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Modeling of wood properties from parameters obtained in nursery seedlings

Raquel Gonçalves, Rafael Gustavo Mansini Lorensani, Esther Merlo, Oscar Santaclara, Manuel Touza, Manuel Guaita, and Francisco José Lario

Abstract: Early selection of trees allows acceleration of genetic improvement, as well as processes related to forest management, to improve the quality of the wood produced; however, to reach this objective, it is necessary to know which parameters can be used as predictors of a tree's aged condition. The objective of this research was to study parameters that are measurable in nursery seedlings and that could be used in prediction models of basic density (BD_t), modulus of elasticity (E_{Mt}), and strength (f_{mt}) of wood from trees. The tests were performed in 240 seedlings (3 and 6 months old) and in 52 trees (72 months old) from seven genetic units of two species: three *Eucalyptus* clones and four *Pinus pinaster* progenies. In the seedlings, measurements of longitudinal velocity of ultrasonic waves (VL_s), basic density (BD_s), height (H_s), diameter (D_s), strength (f_{ts}), and modulus of elasticity (E_{ts}) in tension parallel to the grain were obtained. The E_{Mt} and f_{mt} can be predicted by parameters obtained in seedlings of the same genetic unit. Thus, the use of these parameters, in association with others already used in selection programs, may increase the positive results of the early selection, with economic gains and time reductions in forest management.

Key words: velocity of ultrasound wave propagation, basic density, wood stiffness, wood strength, stem diameter, stem height.

Résumé : La sélection précoce des arbres permet d'accélérer l'amélioration génétique ainsi que les processus associés à l'aménagement forestier pour améliorer la qualité du bois que l'on produit. Mais pour atteindre cet objectif, il est nécessaire de savoir quels paramètres peuvent être utilisés comme prédicteurs de l'état futur des arbres. L'objectif de cette recherche consistait à étudier les paramètres mesurables chez les semis en pépinière qui pourraient être utilisés dans les modèles de prédiction de la densité de base (BD_t), du module d'élasticité (E_{Mt}) et de la résistance du bois (f_{mt}) dans les arbres. Les tests ont été réalisés chez 240 semis (âgés de 3 et 6 mois) et chez 52 arbres (âgés 72 mois) provenant de sept unités génétiques appartenant à deux espèces : trois clones d'eucalyptus et quatre descendances de *Pinus pinaster*. Chez les semis, nous avons mesuré la vitesse longitudinale des ondes ultrasoniques (VL_s), la densité de base (BD_s), la hauteur (H_s), le diamètre (D_s), la résistance (f_{ts}) et le module d'élasticité (E_{ts}) en tension parallèlement au grain du bois. Les valeurs de E_{Mt} et f_{mt} peuvent être prédites avec les paramètres obtenus chez les semis de la même unité génétique. Par conséquent, l'utilisation de ces paramètres, associés à d'autres déjà utilisés dans les programmes de sélection, peut améliorer les résultats positif de la sélection précoce procurant des gains économiques et permettant de sauver du temps en aménagement forestier. [Traduit par la Rédaction]

Mots-clés : vitesse de propagation des ondes ultrasoniques, densité de base, rigidité du bois, résistance du bois, diamètre de la tige, hauteur de la tige.

Introduction

The early selection of wood from young trees is very important for forest-based companies. In companies that aim to use wood as a material, prior grading allows material and destination selection as a function of its properties, avoiding unnecessary spending to process materials that would not meet the minimum requirements for processing. For paper and pulp companies and producers of forest plants, prior selection allows knowledge of the genotypes, avoiding unnecessary investments in materials that do not have the necessary properties to be commercially viable (Apiolaza et al. 2013; Chauhan et al. 2013; Sharma et al. 2016).

For this early selection, it is necessary to use prediction models that involve properties correlated with age and with the property that one wants to infer in aged condition. Among the properties of interest to forest-based companies are stiffness, strength, and density of the wood. On the other hand, among the measurable properties in seedlings and young trees are acoustic properties (Lindström et al. 2002; Chauhan and Walker 2006; Wang et al. 2007; Cherry et al. 2008; Vikram et al. 2011; Gonçalves et al. 2013*a*, 2013*b*; Merlo et al. 2014), density (Wielinga et al. 2009; Lorensani et al. 2015), strength and stiffness (Lindström et al. 2002; Cherry et al. 2008; Vikram et al. 2011), and diameter and height (Simões et al. 1980; Neves et al. 2013; Alves Ferreira et al. 2014), all of which are correlated with age and with the properties of interest to forest-based companies.

The development of nondestructive methods for evaluating young trees to select for adult wood quality is becoming increas-

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R. Gonçalves and R.G.M. Lorensani. School of Agricultural Engineering – FEAGRI – University of Campinas – UNICAMP, Av. Cândido Rondon, 501 – Barão Geraldo 13083-875 – Campinas/SP, Brazil.
E. Merlo and O. Santaclara. MADERA Plus, Parque Tecnológico de Galicia, Rúa de Vigo, 2 32900, San Cibrao das Viñas Ourense, Spain.
M. Touza. GAIN–CIS–MADEIRA, Parque Tecnológico de Galicia, Avda. de Galicia, n° 5, E-32901 – San Cibrao das Viñas – Ourense, Spain.
M. Guaita. University of Santiago de Compostela, Agroforestry Engineering, Polytechnic School of Lugo, R/Benigno Ledo, Campus Universitario, 27002 Lugo, Galicia, Spain.
F.J. Lario. TRAGSA, Vivero Maceda, Carretera Maceda – Baldrei, km 2, 32708 Maceda, Galicia, Spain.
Corresponding author: Raquel Gonçalves (email: raquel@agr.unicamp.br).

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Table 1. Seedlings and trees sampled.

Genotypes	Seedlings	Trees
Eucalyptus clone 1	50	6
Eucalyptus clone 2	20	6
Eucalyptus clone 3	50	6
Pinus pinaster progeny 15	30	8
Pinus pinaster progeny 18	30	9
Pinus pinaster progeny 19	30	8
Pinus pinaster progeny 23	30	9
Total	240	52

Note: Seedlings from clones 1, 2, and 3 were 3 months old; seedlings from progeny families 15, 18, 19, and 23 were 6 months old; and all trees were 72 months old.

ingly important. For this reason, researchers have recently sought to propose protocols for this purpose (Merlo and Santaclara 2012; Apiolaza et al. 2013; Chauhan et al. 2013; Lenz et al. 2013; Lorensani et al. 2015). Models of wood property prediction in trees have been developed (Santaclara et al. 2011; Merlo et al. 2014) but not for such young plants generally or for nursery seedlings, and they do not compare properties with those of trees from the same genotypes in other trials. Therefore, the novel contribution of this paper is the testing of the hypothesis that some parameters measured in nursery seedlings can be used to infer physical and mechanical wood properties in trees. The general objective of this research was to verify the significance of parameters measurable in nursery seedlings in models to predict stiffness, strength, and density in trees from *Eucalyptus* clones and *Pinus pinaster* progenies.

Materials and methods

Sampling

Sampling for the analysis of prediction models consisted of nursery seedlings and 6-year-old trees of seven genetic units of two distinct species: three *Eucalyptus* clones and four *Pinus pinaster* progenies (Table 1). The species were adopted according to the interest of the partner companies, which donated the materials (seedlings and trees) for the research.

The *Eucalyptus* clones were chosen by the company considering their differences in chemical composition (extractives, percentages of lignin), density, and cellulose yield. The three clones were planted and grown in São Paulo State, Brazil, in areas with elevations varying from 650 to 684 m, average annual temperatures from 20.3 to 20.6 °C, and average annual precipitation from 1273 to 1344 mm.

For *Pinus pinaster* progenies, the seedlings and the trees were half-sib progenies from the same open-pollinated mother trees previously selected within a commercial plantation. The seeds (for seedlings and trees) were collected in the same year, preserved in a cold chamber at 5 °C, and then germinated at different times. The progenies were planted and grown in Galicia, Spain.

The tests were performed in the same clone for *Eucalyptus* and in the same progeny for *Pinus pinaster*, at both ages (seedlings and 6-year-old trees).

Methodology

The height, root collar diameter, velocity of longitudinal ultrasonic wave propagation, basic density, strength, and modulus of elasticity obtained in tension tests were evaluated in each nursery seedling. The tests were performed in Brazil (*Eucalyptus* clones) and in Spain (*Pinus pinaster* progenies).

Nursery seedling trials

The height of the seedlings (H_s) considered the entire stem, disregarding the leaves at the extremities. The diameter (D_s) was measured at the interface with the soil (region of the root collar).

To determine the longitudinal velocity of ultrasonic waves in the stem of the nursery seedlings, a minimum distance (L) of 150 mm between the transducers was delimited from the root collar to maintain a ratio of path length (L) and wave length (λ) of approximately 3. This relation is proposed to reduce the interference of the deviation from the theoretical condition of infinite media on wave propagation (Bucur 2006; Trinca and Gonçalves 2009).

The tests were performed with ultrasound equipment (USLAB, Agricef, Brazil) and 45 kHz transducers, with tapered and pointed tips designed and produced by the research group. For the tests, the transducers were positioned at 45° (indirect test), allowing the nursery seedlings to be analyzed without destroying them and constituting a methodology compatible with that applied to trees. According to the ultrasonic wave propagation time, the velocity of the ultrasonic pulse that passed through the stem of the seedlings (VL_s) was calculated. Soon after the ultrasound test, the seedlings were prepared for the tensile test, and their basic density (BD_s) was calculated.

From the stems of the seedlings, which were approximately 150 mm long, samples ranging in length from 30 to 50 mm were taken to determine the basic density. The volume of the samples was obtained under saturated conditions, and the samples were dried in an oven at a temperature of 103 ± 2 °C and then weighed. The dry mass and the saturated volume were used to determine the basic density of the seedlings (BD_s).

Using the velocity (VL_s) and the basic density (BD_s) of the seedlings, the stiffness coefficient (CLL_s; eq. 1) was obtained.

$$\text{(1)} \qquad CLL_s = BD_s \cdot VL_s^2$$

The stiffness coefficient is determined, in general, using the apparent density. However, the use of the apparent density of saturated wood (in the case of seedlings) is not adequate, because it induces results contrary to those expected physically for stiffness (Sobue 1993; Mishiro 1996; Bucur 2006; Gonçalves and Costa 2008). Wielinga et al. (2009) obtained good correlations (R = 0.9) between the stiffness coefficient (called "dynamic modulus of elasticity" by the authors) calculated using the density in the green condition and that calculated using the basic density. Thus, we choose to calculate the stiffness coefficient using the basic density.

For the tension test, we initially discarded the bark in the claw zones. The lengths of the specimens were fixed at 150 mm for *Eucalyptus* clones and 120 mm for *Pinus pinaster*. This length allowed the extensometer to be inserted at the center to measure deformation during the test and to avoid curved portions of the stem. The tension tests were conducted in a universal machine in which it was possible using software to simultaneously receive the signals from the load cell and the extensometer. The speed was adopted according to NBR 7190 (1997) procedures (10 MPa·min^{-1}) and calculated using preliminary tests to obtain the rupture load. After several preliminary tests with different types of claws, the best results were obtained using the same claws as used in synthetic and natural fiber tests.

To calculate the strength (f_{ts}) and the modulus of elasticity of the seedlings in tension tests (E_{ts}), eqs. 2 and 3 (NBR 7190 (1997)) were used, respectively.

$$\text{(2)} \qquad f_{ts} = \frac{F_{t,max}}{A}$$

$$\text{(3)} \qquad E_{ts} = \frac{\sigma_{50\%} - \sigma_{10\%}}{\varepsilon_{50\%} - \varepsilon_{10\%}}$$

where $F_{t,max}$ is the maximum load (newtons); A is the cross-sectional area (mm^2); $\sigma_{50\%}$ and $\sigma_{10\%}$ represent stress corresponding to 10% and 50% of f_{ts}; and $\varepsilon_{50\%}$ and $\varepsilon_{10\%}$ represent respective specific deformation corresponding to $\sigma_{50\%}$ and $\sigma_{10\%}$.

Trials on trees

A log for the static bending test and a disk for determining the basic density (BD_t) were removed from the base of each cut tree.

Static bending tests were conducted according to EN 408 (2010), with the piece on two supports and the application of two-point loading on the thirds of the length. The distance between supports (span) was at least 18 times the diameter of the central section of the log. During the test, the load (P) and the vertical displacement (f) were measured simultaneously. The speed ($mm \cdot s^{-1}$) of the test was used according to EN 408 (2010) and was 0.003 times the section height, which in this research was the diameter of the cross section of the log under the bark at the center point.

The modulus of rupture (f_{mt}) (eq. 4) and the modulus of elasticity (E_{Mt}) (eq. 5) of the logs were calculated according to EN 408 (2010) adapted for roundwood.

$$f_{mt} = \frac{3F_{max}a}{bh^2} = \frac{3F_{max}a}{A \cdot D} \tag{4}$$

$$E_{Mt} = \frac{3aL^2 - 4a^3}{2bh^3\{[2(f_{40\%} - f_{10\%})/(P_{40\%} - P_{10\%})] - 6a/5Gbh\}} = \frac{3aL^2 - 4a^3}{48I[(f_{40\%} - f_{10\%})/(P_{40\%} - P_{10\%})]} \tag{5}$$

where F_{max} is the maximum load (newtons); $a = L/3$, where L is the span; A = the area of the transversal section of the round timber = $\pi D^2/4$, where D is the diameter of the cross section of the log at the center point under the bark; $P_{40\%}$ and $P_{10\%}$ are the ranges used for the calculus representing 40% and 10%, respectively, of the maximum load applied to the log during the bending tests; $f_{40\%}$ and $f_{10\%}$ are the vertical displacements corresponding to the loads $P_{40\%}$ and $P_{10\%}$, respectively; I = inertia of round timber = $\pi D^4/64$; G = shear modulus; and b and h are the base and height of the transversal section, respectively.

Data analysis

The statistical analysis combined both *Eucalyptus* clones and *Pinus pinaster* families. This design permitted the necessary variability of the parameters involved in the analysis and also verification of the consistency and spread of the parameters analyzed from nursery to trees. As hardwoods and softwoods are so different in anatomical characteristics, it is expected that the responses of physical and mechanical properties during growing will also be different. Therefore, despite discrepancies, if it is possible to find significant correlations among properties measured in nursery seedlings and in forest trees at the same genetic units level (clone or progeny), the importance of very early measurements of mechanical, acoustic, and physical properties in breeding programs for genetics selection will be demonstrated.

To analyze the relationship among tree properties (dependent variables) and properties obtained in nursery seedlings (independent variables), simple regression between these variables (dependent and independent) was initially used. From this analysis, the linear regression models were evaluated, as well as the statistics provided by the software (Centurion XV, version 15.1.02, Statgraphics Technologies, Inc., The Plains, Virginia, USA), which evaluates several alternatives of simple regression models, indicating, among all significant models (P values < 0.05), the one with the best coefficients of correlation (R) and determination (R^2).

The number of independent variables (k) to be used in multiple regression models should be adopted as a function of the number of observations of the sample (n) so that at least 2 degrees of freedom (GL) are obtained for residues ($GL = n - k - 1$) (Volpato and Barreto 2011). Thus, in this research, although there were six variables obtained in the seedlings (independent), multiple regressions should contain only four of them because the sampling was composed of seven conditions (three *Eucalyptus* clones and four *Pinus pinaster* progenies) (Table 1). To increase the possibility of using all of the parameters measured in the seedlings, the analysis of the models also counted on the use of the stiffness coefficient (CLL_s, eq. 5), which included the velocity and the basic density, the relationship between height and diameter (H_s/D_s), and the relationship between modulus of elasticity and strength (E_{ts}/f_{ts}) obtained in the tension tests. These three parameters were also evaluated in an isolated way in the simple regression models.

Before multiple regression analysis, we verified the presence of correlations between the independent variables that would be tested in the multiple regression models. Independent variables are considered to be self-correlated when the correlation coefficient (R) between them is greater than 0.5. In this case (R > 0.5), there will be multicollinearity, which is undesirable in multiple correlation models.

The parameters considered not autocorrelated were used in the software to select the independent variables that allowed better adjustment of the multiple regression model. This selection was made by the software based on the highest coefficient of determination (R^2) and the lowest value of the Mallows C_p statistic, which is a measure of the deviation of the model based on the comparison of the average total squared error with the variance of the true error. To analyze the regression models, besides the coefficient of correlation and the P value, the normality of the residuals was observed using the normal probability plot of the residuals.

Results and discussion

The normality, tested by parameter asymmetry, kurtosis, and normal probability graph, was statistically verified for all parameters. From the parameters obtained in the seedlings, relationships were determined (Table 2) and analyzed in a prediction model of wood properties.

Velocity in nursery seedlings

Few authors have used wave propagation in seedlings, and even fewer in seedlings as young as those in this research. For this reason, we consider it appropriate to make comparisons of results using studies that have used seedlings although older and young trees with ages close to the range adopted in this research. Our velocity values ranged from approximately 1700 to 2000 $m \cdot s^{-1}$ with an average coefficient of variation (CV) of 10% for *Pinus* progenies and from 2000 to 2300 $m \cdot s^{-1}$ with an average CV of 7.5% for *Eucalyptus* clones (Table 2). Emms et al. (2012) tested *Pinus radiata* seedlings at 12 and 24 months of age using stress waves and obtained an average velocity of 1133 $m \cdot s^{-1}$ and a CV between 1.0% and 7.4%. Also, in 18-month-old *Pinus radiata*, Emms et al. (2013) obtained velocities of 1047 to 1172 $m \cdot s^{-1}$ (CV of 6.2 to 9.3). Chauhan et al. (2013) performed resonance tests on young plants of *Pinus radiata* between 18 and 20 months of age and obtained a wave propagation velocity between 1260 and 1450 $m \cdot s^{-1}$, with CV of 6.5% to 9.9%. Apiolaza et al. (2011*b*) using 18-month-old *Pinus radiata* obtained a velocity (in resonance test) of 1050 $m \cdot s^{-1}$ (CV = 9.7%) for opposite wood (side opposite to compression wood) and 1230 $m \cdot s^{-1}$ (CV = 7.28%) for compression wood. The differences between the two wood types (reaction and opposite) were identified by wave propagation tests, indicating the usefulness of the test even in very young plants (Apiolaza et al. 2011*b*). Lindström et al. (2002) obtained velocities (ultrasound, stress wave, and resonance) between 1626 and 2193 $m \cdot s^{-1}$ in 48-month-old *Pinus radiata*. Sharma et al. (2016) obtained velocity values between 2520 and 2810 $m \cdot s^{-1}$ (CV of 4.3% to 12.3%) in *Pinus radiata* at 34 months of age. Roth et al. (2007) in 72-month-old loblolly pine stress wave tests obtained

Table 2. Average values (first row) and coefficient of variation (second row) of the parameters measured in seedlings (longitudinal velocity (VL_s), diameter (D_s), height (H_s), basic density (BD_s), strength (f_{ts}), and modulus of elasticity (E_{ts})), the relationships between parameters measured in seedlings (stiffness coefficient ($CLL_s = BD_s \cdot VL_s^2$), H_s/D_s, and E_{ts}/f_{ts}), and wood properties obtained from the trees (basic density (BD_t), strength (f_{mt}), and modulus of elasticity (E_{Mt})).

Seedling measurements									Tree measurements		
VL_s (m·s^{-1})	D_s (mm)	H_s (m)	BD_s (kg·m^{-3})	f_{ts} (MPa)	E_{ts} (MPa)	CLL_s (MPa)	H_s/D_s	E_{ts}/f_{ts}	BD_t (kg·m^{-3})	f_{mt} (MPa)	E_{Mt} (MPa)
***Eucalyptus* clone 1**											
2249	2.48	0.31	350	19.8	1822	1770	125.0	92.0	480	46	8257
10.1	7.2	9.3	17.8	27.3	58.2				4.6	12.0	18.3
***Eucalyptus* clone 2**											
2048	2.83	0.29	360	23.2	2241	1510	102.5	96.6	460	44	7346
4.7	12.5	7.5	15.7	44.9	60.1				5.0	16.0	8.6
***Eucalyptus* clone 3**											
2095	2.51	0.31	270	19.0	1256	1185	123.5	66.1	470	48	7295
7.7	10.1	9.2	17.0	36.5	59.1				4.80	5.7	30.6
***Pinus pinaster* progeny 15**											
1816	3.30	0.33	430	17.1	312	1417	100.0	18.2	440	50	2797
9.9	11.0	7.4	11.7	23.3	25.1				7.7	16.1	25.2
***Pinus pinaster* progeny 18**											
1789	3.59	0.33	430	16.9	313	1376	91.9	18.5	460	59	3183
8.2	9.2	10.4	6.4	21.4	25.6				9.0	11.3	14.1
***Pinus pinaster* progeny 19**											
1735	3.46	0.31	440	18.2	313	1324	89.6	17.2	460	54	2721
11.0	9.9	11.5	16.7	19.6	26.9				11.5	28.4	31.1
***Pinus pinaster* progeny 23**											
1930	3.75	0.36	440	17.4	469	1639	96.0	27.0	480	49	2964
11.1	11.32	9.7	6.3	16.1	17.0				7.8	29.8	16.8

Note: Seedlings from clones 1, 2, and 3 were 3 months old; seedlings from progeny families 15, 18, 19, and 23 were 6 months old; and all trees were 72 months old.

Table 3. Simple regression models correlating modulus of elasticity (E_{Mt}, in MPa) of the wood from the tree, obtained in bending test, with each parameter obtained from the seedlings (longitudinal velocity (VL_s, in m·s^{-1}), basic density (BD_s, in kg·m^{-3}), diameter (D_s, in mm), height (H_s, in m), strength (f_{ts}, in MPa), and modulus of elasticity (E_{ts}, in MPa)) in the tension test, stiffness coefficient (CLL_s, in MPa), and the relationships between height and diameter (H_s/D_s, dimensionless) and between modulus of elasticity and strength (E_{ts}/f_{ts}).

Parameters	Model	*P* value	R^2 (%)	*R*	Error
VL_s (linear)	$E_{Mt} = -19671 + 12.6VL_s$	0.0025	86.3	0.93	1033
VL_s (double squared)	$E_{Mt} = \mathrm{sqrt}(-1.02 \times 10^8 + 34.3VL_s^2)$	0.0017	88.2	0.94	1272
BD_s (linear)	$E_{Mt} = 18154 - 34.0BD_s$	0.0121	74.7	−0.86	1402
BD_s (reciprocal *Y*, squared *X*)	$E_{Mt} = 1/(-0.0000911 + 2.23 \times 10^{-9}BD_s^2)$	0.0047	82.4	0.91	3422
D_s (linear)	$E_{Mt} = 19278 - 4760D_s$	0.0018	88.0	−0.94	964
D_s (squared *Y*, reciprocal *X*)	$E_{Mt} = \mathrm{sqrt}(-1.18 \times 10^8 + 4.5 \times 10^8/D_s)$	0.0011	90.1	0.95	1154
H_s		ns	—	—	—
f_{ts} (linear)	$E_{Mt} = -11439 + 871f_{ts}$	0.05	57.1	0.76	1826
f_{ts} (square root *Y*, reciprocal *X*)	$E_{Mt} = \mathrm{sqrt}(2.32 \times 10^8 - 3.77 \times 10^9/f_{ts})$	0.033	63.4	−0.80	1608
E_{ts} (linear)	$E_{Mt} = 2137 + 2.91E_{ts}$	0.0023	86.8	0.93	1013
E_{ts} (square root *Y*, logarithmic *X*)	$E_{Mt} = (-59.7 + 19.6\ln(E_{ts}))^2$	0.0004	93.5	0.97	759
CLL_s		ns	—	—	—
H_s/D_s (linear)		ns	—	—	—
H_s/D_s (squared *Y*, reciprocal *X*)	$E_{Mt} = \mathrm{sqrt}(2.12 \times 10^8 - 1.86 \times 10^7/(H_s/D_s))$	0.012	74.8	−0.86	1490
E_{ts}/f_{ts} (linear)	$E_{Mt} = 1667 + 68.1E_{ts}/f_{ts}$	0.0004	93.3	0.96	723
E_{ts}/f_{ts} (multiplicative)	$E_{Mt} = \exp(6.09 + 0.64\ln(E_{ts}/f_{ts}))$	0.0002	95.0	0.97	650

Note: Error represents the standard error of the estimative. The nonlinear regression models were those proposed by the statistical program as being those with the highest coefficient of correlation and determination. "ns" indicates that no statistically significant model was found (with *P* value ≤ 0.05). Sample size for all correlations = seven genetic units of two species (three *Eucalyptus* clones and four *Pinus pinaster* progenies).

velocities between 2243 and 2735 m·s^{-1}. For *Eucalyptus* wood, Gonçalves et al. (2013*a*) obtained velocities varying from 3455 to 4456 m·s^{-1} and CV of 15% to 25% in ultrasonic testing in trees of 21 different clones resulting from crossing between *Eucalyptus grandis* and *Eucalyptus urophylla* at 3 years of age. Even considering the different ages, it is verified that the velocity results showed an order of magnitude coherent with the results from the literature for *Pinus* and *Eucalyptus*.

Basic density of nursery seedlings

The basic densities obtained in this research (Table 3) using material from the seedlings (270 to 440 kg·m^{-3}) and from the trees (440 to 480 kg·m^{-3}) also did not differ from those obtained in the literature. For *Pinus radiata*, average values of 385 kg·m^{-3} were obtained in wood at 8 months of age (Apiolaza et al. 2011*a*); 348 to 395 kg·m^{-3} (CV of 4.35% to 6.14%) for wood from trees between 18 and 20 months of age (Chauhan et al. 2013); 358 kg·m^{-3} (CV of

Table 4. Simple regression models correlating the strength obtained in bending test (f_{mt}, in MPa) of the wood from the tree with each parameter obtained from the seedlings (longitudinal velocity (VL_s, in m·s^{-1}), basic density (BD_s, in kg·m^{-3}), diameter (D_s, in mm), height (H_s, in m), strength (f_{ts}, in MPa), and modulus of elasticity (E_{ts}, in MPa)) in the tension test, stiffness coefficient (CLL_s, in MPa), height to diameter ratio (H_s/D_s, dimensionless), and the relationship between modulus of elasticity and strength (E_{ts}/f_{ts}).

		P value				
Parameters	Model	Regression	Intercept	R^2 (%)	*R*	Error
VL_s (linear)	$f_{mt} = 90.4 - 0.0207VL_s$	0.0447	0.0019	58.6	−0.76	3.56
VL_s (double squared)	$f_{mt} = 1/(0.037 - 32.1/VL_s)$	0.0304	0.0012	64.2	−0.80	3.37
BD_s		ns	—	—	—	—
D_s		ns	—	—	—	—
H_s		ns				
f_{ts} (linear)		ns				
f_{ts} (double reciprocal)	$f_{mt} = 1/(0.035 - 0.27/f_{ts})$	0.033	0.0010	63.2	−0.79	3.62
E_{ts} (linear)	$f_{mt} = 54.8 - 0.0049E_{ts}$	0.0328	0.0000	63.1	−0.79	3.37
E_{ts} (square root *Y*, logarithmic *X*)	$f_{mt} = 1/(0.023 - 1.27/E_{ts})$	0.0139	0.0000	73.3	−0.85	3.10
CLL_s		ns	—	—	—	—
H_s/D_s (linear)		ns	—	—	—	—
E_{ts}/f_{ts} (linear)		ns				
E_{ts}/f_{ts} (multiplicative)	$f_{mt} = 1/(0.0147 + 0.0016\ln(E_{ts}/f_{ts}))$	0.0145	0.0006	81.0	0.90	3.10

Note: Error represents the standard error of the estimative. The nonlinear regression models were those proposed by the statistical program as being those with the highest coefficient of correlation and determination. "ns" indicates that no statistically significant model was found (with *P* value ≤ 0.05). Sample size for all correlations = seven genetic units of two species (three *Eucalyptus* clones and four *Pinus pinaster* progenies).

3.8%) for wood from 48-month-old trees (Lindström et al. 2002); and 344 to 384 kg·m^{-3} (CV of 5.1% to 8.6%) for wood from 34-month-old trees (Sharma et al. 2016).

For 72-month-old *Eucalyptus*, values of approximately 450 kg·m^{-3} for *E. grandis* and 500 kg·m^{-3} for *E. urophylla* were obtained (Padula 2013). Frederick et al. (1982) used 66 trees of *Eucalyptus regnans*, ranging in age from 4 to 17 years, from two different locations in New Zealand and obtained values varying from 376 to 428 kg·m^{-3}. Githiomi and Kariuki (2010) measured the density of 14 *Eucalyptus grandis* trees, ranging from 4 to 10 years of age, and obtained basic density values ranging from 414 to 517 kg·m^{-3}, with CV of 8.1%. Mauri et al. (2015) studying the basic density of 72-month-old *Eucalyptus urophylla* and *Eucalyptus grandis* found values of 447 to 501 kg·m^{-3} with CV from 1.5% to 3.12%. Lima et al. (2001) tested 30 trees of *E. grandis*, ranging in age from 6 to 90 months, and found values of basic density varying from 314 to 374 kg·m^{-3}, with CV of 7.46% for 6-month-old trees, compatible with the values obtained in this research for seedlings. For 54- and 90-month-old trees, Lima et al. (2001) found densities ranging from 533 to 570 kg·m^{-3}, with CV from 4.13% to 5.74%.

Stiffness and strength of nursery seedlings

In general, the stiffness of wood varies with age (Wu et al. 2007; Lenz 2011), although this statement cannot be generalized to all species and regions (Sotelo Montes et al. 2017). Data obtained by Wu et al. (2007) in a study using *Pinus radiata* trees show that the modulus of elasticity, determined using SilviScan in strips taken from the trees (breast height), ranged from approximately 2000 MPa for 1-year-old wood to 10 000 MPa for 6-year-old wood (approximately 5 times). In this study, considering the relationship between the modulus of elasticity obtained in bending the logs from the base (E_{Mt}) and the modulus of elasticity in tension tests in seedlings (E_{ts}), the stiffness increased, on average, 4.5 times for the *Eucalyptus* clones and 8.5 times for the *Pinus* progenies. On the other hand, considering the relationship between E_{Mt} and the stiffness coefficient obtained in the seedlings, the stiffness increased by an average of 5.2 times for the *Eucalyptus* clones and 2.0 times for the *Pinus* progenies. The results for *Pinus*, in this case, are probably directly related to the density behavior, which practically did not change during the 66 months of growth.

Models for predicting the properties of wood from trees using one property measured in nursery seedlings (simple regression)

Each parameter obtained in seedlings (independent variables), as well as parameter relations (Table 2), were evaluated, in isolation, as predictors of wood parameters (modulus of elasticity, strength, and density) from trees.

Modulus of elasticity prediction

Except for seedling height (H_s) and seedling stiffness coefficient (CLL_s), all other parameters showed statistical significance with modulus of elasticity of the wood from trees (E_{Mt}) (Table 3). Watt et al. (2010) evaluated the behavior of 13 clones (two trees per clone) aged 3 to 12 years. The different ages were obtained by Watt et al. (2010) within the tree itself by performing tests on growth rings representative of different ages. The authors obtained correlations between the modulus of elasticity (MOE, corresponding in this paper to E_{Mt}) and the microfibril angle (directly associated with age) from 4 years (R = 0.64) and between MOE and density from 7 years (R = 0.39).

The linear models correlating E_{Mt} with seedling parameters do not present the highest coefficients of correlation (R) or determination (R^2) (Table 3) but were the ones that presented the smallest prediction errors for the independent variables velocity (VL_s), basic density (BD_s), and diameter (D_s) (Table 3).

Strength prediction

For the bending strength obtained in the wood from trees (f_{mt}), only the velocity and the tension test in the seedlings had statistically significant correlations (Table 4). Apiolaza (2009) reported that acoustic tools produce better results for wood selection than density. Linear models presented lower coefficients of determination and correlation and higher prediction errors (Table 4) than nonlinear ones.

Basic density prediction

For the basic density obtained in the wood from trees (BD_t), no parameter obtained in seedlings presented a statistically significant correlation. Apiolaza (2009) noted that in trees less than 15 years old, density had a very weak correlation with acoustic properties, a result also obtained by Chauhan and Walker (2006). This result may be related to the radial variation pattern of this

Table 5. Correlations between the variables obtained from the seedlings (independent) (longitudinal velocity (VL_s, in m·s^{-1}), basic density (BD_s, in kg·m^{-3}), diameter (D_s, in mm), height (H_s, in m), strength (f_{ts}, in MPa), and modulus of elasticity (E_{ts}, in MPa)) in the tension test, stiffness coefficient (CLL_s, in MPa), and relationships between height and diameter (H_s/D_s, dimensionless) and between modulus of elasticity and strength (E_{ts}/f_{ts}).

Variable	CLL_s	BD_s	D_s	E_{ts}	E_{ts}/f_{ts}	f_{ts}	H_s	H_s/D_s	VL_s
CLL_s		0.21	−0.042	0.34	0.36	0.21	0.20	0.16	0.46
BD_s	0.21		0.90*	−0.69	−0.74	−0.51	0.55	−0.87*	−0.77*
D_s	−0.042	0.90*		−0.81	−0.85*	−0.63	0.71	−0.91*	−0.84*
E_{ts}	0.34	−0.69	−0.81*		0.99*	0.93*	−0.70	0.65	0.84*
E_{ts}/f_{ts}	0.36	−0.74	−0.85*	0.99*		0.87*	−0.66	0.73	0.90*
f_{ts}	0.21	−0.51	−0.63	0.93	0.87*		−0.78*	0.35	0.58
H_s	0.20	0.55	0.71	−0.70	−0.66	−0.78*		−0.36	−0.36
H_s/D_s	0.16	−0.87*	−0.91*	0.65	0.73	0.35	−0.36		0.90*
VL_s	0.46	−0.77*	−0.84*	0.84	0.90*	0.58	−0.36	0.90*	

Note: Sample size for all correlations = seven genetic units of two species (three *Eucalyptus* clones and four *Pinus pinaster* progenies). An asterisk (*) indicates significance at $P < 0.05$.

Table 6. Multiple regression models correlating the modulus of elasticity obtained in the bending test (E_{Mt}, in MPa) from the wood of the tree with parameters obtained from the seedlings (without collinearity) (longitudinal velocity (VL_s, in m·s^{-1}) and height (H_s, in m)), strength (f_{ts}, in MPa) in the tension test, and the relationship between height and diameter (H_s/D_s, dimensionless).

	P value								
Model	Regression	VL_s	H_s	f_{ts}	H_s/D_s	CLL_s	R^2	R^2 adjusted	Error
$E_{Mt} = -2504 + 10.8VL_s - 42572H_s$	0.0002	0.0003	0.0048			ns	98.5	97.7	384
$E_{Mt} = -18599 + 118.6(H_s/D_s) + 595.4f_{ts}$	0.0010			0.0054	0.0020	ns	96.9	95.3	549

Note: CLL_s represents the stiffness coefficient of seedling ($CLL_s = BD_s \cdot VL_s^2$), where BD_s is the basic density obtained from the seedlings; "ns" indicates a nonsignificant variable in the model. Error represents standard error of estimative. Sample size for all correlations = seven genetic units of two species (three *Eucalyptus* clones and four *Pinus pinaster* progenies).

parameter, which is very large (Lenz 2011; Lenz et al. 2013). Lindström et al. (2002), using 4-year-old *Pinus radiata*, showed that there are significant correlations between MOE and microfibril angle but no correlation between MOE and density. Watt et al. (2010) obtained the same result for correlation between MOE and microfibril angle, but the correlation between MOE and density varied in different ages. In trees up to 6 years old, Watt et al. (2010) obtained nonsignificant correlation between MOE and density, and from this age to 12 years, the correlations were significant, and the R^2 grew from 0.39 to 0.59. No correlations between MOE and density were obtained for *Pinus radiata* juvenile wood (Burdon et al. 2001; Lasserre et al. 2009). Cown et al. (1999) noted that statistically significant correlations between MOE and density begin to exist for trees with high volume of adult wood, an aspect also highlighted by Lenz et al. (2013).

Multicollinearity analysis

Considering the nine independent variables (parameters directly measured in the seedlings and composition of these parameters; Table 2) that can be used in the models, the only ones that are not autocorrelated ($R < 0.50$) are CLL_s (with no variable), f_{ts} with H_s/D_s, and H_s with VL_s (Table 5).

Multiple regression

With the unrelated independent variables, the statistical software selected the most appropriate variables to be inserted into the multiple regression model. In no case was the CLL_s variable selected for the multiple regression models. It is important to remember that the calculation of CLL_s was made based on the basic density of the seedlings, which, according to several authors mentioned earlier, is a very unstable parameter in such young plants. On the other hand, it is not appropriate to use apparent density because of the elevated grade of moisture content.

For the modulus of elasticity obtained in the wood from trees (E_{Mt}), two models were selected, considering independent variables not self-correlated (Table 6). Both were statistically significant, but the model involving the velocity and height of the seedling had better coefficients of determination and smaller errors (Table 6). Moreover, from a practical point of view, obtaining these parameters (velocity and height) is easier than obtaining the tension strength in the seedling. In a study with *Chamaecyparis obtusa*, Kijidani et al. (2014) conclude that tree height had a significant negative effect on microfibril angle (MFA) and thus a positive effect on stiffness. Li et al. (2007), using *Pinus elliottii*, found a statistically significant correlation between tree height and wood stiffness. On the other hand, Sotelo Montes et al. (2017), using species from the Sahelian and Sudanian ecozones of Mali, obtained an effect of tree height on dynamic MOE, either positive, negative, or not significant.

The error of the prediction model using multiple regression (Table 6) is 59% less than the lowest error obtained in the simple regression (Table 3 involving the E_{ts}/f_{ts} variable). Watt et al. (2010) noted that because the MOE is the criterion for which wood is classified, it is better for genetic selection to use this parameter and not density or microfibril angle. Watt et al. (2010) also noted that such a parameter could be obtained with the use of SilviScan (X-ray diffraction) but that acoustic methods are easier because they can be applied directly to the trees and at lower costs, although with the disadvantage of being less precise. Watt and Zoric (2010) analyzed models of correlation between MOE and dimensional (diameter, height, height/diameter), environmental (temperature and rainfall occurrence), age, and planting density parameters for *Pinus radiata*. The authors concluded that age, height/diameter, and minimum autumn temperature accounted for 96% of the variability in the MOE. Our research shows that velocity of ultrasound wave propagation and height obtained in nursery seedlings could explain 98.5% of the E_{Mt} of wood obtained from trees of the same genotype (*Eucalyptus* clones) or progeny (*Pinus pinaster*).

For bending strength (f_{mt}) and basic density (BD_t) obtained in the wood of the tree, no multiple regression model involving independent variables not autocorrelated was statistically significant. The magnitude of variation in these parameters may explain this result. The variability (coefficient of variation) in densities of wood from trees (clones and progenies) was near 3% and the bending strength was near 10%, but for E_{Mt}, this variability was near 50%. A similar result was obtained by Lindström et al. (2002), who noted that density alone did not allow differentiation of clones, but if associated with the microfibril angle, differentiation would be possible.

Wood stiffness varies from the pith to the bark, but the most significant variations occur in the wood near the pith (Downes et al. 2002; Xu and Walker 2004; Wu et al. 2004), representing very young ages of the tree. These results validated the good prediction results obtained from nursery seedlings in this research, as well as future prospects of anticipation of the knowledge of wood properties in very young trees.

Conclusions

In this paper, we evaluated parameters measurable in nursery seedlings (3 and 6 months old) that could be used in models to predict stiffness, strength, and density in trees of the same clones or progenies at 72 months of age. The new contributions provided by this paper are the propositions of tests and measurements that can be performed on very young plants to infer other types of properties in the adult plant. These results can, from the practical point of view, be associated with other tools already used by foresters to improve forest management.

The multiple regression model involving height and longitudinal velocity of ultrasonic waves along the grain direction of the seedlings stem was the most adequate model for the prediction of wood stiffness in trees. These two variables are very simple to measure in seedlings and in young trees and, therefore, could increase knowledge about the forest without hard or complex work.

To correlate the wood bending strength from trees, a simple regression model using the relationship between the E_{Mt} and the strength obtained in the seedling tension test allowed a statistically significant result. These parameters are more complicated for foresters to obtain, but it is easy from the academic point of view. Hence, the results can indicate a path for future research aiming to improve questions relating to forest quality and management.

Finally, the wood density from the trees could not be predicted by any model involving parameters obtained in seedlings of the same clones or progenies. As density is a very important parameter to be known, this result shows the importance of further research in this area.

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