Ultrasound Test for Root Wood Elastomechanical Characterization

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The objective of this study was to verify the applicability and preliminary results of an ultrasound methodology for the complete characterization of root wood. The tests utilized six species: *Swietenia macrophylla*, *Gallesia integrifólia*, *Swietenia sp.*, *Schinus molle*, *Handroanthus heptaphyllus*, and *Acrocarpus fraxinifolius*. The results show expected elastic ratios between properties, indicating that although the properties can differ numerically from roots and other parts of the tree, the orthotropic wood behavior is maintained. The root densities were higher than those reported in the literature for trunk wood, but direct relationships among high density and stiffness or strength properties were not observed. The ultrasound tests allowed 12 elastic constants of root wood to be obtained and were feasible for root dimensions because only one specimen was required.

Keywords: Ultrasound test; Static compression test; Wood root strength; Wood root stiffness

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INTRODUCTION

Roots are essential elements for the stability of trees and are important for biomechanical studies focused on tree risk analysis. However, few studies have focused on the physical, mechanical, and anatomical properties of roots. Fortunel *et al*. (2014), Amoah *et al*. (2012), and Vurdu (1977) are examples of these studies. This lack of research is primarily because of the difficulty of accessing roots and the lack of commercial interest (Fortunel *et al*. 2014; Lemay *et al*. 2018). Because of this knowledge gap, the properties of roots are generally assumed to be equivalent to those of the trunk; however, this assumption may be incorrect.

Root characteristics differ from trunk, stem, and branch characteristics in three main ways: geotropism, coating film, and branching mode (Drénou 2006). The geotropism of roots is positive (roots grow down), whereas the geotropism of stems is negative (stems grow up) (Drénou 2006). The film coating on all aerial organs of terrestrial plants is hydrophobic, and such films reduce the evaporation of water into the environment, thereby maintaining moisture in the tissues (Drénou 2006). Compared with the branching mode of the roots, a more regular branching shape is observed in the trunk; moreover, the meristem of the roots is influenced by external tension, while the trunk presents a single terminal meristem (Drénou 2006). In addition to the differences highlighted by Drénou (2006), there are several additional anatomical differences (Vurdu 1977; Fortunel *et al*. 2014). Characteristics of vessels, fibers, and parenchyma are examples of anatomical differences among root, branch, and stem in studies cited by Fortunel *et al*. (2014), while fiber length and proportions of elements (rays, longitudinal parenchyma, fibers, and vessels) are examples in the research presented by Vurdu (1977). Considering these aspects, the physical and mechanical properties of roots may also differ from those of trunks and branches. Additionally, even in the case of wood from the trunk, limited information is available on the mechanical properties of species used more frequently in urban areas because such species do not have commercial appeal.

Ultrasound techniques have been increasingly studied and applied in mechanical sorting applications, wood characterization and inspection (Brashaw *et al*. 2009), and for studying the acoustic tomography of trees (Arciniegas *et al*. 2014; Palma *et al*. 2018). The use of ultrasound in the characterization of wood has considerable advantages over conventional compression tests because only one specimen is required to obtain 12 elastic constants, whereas six specimens are required for compression tests (Gonçalves *et al*. 2014). This advantage is even more important in the case of urban trees because obtaining samples from such trees should only be performed when necessary and with the proper authorization. In addition, certain species of trees are very rare. In the case of roots, this question is even more complex because obtaining root specimen material is more difficult than obtaining trunk and branch specimen material, as the roots are underground.

Considering the importance and scarcity of data on root wood properties, the objective of this study was to verify the applicability and present the preliminary results of an ultrasound methodology for the complete characterization of root wood in six species.

EXPERIMENTAL

Materials

Root segments from *Swietenia macrophylla*, *Gallesia integrifólia*, *Swietenia sp.*, *Schinus molle*, *Handroanthus heptaphyllus*, and *Acrocarpus fraxinifolius* were obtained during a micro-burst phenomenon that occurred in Campinas, São Paulo, Brazil, in June 2016. From each tree, a healthy root segment (without biodeterioration) corresponding to the lateral supporting root was identified immediately below the base of the trunk, as shown in Fig. 1. The root segments were placed in plastic bags and stored in a freezer to maintain the moisture content. From each root saturated segment, polyhedral and cubic specimens were cut and were placed in bags and stored in a freezer.

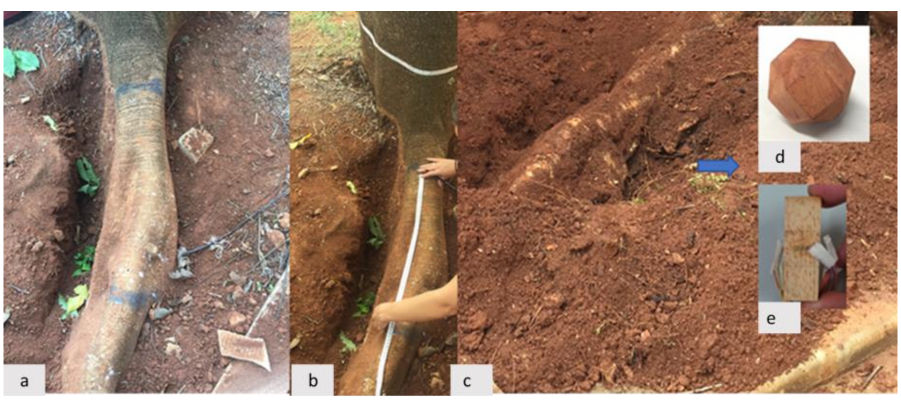


Fig. 1. Illustration of the root segment (a) and the measurement (b), root excavation for the removal process (c) to obtain ultrasonic (polyhedral, d) and static parallel (prismatic, e) specimens

The polyhedral specimens, with 26 faces and 50-mm edges (Fig. 1), were subjected to ultrasound tests. For the compression tests, the prismatic specimens, with dimensions corresponding to standard proportions (height = three times the edge of transversal sections), as indicated in the Brazilian Standard NBR 7190 (1997), were adopted. To facilitate the bonding of the strain gauges, a minimum nominal size of 30 mm × 30 mm × 90 mm was adopted whenever possible. The number of specimens acquired for the tests, as shown in Table 1, varied according to the availability of whole materials for the preparation process.

Table 1. Root Wood Sampling for Ultrasonic and Compression Tests

Species	Number of Ultrasound Specimens	Number of Compression Test Specimens
Swietenia macrophylla	3	3
Schinus molle	4	2
Gallesia integrifolia	4	4
Swietenia sp.	3	3
Acrocarpus fraxinifolius	3	3
Handroanthus heptaphyllus	3	3
Total	20	18

Obtaining the Elastic Parameters of Root Wood by Ultrasound

The complete characterization of root wood by ultrasound was performed using a methodology previously adopted by research groups (Gonçalves *et al*. 2014; Vázquez *et al*. 2015) for the characterization of timber. Using the ultrasound test, the elements of the stiffness matrix [C] were determined and inverted to derive the compliance matrix [S], which was then used to calculate 12 elastic parameters of the wood (three longitudinal moduli of elasticity, three shear moduli, and six Poisson ratios). For these calculations, the material was considered to be orthotropic. Equations 1 through 9 describe the relationships between the terms of the stiffness matrix (obtained by wave propagation methods) and the compliance matrix (obtained by static methods). The nomenclature is related to the symmetric axes of the wood with orthotropic behavior: 1 = longitudinal (L), 2 = radial (R), 3 = tangential (T), 44 = planes 2 and 3 (RT), 55 = planes 1 and 3 (LT), and 66 = planes 1 and 2 (LR),

$$C_{11} = C_{LL} = (1 - \upsilon_{RT}.\ \upsilon_{TR}).\ [E_R.\ E_T.\ S]^{-1} \quad (1)$$
$$C_{22} = C_{RR} = (1 - \upsilon_{LT}.\ \upsilon_{TL}).\ [E_L.\ E_T.\ S]^{-1} \quad (2)$$
$$C_{33} = C_{TT} = (1 - \upsilon_{LR}.\ \upsilon_{RL}).\ [E_L.\ E_R.\ S]^{-1} \quad (3)$$
$$C_{12} = C_{LR} = (\upsilon_{RL} + \upsilon_{RT}.\ \upsilon_{TL}).\ [E_R.\ E_T.\ S]^{-1} \quad (4)$$
$$C_{13} = C_{LT} = (\upsilon_{TL} + \upsilon_{LR}.\ \upsilon_{RT}).\ [E_R.\ E_L.\ S]^{-1} \quad (5)$$
$$C_{23} = C_{RT} = (\upsilon_{TR} + \upsilon_{TL}.\ \upsilon_{LR}).\ [E_L.\ E_T.\ S]^{-1} \quad (6)$$
$$C_{44} = G_{RT} \quad (7)$$
$$C_{55} = G_{LT} \quad (8)$$
$$C_{66} = G_{LR} \quad (9)$$

where C is the term of the stiffness matrix, υ is the Poisson ratio, E is the longitudinal modulus of elasticity (MPa), G is the shear modulus (MPa), and $S = [\ 1 - \upsilon_{LR}.\ \upsilon_{RL} - \upsilon_{RT}.\ \upsilon_{TR} - \upsilon_{LT}.\ \upsilon_{TL} - 2\ \upsilon_{RL}.\ \upsilon_{TR}.\ \upsilon_{TL}]$.

To obtain the diagonal of the stiffness matrix (C_{ij}), ultrasound wave propagation in the L, R, and T axes was used. For the first three terms of this diagonal, a longitudinal wave transducer was used because propagation and polarization must be in the same direction (LL, RR, and TT). To determine the terms C_{44}, C_{55}, and C_{66} (planes RT, LT, and LR, respectively), shear transducers were used because propagation must occur in one direction, and polarization must occur in a perpendicular direction. These six terms were obtained using general Eq. 10, which was deduced using the Kelvin-Christoffel tensor. The Christoffel equation (Eq. 10) allowed the relation of the elastic constants and the ultrasound propagation velocities that form the basis of ultrasound application studies to determine the properties of orthotropic materials,

$$C_{ii} = \rho . V_{ii}^2 \tag{10}$$

where i = 1, 2, 3, 4, 5, and 6, ρ is the material density (kg.m^{-3}), and V is the velocity of wave propagation (m.s^{-1}).

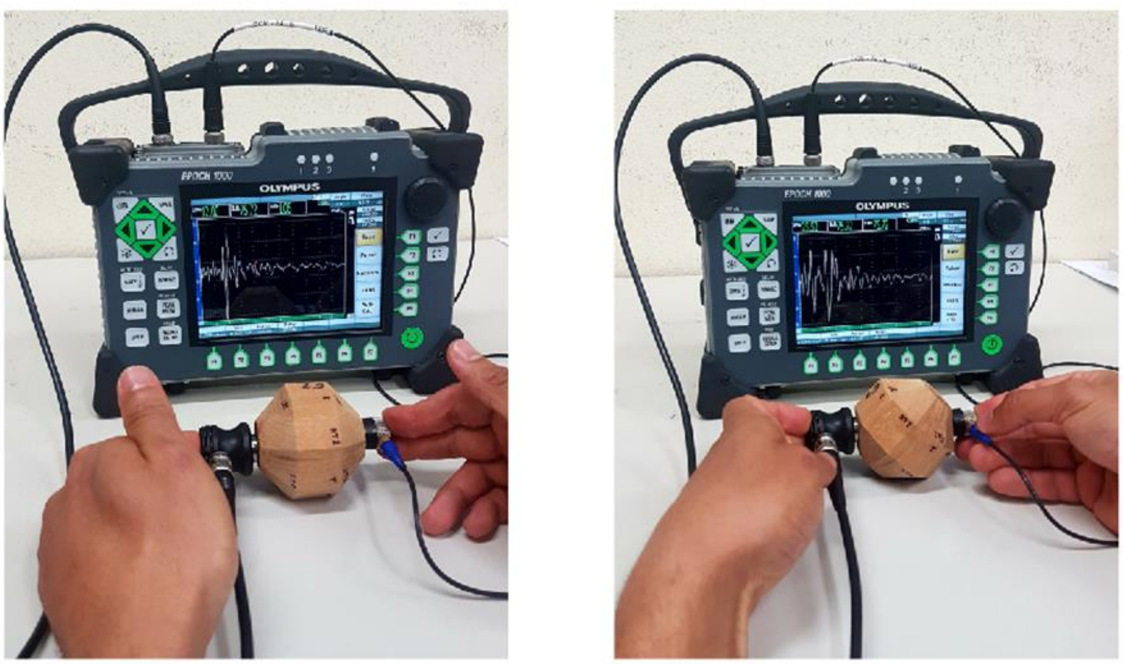
Equations 11 through 13 were used to obtain the three off-diagonal terms (C_{12}, C_{23}, and C_{13}). For this derivation, the wave had to propagate outside the symmetric axes, and quasi-longitudinal and quasi-transversal propagations were obtained,

$$(C_{12} + C_{66})\, n_1 n_2 = \pm [(C_{11}\, n_1^2 + C_{66}\, n_2^2 - \rho\, V_\alpha^{\ 2})\,(C_{66}\, n_1^2 + C_{22}\, n_2^2 - \rho\, V_\alpha^{\ 2})]^{1/2} \tag{11}$$

$$(C_{23} + C_{44})\, n_2 n_3 = \pm [(C_{22}\, n_2^2 + C_{44}\, n_3^2 - \rho\, V_\alpha^{\ 2})\,(C_{44}\, n_2^2 + C_{33}\, n_3^2 - \rho\, V_\alpha^{\ 2})]^{1/2} \tag{12}$$

$$(C_{13} + C_{55})\, n_1 n_3 = \pm [(C_{11}\, n_1^2 + C_{55}\, n_3^2 - \rho\, V_\alpha^{\ 2})\,(C_{55}\, n_1^2 + C_{33}\, n_3^2 - \rho\, V_\alpha^{\ 2})]^{1/2} \tag{13}$$

where α is the propagation of the ultrasonic wave angle (outside the symmetry axes), n_1 is the cos α, n_2 = sen α e $n_3 = 0$ when α is considered with respect to axis 1 (Plane 12), n_1 = cos α, n_3 = sen α e $n_2 = 0$ when α is considered with respect to axis 1 (Plane 13), and n_2 = cos α, n_3 = sen α e $n_1 = 0$ when α is considered with respect to axis 2 (Plane 23).



(a) (b)

Fig. 2. Example of ultrasonic testing on the main axes (a) and at a 45° angle to the main axis (b)

The tests were performed using ultrasound equipment (Epoch 1000 series, Olympus, Tokyo, Japan) and 1 MHz frequency longitudinal and shear transducers. All tests were performed using starch glucose as the coupling media according to the results obtained by Gonçalves *et al*. (2011).

By positioning the longitudinal transducers on the faces parallel to the symmetric axes (Fig. 2a), wave propagation and polarization occurred on the main axes L, R, or T, which made it possible to obtain V_{LL}, V_{RR}, and V_{TT}. Similarly, by positioning the shear transducers on the straight faces of the specimens, propagation occurred on the main axes L, R, or T, and polarization occurred on the perpendicular axis T, R, or L, thus resulting in measurements of the velocities V_{LR}, V_{LT}, V_{RL}, V_{RT}, V_{TR}, and V_{RT}. For the velocities outside the symmetry axes, the shear transducers were positioned on the inclined faces with respect to each of the planes (Fig. 2b).

Methods

Compression tests

For orthotropic material, obtaining a complete compliance matrix using a static compression test requires the removal of six prismatic specimens, with three aligned with the symmetry axes and three inclined in relation to the symmetric planes. For this study, because of the difficulty obtaining such a large number of specimens from root segments, only specimens taken from longitudinal symmetric axes were used. These specimens were used to estimate compression strength because this parameter is not obtained from the ultrasound test. To make the best use of the material during the removal process, both the alignment of the longitudinal direction and the proper orientation of the radial and tangential directions in the cross-section of the specimen were attempted. This alignment enabled the longitudinal elastic modulus (E_L) and two Poisson ratios (υ_{LR} and υ_{LT}) to be obtained in a complementary way. In certain cases, specimens could not be obtained with well-directed radial and tangential axes. In these cases, the test was performed by measuring the strain only in the direction coincident with the load application; moreover, the Poisson ratios could not be calculated.

The load was applied in the longitudinal direction (L), and the strain was measured in the same direction, along with the two perpendicular directions (R and T), if possible. To determine the strain, the specimens were instrumented with extensometers (Fig. 3). A data acquisition system (HBM, Spider 8, Darmstadt, Germany) was used to simultaneously obtain the applied load and the strain in the different directions to obtain the modulus of elasticity in the longitudinal direction E_L, (Eq. 14), the compressive strength f_c (Eq. 15), and Poisson ratios υ_{LR} (Eq. 16) and υ_{LT} (Eq. 17),

$$E_L = \frac{\sigma_L}{\varepsilon_L} \tag{14}$$

$$f_c = \frac{P_{rup}}{S} \tag{15}$$

$$\upsilon_{LR} = \frac{\varepsilon_R}{\varepsilon_L} \tag{16}$$

$$\upsilon_{LT} = \frac{\varepsilon_T}{\varepsilon_L} \tag{17}$$

where σ_L is the stress (MPa) in the longitudinal direction L (load direction), ε_L is the specific strain in the same load direction (L), P_{rup} is the rupture load (N), S is the transversal section area (m^2), and ε_R and ε_T are the specific strains at perpendicular directions relative to the load directions R and T, respectively.

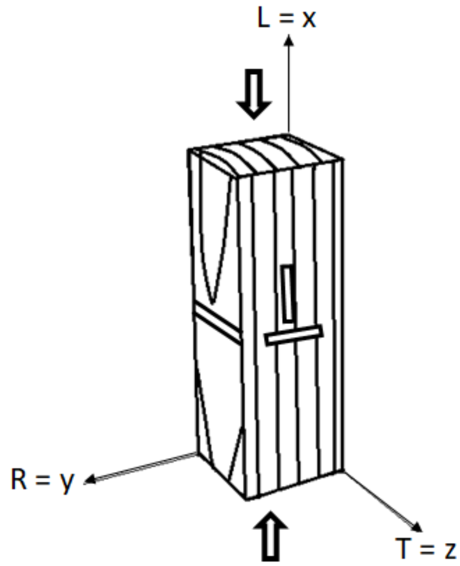


Fig. 3. Positioning of the extensometers in the compression test specimens and direction of application of the applied load; source: adapted from Vázquez *et al*. (2015)

Compression tests were performed using a universal test machine (DL 30000, EMIC, São José dos Pinhais, Brazil). The strain was determined using strain gauges (KFG-5-120-C1-11, KYOWA, Tokyo, Japan) at 5 mm in length with gauge factors of 2.10 +/- 1.0% and gauge resistances of 119.8 +/- 0.2 Ω.

The specimens with fibers and well-positioned growth rings were instrumented with six extensometers, with two in parallel faces to measure strain in each direction (longitudinal, radial, and tangential). Applying the load in the longitudinal direction (L) allowed the stress in the longitudinal direction (σ_L) to be obtained, and applying specific strain in the longitudinal (ε_L), radial (ε_R), and tangential (ε_T) directions (Fig. 4) allowed E_L (Eq. 14) as well as υ_{LT} and υ_{LR} (Eqs. 16 and 17, respectively) to be calculated. The test methodology (speed and load cycles) was performed according to the Brazilian Standard NBR 7190 (1997). To determine the modulus of elasticity in the longitudinal direction, the section of the stress diagram (σ_L) *versus* specific strain (ε_L) in the stress range of approximately 20% to 60% of the rupture was used, provided that in this range, there was a linear behavior with a coefficient of determination (R^2) greater than 0.99 (UNE 56535 1977). The same range was used to calculate υ_{LR} and υ_{LT}. The values calculated from Eqs. 14, 16, and 17 (E_L, υ_{LT}, and υ_{LR}) were compared with the root wood characterization parameters obtained *via* the ultrasound test. The specimens (prismatic) used in the compression tests were also used to determine the volume, initially in the green condition (V_{sat}). Following the compression test, the specimens were placed in an oven for drying, and then the ovendry mass (m_0) was calculated. The relationship between the ovendry mass (anhydrous) and the saturated volume was used to calculate the basic density.

Analysis of results

The results of the physical (density) and mechanical properties (stiffness and strength) were compared with data from previous literature when available. The properties of the roots of different species were also compared numerically and statistically. The numerical comparison attempted to verify whether direct relationships occurred between the physical and mechanical properties. The statistical comparison attempted to identify groups of species with similar mechanical behaviors (strength and stiffness). For statistical analysis, an analysis of variance (ANOVA) table, generated using StatGraphics (StatGraphics Inc., Centurion, VA, USA), was used to decompose the variance of the parameter under analysis into two components: within each group (species) and between groups (different species). If the P-value of the F-test was less than 0.05, then a statistically significant difference occurred between the groups (species) at a 95% confidence level. For significant differences, the Multiple Range Test was applied to verify that the species were significantly different.

RESULTS AND DISCUSSION

In general, the average root basic density was higher than that reported in the literature for trunk or branches (Fig. 4). The basic densities of the *Swietenia* sp. and *Handroanthus heptaphyllus* root wood were the lowest. The basic density of the *Handroanthus heptaphyllus* root wood could not be compared with values from the literature because of a lack of available data.

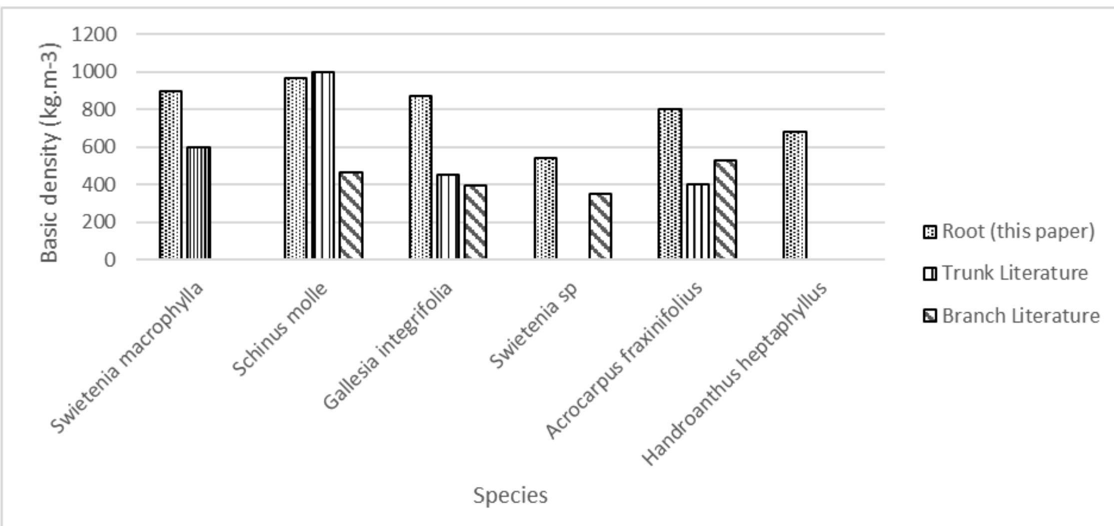


Fig. 4. Basic density values of root (data from this paper), trunk and branches (from the literature)
Trunk Literature:
Swietenia macrophylla: Langbour *et al.* 2011 and WWF Brazil 2017
Schinus mole: REMADE 2017
Gallesia integrifolia: Lima and Garcia 2010; Motta *et al.* 2014
Acrocarpus fraxinifolius: Trianoski *et al.* (2011)
Branche Literature: Garcia 2018

The modulus of elasticity in the longitudinal direction (E_L), obtained by ultrasound test (Table 2), presented lower coefficients of variation than those obtained by compression test (Table 3). Although there were some non-expected higher values for the coefficients of variation in shear modulus and Poisson ratios (Table 2), in general, the values had an acceptable range (up to 25% for strength and up to 35% for stiffness), considering the discussion and results presented by Burdon *et al.* (2001) for trunk wood. For clear wood at 12% moisture content, the average coefficients of variation expected are approximately 22% for stiffness and 18% or 25% for strength, considering compression and tension parallel to grain, respectively (Wood Handbook 2010). We did not find information about the expected values for the coefficients of variation of the Poisson ratios.

Table 2. Average Values (MPa) and Coefficients of Variation (CV in %) of the Elastomechanical Parameters (Modulus of Elasticity (longitudinal - E_L, radial - E_R and tangential - E_T), Shear Modulus (plane RT - G_{RT}, plane LT – G_{LT} and plane LR – G_{LR}) and Poisson Ratios (υ_{RL}, υ_{TL}, υ_{LR}, υ_{TR}, υ_{LT}, and υ_{RT}) of Wood Root Using the Ultrasound Test

	Swietenia macrophylla	*Schinus molle*	*Gallesia integrifólia*	*Swietenia* sp.	*Acrocarpus fraxinifolius*	*Handroanthus heptaphyllus*
E_L	10807	6498	10242	4651	7892	5775
CV	8	7	9	4	15	16
E_R	1551	1101	1225	538	1483	797
CV	4	37	18	2	8	11
E_T	1224	1000	941	449	937	699
CV	4	36	23	12	3	11
G_{RT}	350	320	362	146	365	219
CV	11	76	13	8	2	9
G_{LT}	716	688	955	495	955	642
CV	21	24	13	4	20	9
G_{LR}	1296	908	1075	676	1306	843
CV	4	19	11	12	7	9
υ_{RL}	0.101	0.108	0.068	0.073	0.134	0.079
CV	3	49	57	1	36	19
υ_{TL}	0.0406	0.065	0.061	0.046	0.059	0.059
CV	59	85	22	28	46	17
υ_{LR}	0.404	0.383	0.542	0.490	0.501	0.481
CV	55	50	47	43	49	15
υ_{TR}	0.549	0.681	0.442	0.608	0.482	0.647
CV	7	24	15	12	8	4
υ_{LT}	0.701	0.631	0.646	0.631	0.694	0.577
CV	4	24	11	5	29	27
υ_{RT}	0.694	0.748	0.584	0.730	0.762	0.736
CV	4	24	23	2	10	3

Table 3. Average Values (MPa) and Coefficients of Variation (CV in %) of the Elastomechanical Parameters (Modulus of Elasticity (longitudinal - E_L) and Poisson Ratios (υ_{LR}, υ_{LT}) and Compression Strength (f_c) of Wood Root Using the Compression Test

	Swietenia macrophylla	*Schinus molle*	*Gallesia integrifólia*	*Swietenia* sp.	*Acrocarpus fraxinifolius*	*Handroanthus heptaphyllus*
E_L	7000	6300	6050	915	5967	2300
CV	14	9	43	7	24	51
υ_{LR}	0.460			0.200		
CV	21			35		
υ_{LT}	0.640			0.433		
CV	10			11		
f_c	28.7	23.2	17.9	10.9	20.4	4.7
CV	22	9	11	6	40	63

The longitudinal modulus of elasticity (E_L) obtained by ultrasound and compression tests was statistically equivalent (at 95% confidence) in only three (*Schinus mole*, *Gallesia integrifolia*, and *Acrocarpus fraxinifolius*) of the six species studied, but with both methods, significantly different groups of species could be identified based on the strength and stiffness properties of the root wood (Fig. 5). Differences in these properties will directly impact studies aiming to analyze the biomechanical behaviors of trees. Therefore, characterization methods must be proposed so that researchers can define all the parameters of orthotropic materials. The ultrasound test seems to be more sensitive for detecting differences because the species are separated into three groups, while in the compression test, the species are separated into two groups (Fig. 5).

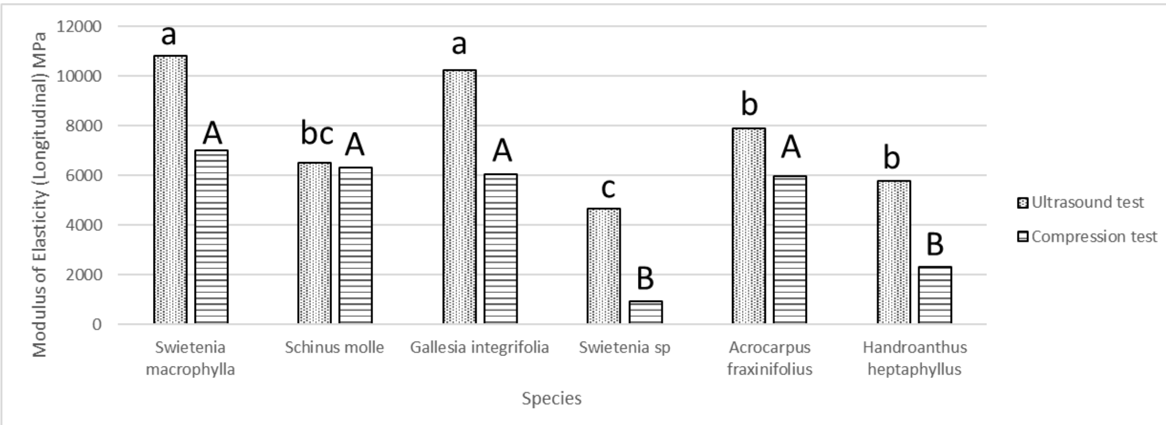


Fig. 5. Longitudinal modulus of elasticity (E_L) among species using ultrasound and compression tests. For statistical comparison among species, equal and lowercase letters indicate statistical equivalence (95% confidence level) for the results obtained in ultrasound tests. Equal and capital letters indicate statistical equivalence (95% confidence level) for the results obtained in compression tests

The species tested in this research are used mostly in urban areas, so they have no commercial appeal, and their properties are not available, even for trunk wood. Thus, for the same species, it is very difficult to compare the properties of root wood obtained in this research with data from the literature. To allow some discussion, we resorted to a few results obtained for trunk and branches. In the case of trunk wood, strength and stiffness data had been obtained at 12% moisture content, so they were corrected for the saturated condition using the moisture content correction proposed in the Brazilian standard (ABNT NBR 7190, 1997) and were then used in the comparisons. With the values obtained with 12% moisture content, the correction factor resulted in 0.80 for strength and 0.86 for stiffness.

For *Swietenia macrophylla*, the average E_L values obtained by ultrasound were 25% higher than those indicated in the literature for wood from trunk (Fig. 6). For the compression test, both the average E_L and the f_c obtained in wood roots were inferior to those from trunks, 23% (Fig. 6) and 35% (Fig. 7), respectively.

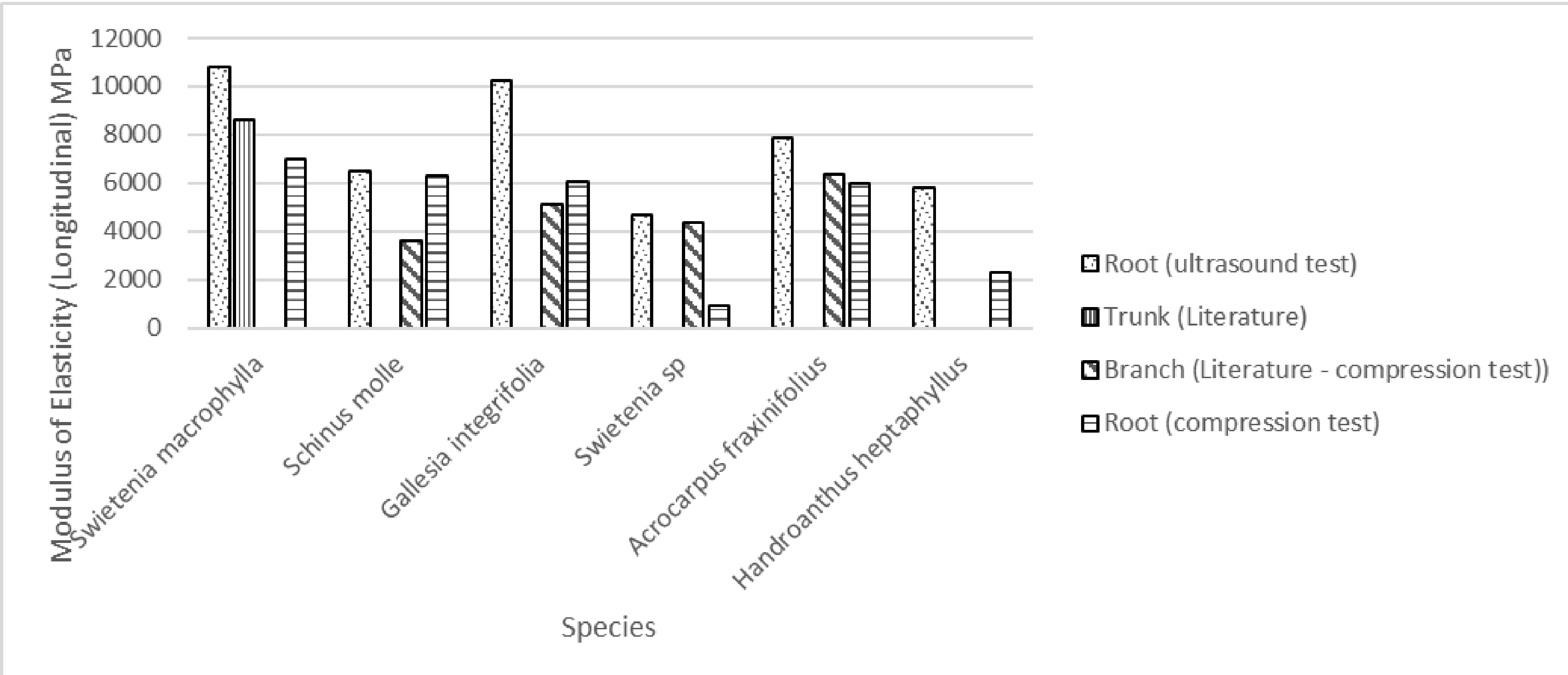


Fig. 6. Longitudinal modulus of elasticity obtained in wood root (ultrasound and compression test) and in wood trunk and wood branches (Literature)
Literature for wood trunk data: Langbour *et al*. (2011) and Portal da Madeira (2017)
Literature for wood branches: Garcia (2018)

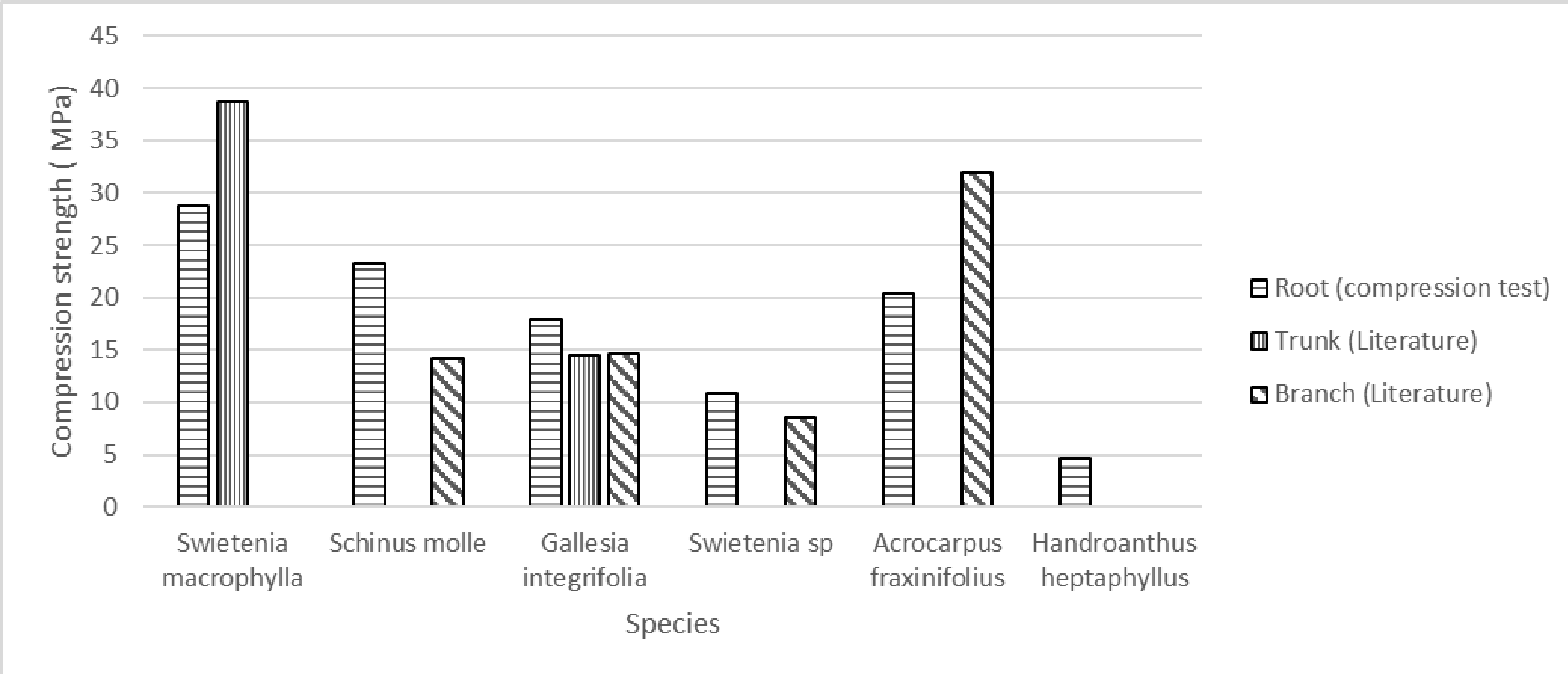


Fig. 7. Compression strength obtained in wood root (ultrasound test) and in wood trunk and wood branches (Literature)
Literature for wood trunk data:
Swietenia macrophylla: Portal da Madeira (2017)
Gallesia integrifólia: Lima and Garcia (2010)
Literature for wood branches data: Garcia (2018)

For *Schinus molle*, numerical information was not obtained from the literature for the mechanical properties of trunk wood, where these parameters were only described using qualitative terms, such as "great strength" and "very rigid", which are not useful for biomechanical analyses. For branch wood, both E_L and f_c were smaller (75% and 63%, respectively) than those for root wood (Figs. 6 and 7). *Schinus molle* root wood had a higher density than the root wood from *Swietenia. macrophylla* (Fig. 4) and presented a 40% lower E_L value in the ultrasonic tests (Table 2). Similarly, the f_c strength obtained in the compression test was also approximately 20% lower than that obtained for *S. macrophylla* (Table 3). This result was inconsistent with previous results showing that trunks with higher-density wood had higher stiffness levels than those with lower-density wood (Niklas and Spatz 2010), although this result is consistent with other studies in which trunk stiffness decreased with increasing density (Larjavaara and Muller-Landau 2010, 2012). The logical conclusion was that all species of wood cannot be categorized using the same behavioral traits. Moreover, the authors' knowledge about the physical and mechanical properties of wood and their relationships is scarce, particularly for wood from freshly sampled trunks in green conditions (Niklas and Spatz 2010).

The root wood of *Gallesia integrifolia* presented an E_L approximately 20% higher than those of branch wood (Fig. 6) and an f_c approximately 20% higher than the values indicated in the literature for trunk and branch wood (Fig. 7). Both the densities (Fig. 4) and E_L obtained by the ultrasound and compression tests (Fig. 6) presented values close to those obtained for *S. macrophylla*, although the f_c was approximately 40% lower (Fig. 7).

For *Acrocarpus fraxinifolius*, the reference values for wood trunk are not available for comparison with the E_L and strength results, although the stiffness (E_L) and f_c values were on the same order of magnitude as those obtained for the species *Schinus molle* (Figs. 6 and 7), whose density was higher (Fig. 4). For wood from branch, although the basic density was inferior to that of root wood, both E_L and f_c were superior than those obtained for root wood (6% and 56%, respectively) (Figs. 6 and 7).

The basic densities of the root wood of the *Swietenia* sp. and *Handroanthus heptaphyllus* were the lowest (Fig. 4). Values obtained for these species could not be compared with trunk wood values from the literature because of a lack of available data. For *Swietenia* sp., the E_L obtained in root wood was 6% higher than that obtained in branch wood, while the f_c was 26% higher. The mean E_L obtained for the *Handroanthus heptaphyllus* species was not lower than that of *Swietenia* sp. (Fig. 6), although the f_c was the lowest among all the evaluated species (Fig. 7).

The results of this study indicated that root wood presented a higher basic density than the values published in the literature for trunk wood of the same species (Fig. 4). Different results were obtained by Vurdu (1977), who conducted a study calculating specific gravity, fiber length, and proportion of wood elements in wood from trunk, root, and brunch from European black alder (*Alnus glutinosa*). The results obtained by Vurdu (1977) show that the average specific gravity values from branch (0.43) are superior to those from trunk and root, which presented a small value (0.25). In contrast, Amoah *et al*. (2012) investigated the physical and mechanical properties of branch, stem, and root wood from the tropical trees Iroko (*Milicia excelsa*) and Emire (*Terminalia ivorensis*) and concluded that the root woods of both species exhibited the highest basic densities compared with those of branch and trunk. The same results were obtained by Lemay *et al*. (2018), who showed that the density of the root wood of the black spruce (*Picea mariana*) was higher than that of the trunk wood. These authors argued that the greater density protects the xylem of the roots, which present higher hydraulic stress, thereby avoiding the process of cavitation. This argument is based on research showing that high densities are directly related to high resistance embolism induced by negative drought-induced pressure (Hacke *et al*. 2001). The xylem pressure of plants with greater drought tolerance present greater negative values to avoid cavitation, which leads to a greater internal charge on the walls of the xylem driver (Hacke *et al*. 2001), whose driving function is fundamental. Lemay *et al*. (2018) observed that the trunk tracheid was significantly longer and narrower than the tracheid of the roots. However, this result differed from that obtained by Pittermann *et al*. (2006), who found longer and wider tracheids when studying the roots of several conifers. Because of these conflicting results, Lemay *et al*. (2018) concluded that the root tracheid could not be assumed to be systematically longer than the trunk tracheid. Fortunel *et al*. (2014) explained differences in the specific gravity of roots by the optimization of their performance in support or transport as a function of the environmental condition. This statement supported Lemay *et al*. (2018)'s hypothesis of superior root densities but also contradicted the results from Vurdu (1977).

Scurfield *et al*. (1972) performed scanning electron microscopy analyses of wood under compression applied parallel to the fibers and concluded that the positive relationship between strength and density decreases with increasing fiber length. A comparison of the results of this research with those obtained in the literature showed that despite the consistently higher densities obtained in the root wood, a correlation with compression strength was dependent on the anatomical characteristics of the wood. These same questions (regarding the density and anatomical characteristics) will have a direct influence on the results obtained by ultrasound tests. Bucur (2006) deepened the theoretical basis of the ultrasonic wave propagation method and indicated that velocity is affected to a greater degree by the anatomical characteristics of the wood than it is by density. Because the calculation for the stiffness matrix elements involves both density and velocity, with the latter value being squared (Eq. 10), the stiffness obtained by ultrasound under equal anatomical structure conditions is expected to increase with increasing density but will not increase under different anatomical structures. Niemz and Aguilera (1995) obtained positive correlations between ultrasonic wave propagation velocities and fiber length in softwoods and hardwoods, with better correlation coefficients obtained for hardwoods ($R = 0.6$) than for softwoods ($R = 0.39$). Vurdu (1977) obtained longer fibers on roots than on branch and trunk. Thus, high-density values and larger fibers (Niemz and Aguilera 1995) will have a positive effect on the root stiffness values obtained *via* ultrasound tests, but not necessarily on the results obtained *via* compression tests (Scurfield *et al*. 1972). This effect may explain the lower values obtained in compression tests than those from ultrasound tests (Fig. 7).

For the other elastic constants (modulus of elasticity in the radial and tangential directions, shear modulus, and Poisson's ratios), even less information is available in the literature for wood in green conditions, and virtually no data are available for urban tree species. Ozyhar *et al*. (2013) showed that when compared with the longitudinal and shear modulus of elasticity, statistically significant differences did not occur between the Poisson ratios obtained in different moisture conditions. This finding facilitates additional comparisons with values in the literature because more data are available for wood at equilibrium moisture levels than for saturated wood. Additionally, the Poisson ratio has less variability among species than other elastic parameters (Bodig and Jayne 1982).

In general, the Poisson ratios obtained by ultrasound were statistically equivalent (at the 95% confidence level) among species (Fig. 8).

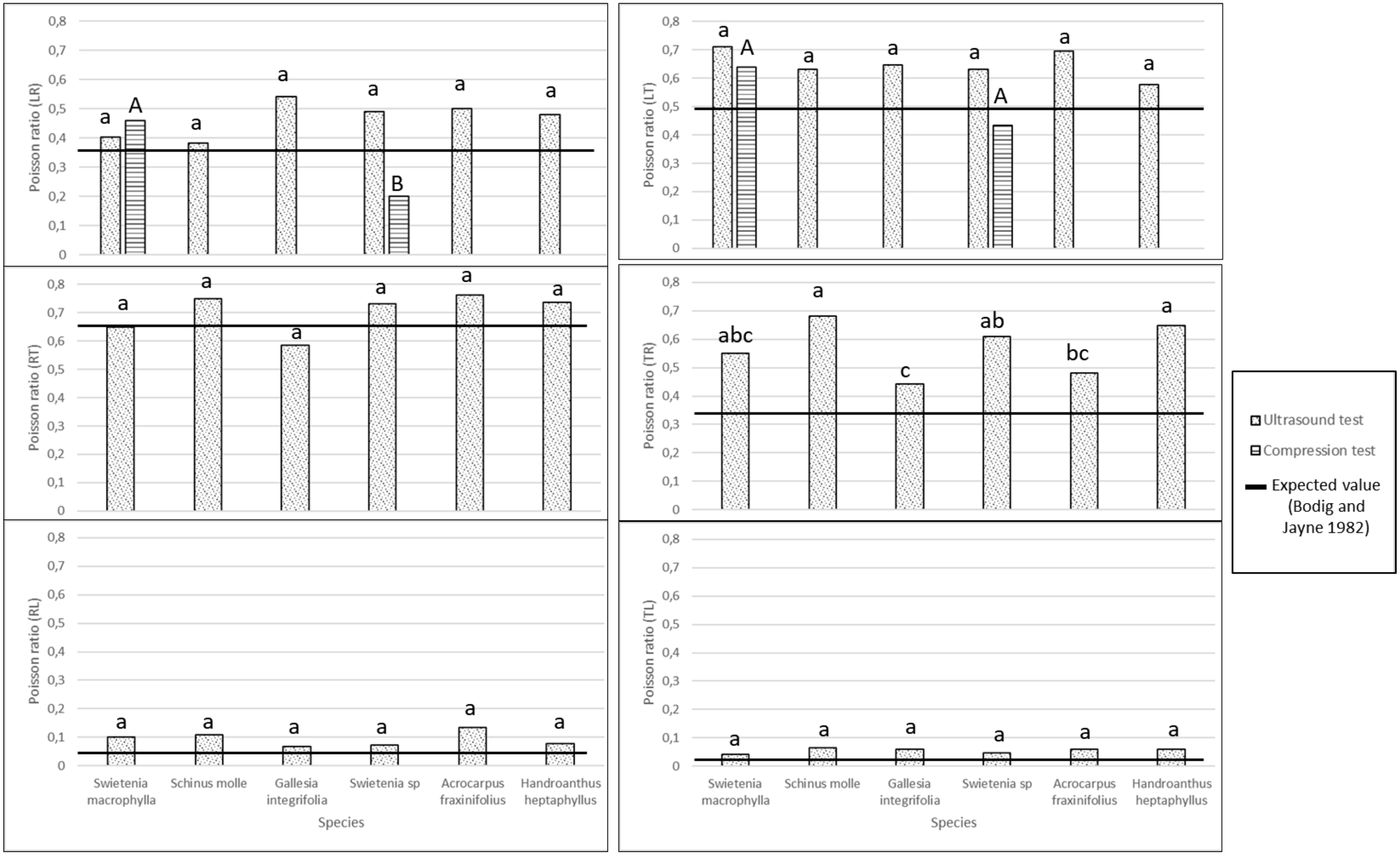


Fig. 8. Poisson ratios among species using ultrasound and compression tests
For statistical comparisons among species, equal and lowercase letters indicate statistical equivalence (95% confidence level) for the results obtained in ultrasound tests. Equal and capital letters indicate statistical equivalence (95% confidence level) for the results obtained in compression tests.

Except for υ_{LR} in *Swietenia* sp., the Poisson ratios obtained by ultrasound were statistically equivalent to those obtained by compression test at the 95% confidence level. However, high variability has been observed in the Poisson ratio of wood (Bodig and Jayne 1982; Bucur 2006); thus, data evaluations are appropriate when considering orders of magnitude instead of exact numerical values and for assessing the coherence between the observed values and the expected behavior for wood based on its orthotropic behavior. Small Poisson coefficients were expected under passive deformations in the longitudinal direction because this direction was the most rigid and therefore less deformable. For these Poisson coefficients (υ_{RL} and υ_{TL}), Bodig and Jayne (1982) provided reference values for hardwoods of 0.040 and 0.027, respectively, and commented that these values are the most difficult coefficients to obtain in static tests because they involve measuring small strain values. Additionally, because of the behavior of the wood, the highest expected Poisson ratio value should be obtained for the relationship between the passive deformation in the tangential direction (of less rigidity) and the active deformation in the radial direction (υ_{RT}). For this Poisson ratio (υ_{RT}), the reference value proposed by Bodig and Jayne (1982) for hardwoods is 0.67. For the other Poisson ratios, the reference values suggested by Bodig and Jayne (1982) for hardwoods are υ_{LT} = 0.50, υ_{LR} = 0.37, and υ_{TR} = 0.33.

In this study, the average of the Poisson ratio LR values (considering all species studied) were 0.467 in the ultrasound test and 0.330 in the compression test (Fig. 6). For the Poisson ratio LT, the values were 0.647 in the ultrasound test and 0.537 in the compression test (Fig. 6). Vázquez *et al*. (2015) obtained values of 0.60 and 0.47 (same order of magnitude) for the Poisson ratio LR under 12% moisture content *via* ultrasound and compression tests and values of 0.66 and 0.52 for the Poisson ratio LT using ultrasound and compression tests, respectively. The lowest Poisson coefficient υ_{RL} and υ_{TL} values were obtained in this study, whereas the highest υ_{LR} value was obtained (Fig. 6) as expected (Bodig and Jayne 1982).

Table 4. Elastic Ratios for the Compliance Matrix (10^{-5}) Terms Obtained in this Research Using Ultrasound and the Intervals Obtained in the Literature

Test	E_L/E_T	E_R/E_T	G_{LR}/G_{RT}	G_{LT}/G_{RT}	E_L/G_{LR}
Swietenia macrophylla	8.8	1.3	3.7	2.0	8.3
Schinus molle	6.5	1.1	2.8	2.1	7.2
Gallesia integrifolia	10.9	1.3	3.0	2.6	9.5
Swietenia sp.	10.4	1.2	4.6	3.4	6.9
Acrocarpus fraxinifolius	8.4	1.6	3.6	2.6	6.0
Handroanthus heptaphyllus	8.3	1.1	3.9	2.9	6.9
Bucur (2006)*	4.5 to 33.1	1.0 to 2.1	2.9 to 16.9	2.4 to 13.1	4.9 to 7.6
Bodig and Jayne (1982)**	20	1.6	10	9.4	14
Preziosa *et al.* (1981)***	7.1 to 8.5	1.5 to 1.7	2.3 to 5.4	1.8 to 4.4	6.8 to 9.8

*Tulip tree, oak, beech, and Douglas fir;
**Theoretical values proposed;
***Oak and Douglas fir

One method of evaluating the validity of elastic constant results if comparative values are not available, such as for root wood, is to verify the theoretical values of the elastic ratios between the constants, based on the orthotropic behavior assumed for wood. Using these elastic ratios, the authors found that the results obtained in this study for root wood (Table 4) generally did not present discrepancies in relation to the expected behavior for wood; this finding validated the results in terms of their compatibility and coherence with the wood mechanical behavior.

CONCLUSIONS

1. The elastic ratios for properties of root wood were consistent with the expected values based on their orthotropic behavior and the anatomic structure of wood in general. This result shows that the ultrasound test had a consistent result and indicated that root wood did not differ from trunk wood in terms of its elastic behavior. Although it was not possible to compare the strength and stiffness of wood from roots and trunk using the same material, literature comparisons indicated that properties can vary greatly among different parts of the tree, highlighting the importance of studies focused on the study of methodologies that allow access to the properties from different parts of the tree.
2. The root densities obtained in this study were higher than those reported in the literature for branch and trunk of same species of wood, but direct relationships among high density and stiffness or strength properties were not observed.
3. Based on our results, ultrasound and compression tests showed their potential to be used to obtain the stiffness and strength properties of roots. The ultrasonic test, as presented, allows 12 elastic constants of root wood to be obtained and is feasible for this part of the tree, with less volume of material available, because only one specimen is required. Further research is important to confirm the consistency of these results to differentiate species based on the strength and stiffness properties of the root wood.

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