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NONDESTRUCTIVE EVALUATION OF A TROPICAL HARDWOOD: INTERRELATIONSHIP BETWEEN METHODS AND PHYSICAL-ACOUSTICAL VARIABLES

Ricardo Faustino Teles[1], Cláudio Soares Del Menezzi[2], Frederico de Souza[1], Mário Rabelo de Souza[3]

Abstract: The paper aimed at evaluating the interrelationship between three nondestructive methods to predict the stiffness of a tropical hardwood (*Sextonia rubra*). Lumber material from *Sextonia rubra* was collected, ripped and planned and boards were then nondestructively tested using three methods: stress wave, transverse vibration and static bending. Stress wave (E_{dsw}) and transverse vibration (E_{dtv}) testing were done using commercial equipment while the static bending testing (E_{sb}) was conducted according to the ASTM D4761. According to the results, linear regression models could be fitted to explain the interrelationship between the nondestructive properties. The best model was observed for the relationship between E_{sb} and E_{dtv} (R^2=0.946), followed by E_{sb}/E_{dsw} (R^2=0.834) and E_{dtv}/E_{dsw} (R^2=0.817). The values of dynamic modulus of elasticity were frequently higher (E_{dsw}=4.19 %; E_{dtv}= 9.44 %) than the E_{sb} values (15314 N/mm^2). On the other hand, E_{dtv} values were higher (5.35%) than E_{dsw} values. It can be concluded that the three nondestructive testing methods studied are suitable to estimate the stiffness of this tropical hardwood. However, corrected models must be employed to improve the reliability of the predicted values.

Keywords: nondestructive evaluation; stress wave, transverse vibration.

AVALIAÇÃO NÃO DESTRUTIVA DE MADEIRA TROPICAL: INTER-RELAÇÕES ENTRE MÉTODOS E VARIÁVEIS FÍSICO-ACÚSTICAS

Resumo: O presente trabalho teve como objetivo avaliar as inter-relações entre três métodos não destrutivos para a estimativa da rigidez de peças de madeira de louro-vermelho (*Sextonia rubra*). Inicialmente, pranchas de louro-vermelho foram resserradas, aplainadas e as tábuas produzidas foram avaliadas por meio de três métodos não destrutivos: ondas de tensão,

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[1] Eng. Florestal, MSc em Ciências Florestais, Doutorando em Ciências Florestais; Professor do IFB, Instituto Federal de Brasília, Brasília, DF.

[2] Eng. Florestal, Professor Adjunto III, Departamento de Engenharia Florestal, Universidade de Brasília, Brasília, DF, <cmenezzi@unb.br>

[3] Doutor em Ciências Florestais, Pesquisador do Serviço Florestal Brasileiro (MMA).

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vibração transversal e flexão estática. As avaliações por meios de ondas de tensão (E_{dsw}) e de vibração transversal (E_{dtv}) foram feitas empregando-se equipamento comercial, enquanto o ensaio de flexão estática foi feito segundo a norma ASTM D4761. Os resultados demonstraram que foi possível ajustar bons modelos lineares de regressão para explicar a inter-relação entre os três métodos estudados. O melhor modelo foi obtido para a relação entre E_{sb}/E_{dtv} (R^2=0,946), seguido por E_{sb}/E_{dsw} (R^2=0,834) e E_{dtv}/E_{dsw} (R^2=0,817). Os valores dos módulos de elasticidades dinâmicos foram sempre mais altos (E_{dsw}=4,19 %; E_{dtv}= 9,44 %) que os valores de E_{sb} (15314 N/mm^2). Por outro lado, os valores de E_{dtv} foram maiores (5,35%) que os valores de E_{dsw}. Concluiu-se que os três métodos não destrutivos estudados são adequados para se estimar a rigidez da madeira amazônica estudada. Entretanto, modelos corrigidos devem ser utilizados para aumentar assim a confiabilidade dos valores preditos.

Palavras-chave: avaliação não destrutiva; ondas de tensão; vibração transversal.

1 INTRODUCTION

The Brazilian wood processing industry does not use any kind of wood grading method, whether visual or based on strength/stiffness to assess the lumber quality. It is believed that these methods are not cost-effective. However, in Brazil the increase in wood prices could make these methods suitable for the wood industry. Additionally, final consumers could use a classified material which would have higher quality and reliability than unclassified ones. Nowadays, the draft version of the Brazilian wood design code (ABNT 2010) comprises strength/stiffness grading of wood employed for structural purposes. Besides the visual grade, the code includes other grading methods based on the acoustic behavior of wood. Additionally, nowadays there already is a Brazilian standard (ABNT 2007) especially devoted to nondestructive evaluation of hardwood through ultrasound measurement. Recently, Sales et al. (2010) proposed the calibration of the modification coefficient ($k_{\mathrm{mod},3}$) to include the nondestructive evaluation in the that new version of the Brazilian wood design code.

The Amazonian Rain Forest is the ecosystem with highest woody plant biodiversity in the World. It is believed to house more than 4000 woody species but less than 400 have already been studied from the technological point of view. Physical and mechanical properties data on Brazilian hardwoods are available, which have been obtained by using destructive testing that required extensive labor and involved high costs. In this context, it is important to study methods to estimate properties of the Amazonian wood that are fast and economical.

According to Pellerin; Ross (2002) the nondestructive evaluation (NDE) is the science that aims to obtain properties of the material without altering its end-use, and use this information to make decisions regarding appropriate applications. For isotropic materials, NDE is used to detect voids, no homogeneous spots and other irregularities. However, in wood products these irregularities are common and then NDE is used to evaluate its effect on physical and mechanical properties.

The utilization of acoustic nondestructive methods for grading or evaluating the properties of tropical hardwoods is not typical. The main methods employed for this purpose are those related to stress wave (DEL MENEZZI et al. 2010; FERRAZ et al. 2009; RAVENSHORT et al. 2008), ultrasonic (STANGERLIN et al. 2010; GONÇALVES; COSTA, 2008; KARLANASARI et al. 2008; OLIVEIRA et al. 2005, OLIVEIRA et al. 2002; GONÇALEZ et al. 2001) and transverse vibration measurements (TELES et al. 2010; GREEN; ROSALES 2006; ILIC 2003). In general, the results pointed out that these methods are suitable for measuring dynamic modulus of elasticity and have a good relationship with destructive static bending tests. Louro-vermelho (*Sextonia rubra* – Lauraceae) is an Amazonian hardwood widely used in light construction and often found in Northern states of Brazil. The wood basic density is around 0.55 g/cm^3 and it can be classified as a medium strength wood. It has brownish heartwood which presents some durability against biodegradation. Recently, Teles et al. (2010) found that this species is suitable for manufacturing of glulam beams. In this context, the paper aimed at evaluating the interrelationship between three nondestructive methods (static bending, stress wave and transverse vibration) for *Sextonia rubra* lumber. Additionally, physical-acoustical properties were studied in order to predict more easily the stiffness of the boards.

2 MATERIAL AND METHODS

2.1 Wood Material

Lumber material from louro-vermelho (*Sextonia rubra*) was collected at trading companies and macroscopically identified through comparing with the standard samples deposited at Forest Products Laboratory Wood Anatomy Section (*Index Xilarium* FPBw), Brazilian Forest Service, Brasília, Brazil. Afterwards, the material was edged, ripped and planned and 52 boards measuring 45 mm by 20 mm by 1900 mm (*width x thickness x length*) were produced. The boards were then air-dried for 45 days and subsequently stored in air-conditioned room (20ºC; 65% RH) for final moisture equalizing.

2.2 Nondestructive Testing

The boards were nondestructively tested using three techniques: stress wave, transverse vibration and static bending. Stress wave and transverse vibration testing were done using commercial equipment. The Metriguard Stress Wave Timer 239A generates and measures the velocity of a stress wave through the board and uses the board's density to calculate the dynamic modulus of elasticity (E_{dsw}). On the other hand, the Metriguard 340 E-computer measures the beam's natural frequency after the board has been hammered, and together with board weight and dimensions determines the dynamic transverse modulus of elasticity (E_{dtv}). The static bending testing (E_{sb}) was conducted according to the ASTM D4761 (2003) (long span) and the mid-span (900 mm) board deflection was measured for a 50 N weight. Equations 1, 2 and 3 were employed to calculate E_{dsw}, E_{dtv} and E_{sb} respectively.

$$E_{dsw}(N/mm^2) = \frac{wv^2 \cdot \rho}{g} \cdot 10^{-5} \qquad \text{(Equation 1)}$$

$$E_{dtv}(N/mm^2) = \frac{fr^2 \cdot w \cdot L^3}{2.46 \cdot I \cdot g} \qquad \text{(Equation 2)}$$

$$E_{sb}(N/mm^2) = \frac{50 \cdot L^3}{48 \cdot \delta \cdot I} \qquad \text{(Equation 3)}$$

Where: wv: stress wave velocity, m/s; ρ: board density, kg/m^3; g: acceleration of gravity, m/s^2; fr: resonance frequency, Hz; w: board weight, N; I: moment of inertia, m^4 or mm^4; L: span, m or mm; δ: mid-span deflection, mm.

2.3 Statistical Analysis

Initially, the physical parameters obtained in the nondestructive evaluation (wv, ρ, fr and δ) and the three modulus of elasticity (E_{dsw}, E_{dtv} and E_{sb}) were analyzed using Pearson correlation (r). Afterwards, data about the three moduli of elasticity were statistically evaluated by simple linear regression analyses by origin $(y = b \cdot x)$, in order to determine the interrelationship between the three nondestructive methods: E_{dsw} *x* E_{sb}, E_{dtv} *x* E_{sb}, and E_{dtv} *x* E_{dsw}. Additionally, the three nondestructive modulus of elasticity were also modeled (*y*) using wv, fr and δ as predictors (*x*). For this purpose, stepwise regression analysis was run and the model employed is presented in equation 4. The significance of the all models was verified by the analysis of variance (ANOVA).

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon \qquad \text{(Equation 4)}$$

Where: β_0 is the constant, β_i are the coefficients and the x_i the predictors that entered in the model.

3 RESULTS AND DISCUSSION

3.1 Nondestructive Variables

Table 1 presents the descriptive statistics of the evaluated properties. The following boards mean physical-acoustical parameters were obtained: stress wave velocity, 4820 m/s (standard deviation: 5.8%); 12% moisture content density, 0.682 g/cm^3 (11.3%); mid-span deflection, 14.6 mm (18.9%) and natural frequency, 12 Hz (7.2%).

Table 1. Descriptive statistics of the three nondestructive modulus of elasticity and the physical parameters of the boards. (N=52 boards).

Tabela 1. Estatística descritiva para os três módulos de elasticidade e para os parâmetros físicos e acústicos das tábuas. (N=52 tábuas).

Variables	Mean	Maximum	Minimum	Std. Deviation
E_{dsw} (N/mm^2)	15861.4	20049.0	10637.0	2330.2
E_{dtv} (N/mm^2)	16739.6	22358.0	10269.0	2730.5
E_{sb} (N/mm^2)	15314.1	20455.0	10266.0	2495.2
Density (g/cm^3)	0.682	0.840	0.460	0.064
Frequency (Hz)	12.0	13.7	9.5	0.832
Stress wave velocity (m/s)	4819.7	5272.9	3955.6	275.5
Mid-span deflection (mm)	14.6	21.3	10.8	2.52

Del Menezzi et al. (2010) employed stress wave method to study six tropical hardwoods, with density ranging from 0.62 to 1.22 g/cm^3. For freijo wood (*Cordia goeldiana*), whose density is closer to that of louro-vermelho, 4555 m/s was observed for the stress wave velocity. On the other hand, Oliveira et al. (2002) when studying heavier wood species using ultrasonic measurement obtained wave velocities of 4514 m/s for cupiúba (*Goupia glabra*, 0.83 g/cm^3) and 4279 m/s for jatobá (*Hymenaea* sp., 1.15 g/cm^3). Ilic (2003) evaluated the dynamic MOE of 55 wood species, comprising nine African and South American hardwood species. For this group, although the density had a wide ranging (0.097 to 0.855 g/cm^3), the wave velocity ranged just from 4210 to 5540 m/s. In fact, a direct relationship between density and wave velocity was not identified by the authors.

The results of the Pearson correlation between the nondestructive variables are presented in Table 2. All the r values were highly significant, except for resonance frequency *x* density and stress wave *x* density. As mentioned above, other authors have not also identified clearly the relationship between density and stress wave velocity (DEL MENEZZI et al. 2010; ILIC, 2003; OLIVEIRA et al. 2002). According to Ilic (2003), the S2 cell wall microfibrilar angle (MFA) plays an important role on the stress wave propagation. The lower the MFA the higher the stress wave velocity. It can also be observed a direct relationship between the three nondestructive moduli of elasticity. The r values ranged from 0.913 (E_{dsw} *x* E_{sb}) to 0.973 (E_{dtv} *x* E_{sb}) and were highly significant. Thus, it can be stated that simple linear regression models are suitable to explain the interrelationship between them. Regarding the variables required to determine the two dynamic modulus of elasticity, it should be highlighted that stress wave velocity achieved high r (0.724) value with E_{dsw}. It is a very important finding since it means that only measuring the stress wave velocity it is possible to predict the stiffness of the board at reasonable level. Therefore, the extra labor required to determine the board density – a mandatory variable to calculate E_{dsw} – can be avoided, which is very interesting because the dimensions of the boards. Actually, other authors have found that stress wave velocity only has the potential to predict flexural properties of wood and wood products (SOUZA et al. 2011).

Table 2. Pearson correlations (r) between the nondestructive variables.
Tabela 2. Correlação de Pearson (r) para as variáveis não destrutivas avaliadas.

Variables	E_{dsw}	E_{dtv}	E_{sb}	Density	Frequency	wv
E_{dtv}	0.923**	1				
E_{sb}	0.913**	0.973**	1			
Density	0.610**	0.620**	0.628**	1		
Frequency	0.708**	0.799**	0.758**	0.068 ^{NS}	1	
wv	0.724**	0.764**	0.719**	0.038 ^{NS}	0.947**	1
δ	-0.856**	-0.909**	-0.928**	-0.561**	-0.761**	-0.711**

** Significant at 0.01 level; ^{NS}: no significant.

Likewise, the resonance frequency of vibration only was also found having a good relationship (0.799) with the transverse vibration modulus of elasticity. According to equation 2 it is an obvious finding; however, it should be taken in account that transverse vibration method requires the measurement of the thickness and the width of the board to calculate its moment of inertia, which is necessary to calculate E_{dtv}. Additionally, according to the results showed in Table 2, board mid-span deflection (δ) has an inverse direct and highly significant relationship (-0.856 to -0.928) with the three nondestructive modulus of elasticity. Undoubtedly it is very important finding, since within the four physical-acoustical properties evaluated it is easiest and cheapest one to obtain. These relationships will be discussed again in the next item. Figure 1 shows the histogram for cumulative frequency of board stiffness according to the three nondestructive methods. It can be observed that the static bending method presented better data distribution and a half-bell curve is also clear, thus evincing a normalized distribution of data. The mean values for E_{sb}, E_{dsw} and E_{dtv} were 15314 N/mm^2, 15861 N/mm^2 and 16740 N/mm^2 respectively.

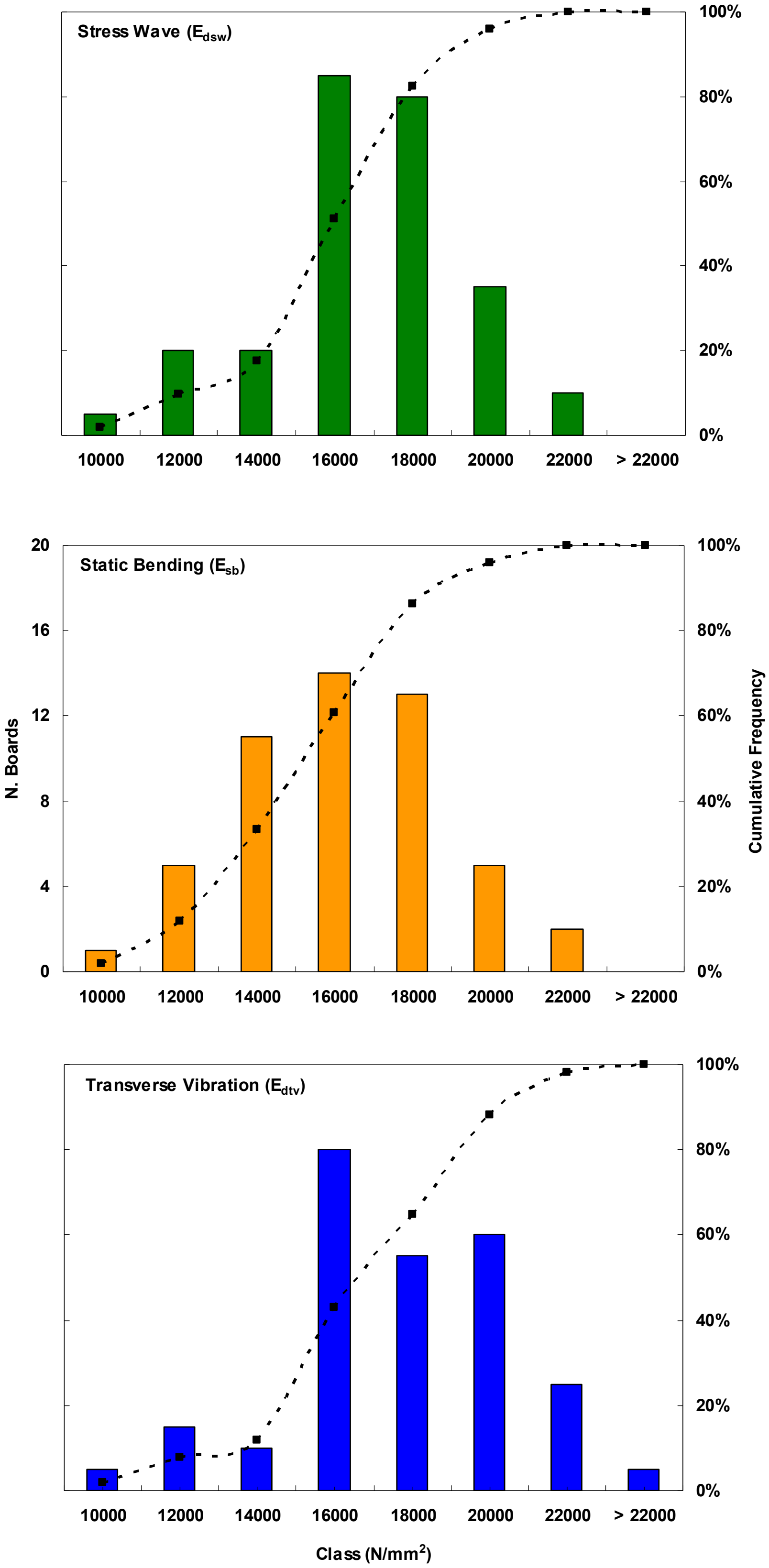

Figure 1. Number of boards and cumulative frequency per stiffness class according to the three evaluated nondestructive methods.

Figura 1. Número de tabuas e freqüência relativa por classe de rigidez, segundo o método não destrutivo avaliado.

Therefore, the values obtained through the dynamic methods were 3.5% (E_{dsw}) and 9.4% (E_{dtv}) higher than E_{sb} values. Several authors have observed that values of dynamic modulus of elasticity are frequently higher than those obtained using static bending testing even for other kinds of wood species (KARLINASARI et al. 2008; BUCUR 2006; OLIVEIRA et al. 2002). Calil Jr.; Miná (2003) evaluated *Pinus taeda* using transverse vibration method and static bending. They observed that dynamic values were approximately 3.2% higher than those obtained in the nondestructive static bending testing. Karlinasari et al. (2008) studied nondestructive testing of *Gmelina arborea* wood. In general, static bending values were 9-11% lower than ultrasonic modulus of elasticity values. According to these authors the difference is probably due to the viscoelastic behavior of wood when evaluated through dynamic and static methods.

3.2 Interrelationship between Nondestructive Methods

Figure 2 presents the linear model to explain the interrelationship between the three evaluated methods. As can be observed E_{dsw} could explain almost 84% of the E_{sb} (Fig. 2A) while for E_{dtv} this value increased to 95% (Fig. 2B). By assuming ASTM D4761 as a reference, the vibration method could fit the data better than stress wave. On the other hand, the relationship between two dynamic methods (Fig. 2C) presented the lower R^2.

When a linear regression curve is fitted, it represents the trend for the relationship between both variables and coefficient b defines its slope. However, the observed data can be above or below this curve, which means that the predicted value can be either overestimated or underestimated. To overcome this limitation, corrected linear models were fitted. In the graphs below, dashed lines represent the models which assure that 95% of the predicted values are above the curve. These can be considered the “corrected models” and they have been determined in order to improve predictability, reliability and safety.

Barrett el al. (2008) studied the interrelationship between nondestructive methods: transversal vibration, ASTM D4761 and stress wave. For Canadian hemlock lumber (*Tsuga canadensis*), they obtained the highest coefficient of determination (R^2=0.981) when the transverse vibration method was employed to predict the modulus of elasticity determined according to ASTM D4761.

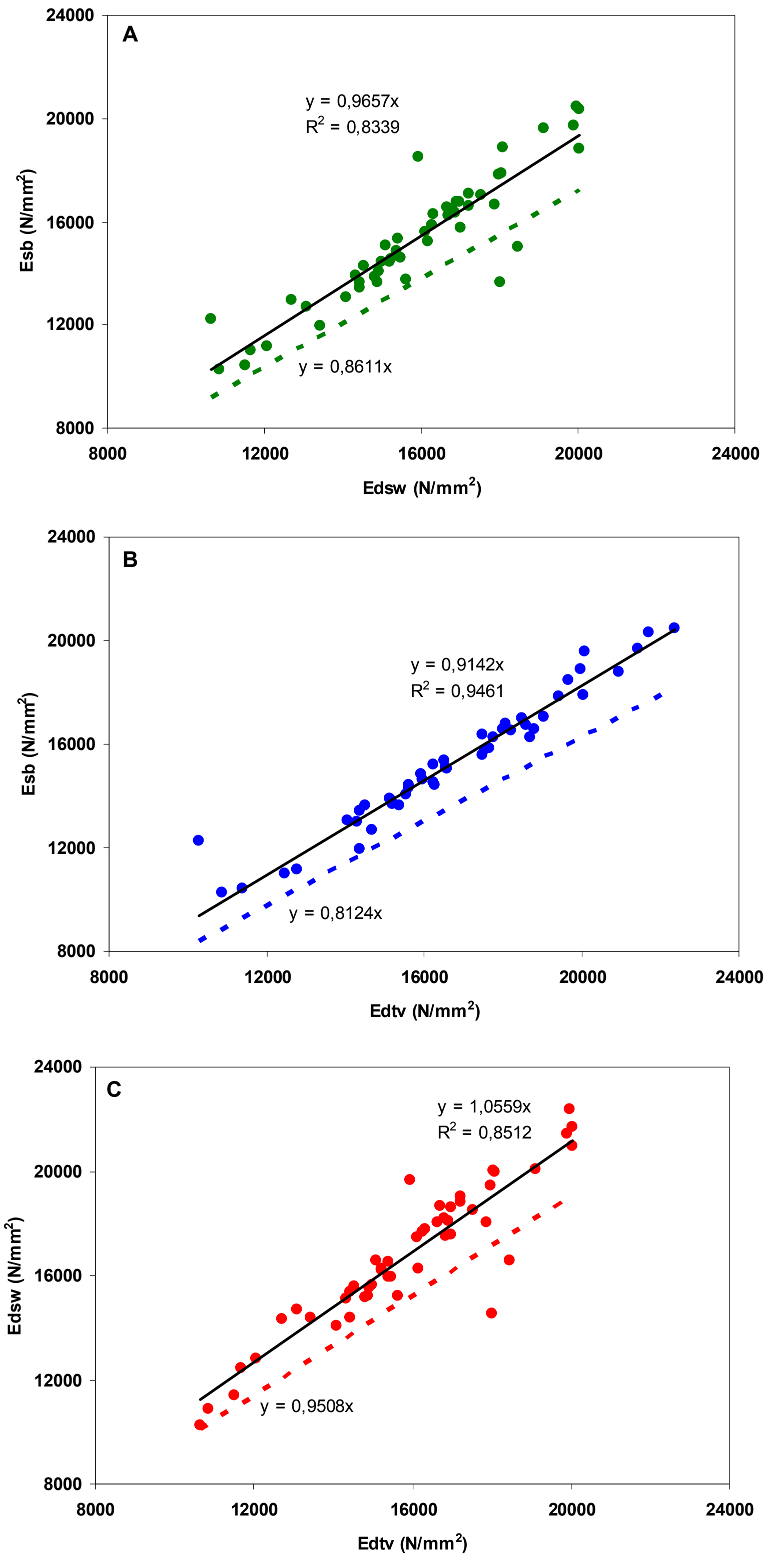

Figure 2. Linear models to explain the relationship between E_{dsw} *x* E_{sb} (A), E_{dtv} *x* E_{sb} (B) and E_{dtv} *x* E_{dsw} (C) for *Sextonia rubra* boards. All models were highly significant (*p<0.000*). N=52 boards. Dashed lines indicate corrected models.

Figura 2. Regressão linear para as relações entre E_{dsw} *x* E_{sb} (A), E_{dtv} *x* E_{sb} (B) e E_{dtv} *x* E_{dsw} (C) para tábuas de *Sextonia rubra*. Todos os modelos foram altamente significativos. (*p<0.000*). N=52 tábuas. Linhas tracejadas indicam os modelos corrigidos.

When the stress wave method was used for predicting flexural stiffness according to ASTM D198, the authors obtained R^2 about 0.847, which can be considered very close to the values obtained in the present paper. On the other hand, Calil Jr.; Miná (2003), cited above, obtained R^2=0.98. Zangiácomo (2003) evaluated wood from cedrinho (*Erisma* sp.) and the results showed R^2 about 0.92 for the relationship between transverse vibration and nondestructive static bending testing. According to the results obtained here, it can be stated that three nondestructive methods can be used for grading wood from louro-vermelho.

In this context, future work will be conducted to evaluate the relationship of flexural properties obtained both destructively and through these evaluated methods. This kind of evaluation is very important because data on acoustic behavior of tropical hardwood is rare, as well as on the relationship between destructive and nondestructive testing. In general, for tropical hardwood the regression models present lower R^2 than those fitted for temperate hardwood or softwood. This happens probably because the material variation within a piece of lumber is lower in tropical hardwoods.

Del Menezzi et al. (2010) studied six well-known Brazilian hardwoods (*Balfourodendron riedelianum*, *Cedrela fissilis*, *Cordia goeldiana*, *Bowdichia virgilioides*, *Dipteryx odorata* and *Tabebuia* sp.). For the group analysis (between species, N=120), they observed R^2=0.9 for the relationship between E_{dsw} and flexural properties determined according to ASTM D143. However, in the within species analysis (N=20) very low values of R^2 were obtained. This same behavior was found by Oliveira; Sales (2006) when studied five Brazilian tropical woods (three plantation wood and two native hardwoods). The variation of wave velocity between species was much more predictable than that done within species. Oliveira et al. (2002) obtained R^2 ranging from 0.36 to 0.63 for the relationship between destructive flexural properties and the ultrasonic coefficient (C_{LL}) for two Brazilian tropical hardwoods (*Goupia glabra* and *Hymenea* sp.). Ravenshorst et al. (2008) studied nine tropical hardwoods from South America, Africa and Oceania using stress wave method. They obtained R^2=0.63 to predict destructive bending stiffness according to European standard EN408 by using dynamic modulus of elasticity. They argued that the analysis showed that it is not possible to have reliable predicting models for all hardwood pieces individually, contrary to what is observed for softwood species like pine and spruce.

Table 3 presents the results of the models fitted to predict the three nondestructive modulus of elasticity. All the methods require the dimensions of the board to determine the stiffness of the board. Additionally, stress wave and transverse vibration methods require either weight or density, which means sometimes a huge labor depending on the dimensions of the boards. This way, according to the results showed in Table 3 the two dynamic modulus of elasticity can be estimated more easily at reasonable level using only stress wave velocity or natural frequency. Nevertheless, it should be highlighted that further measurement of the board mid-span deflection (δ) can improve predictability or lead to better fitted models.

Table 3. Models fitted to predict nondestructive stiffness through physical-acoustical properties.
Tabela 3. Modelos para estimativa da rigidez por meio das variáveis físicas e acústicas.

				β_i coefficient**				
Property	Model	Fcalc**	β_0**	wv	fr	δ	R^2	SEE
E_{dsw}	1	52.9	-13734.3	6.12	^{NS}	^{NS}	0.524	1624.1
	2	131.2	27318.7	^{NS}	^{NS}	-790.9	0.732	1218.3
	3	74.1	15531.5	1.98	^{NS}	-637.2	0.759	1167.3
E_{dtv}	1	84.6	-14754.6	^{NS}	2618.6	^{NS}	0.638	1659.6
	2	138.7	16929.6	2.36	^{NS}	-801.4	0.855	1061.1
	3	229.5	31007.9	^{NS}	^{NS}	-984.9	0.827	1147.3
E_{sb}	1	300.1	28626.5	^{NS}	^{NS}	-918.9	0.862	936.2

** Significant at 0.01 level; ^{NS}: no significant

4 CONCLUSIONS

It can be concluded that the three nondestructive studied methods (static bending, stress wave and transverse vibration) are suitable to estimate the stiffness of a tropical hardwood (*Sextonia rubra*). Highly significant interrelationships between the three methods were found. However, corrected models must be employed to improve the reliability of predicted values. The physical-acoustical properties evaluated can be used to estimate the stiffness of the boards. Therefore, according to the results the two dynamic moduli of elasticity studied can be estimated more easily at reasonable level using only stress wave velocity or natural resonance frequency. It should be highlighted that further measurement of the board mid-span deflection can improve predictability or lead to better fitted models. Further studies will be conducted for other Amazonian tropical hardwoods.

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