for each wood species.

The apparent density (ρ_{apar}, g cm^{-3}) was determined using test samples (n=10) with a moisture content of 12%, which was achieved by exposing the material in a climate-controlled room (20±2°C, 65±5% humidity). This variable is estimated by the ratio between mass, obtained with a digital scale (0.01 g), and volume, measured with a digital caliper (1.00 mm), both at the specified moisture content (NBR7190/2022). The basic density (ρ_{bas}, g cm^{-3}) was determined by first saturating 10 samples in water and measuring their dimensions with a digital caliper to calculate the green volume. The samples were subsequently dried in an oven (100±3°C) until they reached a constant weight to determine the oven-dry mass on a digital scale. This variable is estimated by the ratio of oven-dry mass to green or saturated volume (COPANT30/1971).

The determination of wood stiffness was carried out on test samples with 12% moisture content subjected to destructive static bending tests (BS338:2009). The samples were horizontally mounted on a universal testing machine and subjected to a centralized load (loading speed of 1.0 mm/min), where the support span was fixed at 280 mm. The stiffness was calculated using the load and corresponding deformation below the proportional limit.

To compare to the standard method, wood stiffness was estimated using nondestructive testing methods: NDT 1, based on the previously determined ρ_{bas} values, applied to the regression equation: Stiffness = $-1741.8+32414\times\rho_{bas} - 12889\times\rho_{bas}^2$ (R^2=0.81, n=159, Araújo 2007); NDT 2, in which stress wave variables are obtained using the stress wave timer 239A (Metriguard, Pullman/WA) and used to calculate stiffness with the equation (MOEd, dynamic modulus of elasticity) = $(L/t)^2\times\rho_{apar}/g\times10^{-5}$, where L = length of the test sample (m), t = wave propagation time (s), $\times\,\rho_{apar}$ = apparent density (kg m^{-3}), and g = gravitational acceleration (m s^{-2}) (Araújo et al. 2022). NDT 3 consisted of obtaining near-infrared (NIR) spectra of wood samples with a moisture content of 12%, in the radial and tangential planes using a Thermo Fisher Scientific Fourier transform near-infrared spectrometer (FT-NIR) (model Antaris II). The system operates in the range of 10000-4000 cm^{-1}, with 16 scans and a resolution of 8 cm^{-1}, controlled by the Result Integration software. Three readings were taken from each sample to obtain a representative average spectrum for each sample. To predict stiffness, the partial least squares regression model was used (Nascimento et al. 2016). The model was built using a dataset comprising 1200 samples of 40 Amazonian tree species, collected in the Amazonas region, Brazil. Each species was represented by three individuals, from which the samples were extracted and analyzed. The spectral data was processed and analyzed in the TQ Analyst™, software, and preprocessing techniques such as multiplicative dispersion correction and Savitzky-Gola smoothing filter were applied to improve signal quality and reduce noise. The chemometric parameters used in the modeling were the coefficient of determination (R^2=0.90) and the performance-to-deviation ratio (RPD=4.09), indicating strong predictive capacity. The uncertainty of the predicted values was <10%, confirming the robustness of the model. These parameters were validated by comparing the NIR predictions with stiffness values obtained through traditional destructive methods.

The mechanical property data were subjected to a parametric statistical test (ANOVA one -way), to compare the treatment means and assess the influence of the different tested methodologies. When the residuals of the ANOVA model did not meet the assumptions of normality and homogeneity of variance, a nonparametric Kruskal–Wallis test was applied at a 5% significance level. The analyses were performed using the software programs PAST (4.08), TQ Analyst™, and R (4.3.1).

This study investigated the potential of recommending nondestructive testing methods for estimating the stiffness of *Protium puncticulatum* and *Micrandropsis scleroxylon* wood. The destructive (standard) methodology was used as a reference, yielding stiffness values of 9890 MPa for *P. puncticulatum* and 15002 MPa for *M. scleroxylon*, as shown in Table 1. The stiffness estimation using NDT 1 and 2 was based on the variables ρ_{bas} and ρ_{apar}, with results presented in Table 2. *M. scleroxylon* presented the highest density values, reaching 0.86 g cm^{-3} (ρ_{bas}) and 1.18 g cm^{-3} (ρ_{apar}).

A high correlation (r=0.83) was observed between the stiffness values determined using the standard methodology and NDT 1 for *P. puncticulatum*, while for *M. scleroxylon*, NDT 1 and 3 also yielded strong correlations with the standard method (r=0.72; 0.79) (Figure 1). When the NDTs were evaluated without distinguishing between species (n =20 per model), the Kruskal–Wallis test did not indicate a significant difference (df=3, p=0.144) between NDT 1, 2, 3, and the standard methodology (Figure 2). However, despite the absence of statistical differences, a systematic bias was observed, where NDT 1 tended to overestimate stiffness, whereas NDT 3 tended to underestimate it when applied across multiple species (Figure 2). These findings align with previous studies that have reported potential biases in NDT-based stiffness estimation when applied to diverse wood species (Bucur 2023).

The application of NDTs to assess wood stiffness has proven effective in evaluating mechanical properties of various Brazilian wood species (Medeiros Neto et al. 2016; Vargas

Table 1. Results of the statistical analysis of the stiffness values (MPa) of the studied wood samples from the Central Amazon. NDT1 = regression equation based on wood density; NDT2 = based on stress wave timer measurements; NDT3 = based on FT-NIR measurements.

Woods	Statistic	Standard	NDT Methods		
			1	2	3
Protium puncticulatum (Breu-vermelho)	Minimum	9890	9598	9710	9000
	Maximum	12450	11628	12000	11750
	Average	10824	10436	11049	9830
	SE	234	195	205	316
	CV (%)	6.83	5.90	5.86	10.17
Micrandropsis scleroxylon (Piãozinho)	Minimum	13200	15699	13200	12200
	Maximum	15002	17512	15200	14420
	Average	14145	16650	14212	13398
	SE	220	188	161	234
	CV (%)	4.92	3.59	3.59	5.53

SE = standard error; CV = coefficient of variation

Table 2. Density results for the studied wood samples from the Central Amazon. ρ_{apar} = apparent wood density; ρ_{bas} = basic wood density.

Woods	Statistic	ρ_{apar}*	ρ_{bas}*
Protium puncticulatum (Breu-vermelho)	Average	0.97 (±0.02)	0.46 (±0.03)
	Min–Max	0.94-1.00	0.42-0.52
Micrandropsis scleroxylon (Piãozinho)	Average	1.18 (±0.06)	0.86 (±0.06)
	Min–Max	1.09-1.26	0.78-0.96

***** g cm^{-3}; value in parentheses show the standard deviation

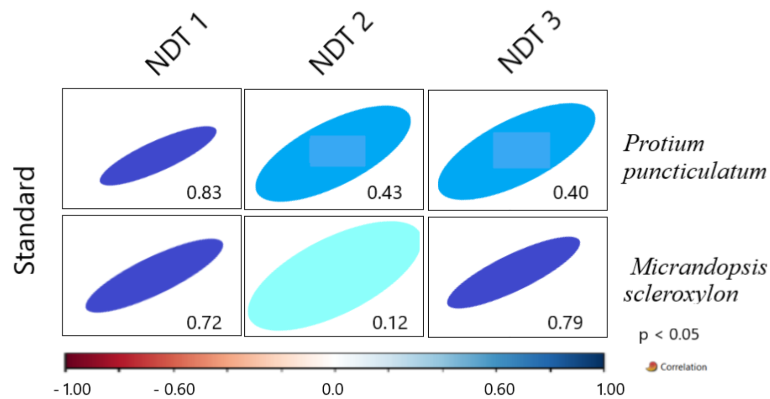

Figure 1. Results of Pearson's correlation between variables obtained from *Protium puncticulatum* and *Micrandropsis scleroxylon* wood based on the relationships between the methods.NDT1 = regression equation based on wood density; NDT2 = based on stress wave timer measurements; NDT3 = based on FT-NIR measurements.

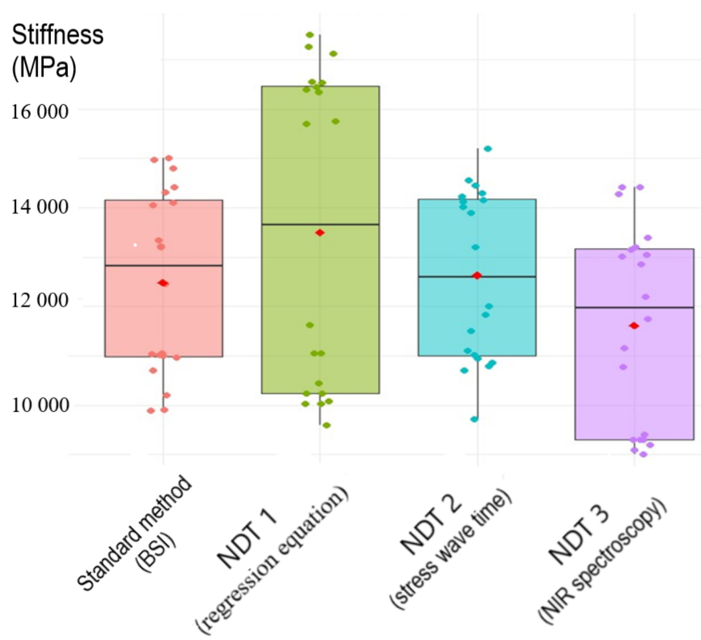

Figure 2. Results of the estimation of wood stiffness by different nondestructive testing methods (NDTs).

et al. 2018). Methods such as impulse excitation, stress wave timer, ultrasonic wave velocity, transverse vibration, and NIR spectroscopy enable stiffness estimation without destructive testing (Almeida et al. 2020; Bucur 2023). However, each method presents specific advantages and limitations depending on the species analyzed.

NDT 1 presented a high correlation with the standard method, particularly for *P. puncticulatum* (r=0.83). However, its dependence on ρ_{bas} can introduce bias if density values are externally sourced rather than directly measured. Additionally, this method tended to overestimate stiffness when applied across multiple species, indicating a limitation in its generalization (Ross 2015). NDT 2, a stress wave timer, estimates stiffness based on wave propagation time and ρ_{apar}, eliminating the need for destructive sampling. Although its estimates aligned more closely with the standard method (Figure 2), its correlation varied. For *P. puncticulatum*, it showed weaker correlation than NDT 1, and for *M. scleroxylon*, it demonstrated variability, suggesting its accuracy may depend on anatomical structure and physical properties such as anisotropy (Kollmann and Cotê Jr. 1968; Bucur 2023).

NDT 3, which employs NIR spectroscopy, is influenced by the molecular excitation of wood chemical components, particularly lignin (Nascimento et al. 2024), as well as polysaccharides, cellulose, and hemicellulose (Schwanninger et al. 2011), which are directly related to stiffness. Although effective for *M. scleroxylon* (r=0.79), it tended to underestimate stiffness across species due to its dependence on the calibration model. The accuracy of NIR predictions is strongly influenced by the spectral database used for training; if the calibration set does not adequately represent the analyzed samples, systematic biases may occur (Tsuchikawa and Kobori 2015; Mancini et al. 2019).

Another critical factor in selecting an NDT method is the time required for data acquisition and associated measurement errors. NDT 1 relies on prior density knowledge (ρ_{bas}), which may be obtained from literature or direct measurement. If measurement is necessary, the process can be time-consuming (several days), involving specimen preparation, saturation, and oven drying. However, once density is known, stiffness estimation is rapid (<60 s per sample), with an error margin <10% (Araújo 2007). NDT 2 is the fastest technique (< 30 s per sample), but its accuracy is affected by wood anisotropy and internal defects, resulting in an error margin of 10–20% (Ross 2015; Medeiros Neto et al. 2016; Araújo et al. 2022). NDT 3 is also rapid (<60 s per sample) but requires a well-developed spectral calibration model. Its error margin depends on the spectral library used but was estimated at ±10% in this study.

This study highlights the importance of selecting an appropriate NDT method based on species characteristics. While all methods estimated stiffness satisfactorily, their effectiveness varied. NDT 1 had the highest correlation but overestimated stiffness. NDT 2 provided better distribution but varied in accuracy. NDT 3 showed strong correlations with the standard method for M. *scleroxylon* but underestimated stiffness across species. Considering these findings, researchers and industry professionals can select the most suitable NDT method based on accuracy, speed, and applicability. Future studies should refine calibration models, improve density estimation techniques, and develop hybrid approaches integrating multiple NDTs to enhance accuracy.

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