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**MODELING OF WOOD PROPERTIES FROM PARAMETERS OBTAINED IN
NURSERY SEEDLINGS**

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28 ABSTRACT

29 The early selection of trees allows the acceleration of genetic improvement, as well as
30 processes related to forest management to improve the quality of the wood produced. But, to
31 reach this objective it is necessary to know which parameters can be used as predictor of aged
32 condition of the tree. The objective of this research was to study parameters that are
33 measurable in nursery seedlings and that could be used in prediction models of basic density
34 (BD_t), modulus of elasticity (E_{Mt}) and strength (f_{mt}) of wood from trees. The tests were
35 performed in 240 seedlings (3 and 6 months old) and in 52 trees (72 months old) from 7
36 genetics units of 2 species : 3 *Eucalyptus* clones and 4 *Pinus pinaster* progenies. In the
37 seedlings were obtained the longitudinal velocity of ultrasonic waves (V_{Ls}), basic density
38 (BD_s), height (H_s), diameter (D_s), strength (f_{ts}) and modulus of elasticity (E_{ts}) in tension
39 parallel to the grain. The E_{Mt} and f_{mt} can be predicted by parameters obtained in seedlings of
40 the same genetic unit. Thus, the use of these parameters, in association with others already
41 used in selection programs, may increase the positive results of the early selection, with
42 economic gains and time reducing in forest management.

43

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

46 INTRODUCTION

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

55 For this early selection, it is necessary to use prediction models that involve properties
56 correlated with age and with the property that one wants to infer in aged condition. Among
57 the properties of interest of forest-based companies are the stiffness, strength and density of
58 the wood. On the other hand, among the measurable properties in seedlings and in young
59 trees are acoustic properties (Lindström *et al.* 2002, Chauhan and Walker 2006, Wang *et al.*
60 2007, Cherry *et al.* 2008, Vikran *et al.* 2011, Gonçalves *et al.* 2012, Merlo *et al.* 2014,
61 Gonçalves *et al.* 2013), density (Wielinga *et al.* 2009, Lorensani *et al.* 2015), strength and
62 stiffness (Lindström *et al.* 2002, Cherry *et al.* 2008, Vikram *et al.* 2011) and diameter and
63 height (Simões *et al.* 1980, Neves *et al.* 2013, Alves Ferreira *et al.* 2014), all of which are
64 correlated with age and with the properties of interest of forest-based companies.

65 The development of nondestructive methods for evaluating young trees in order to
66 select for adult wood quality is becoming increasingly important. For this reason, researchers
67 have recently sought to propose protocols for this purpose (Merlo and Santaclara 2012,
68 Apiolaza *et al.* 2013, Chauhan *et al.* 2013, Lenz *et al.* 2013, Lorensani *et al.* 2015).

69 Models of wood property prediction in trees have been developed (Santaclara *et al.*
70 2011, Merlo *et al.* 2014) but, in general, do not use tests in such young plants, do not

compare properties with those of trees from the same genotypes in other trials, and do not propose use with properties obtained from nursery seedlings. Therefore, the novel contribution of this paper is testing 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 7 genetics units of two distinct species: 3 *Eucalyptus* clones and 4 *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.

Tab. 1

The *Eucalyptus* clones were chosen by the company considering its 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 altitudes varying from 650 m to 684 m, average annual temperatures from 20.3°C to 20.6°C and average annual precipitation from 1273 mm 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.

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

99

100 **Methodology**

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

105

106 **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 in order 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 (V_{Ls}) 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 stem of the seedlings, which were approximately 150 mm long, samples of lengths ranging 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 $103 \pm 2^\circ\text{C}$ 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 (V_L) and the basic density (BD_s) of the seedlings, the stiffness coefficient (CLL_s - Equation 1) was obtained.

$$CLL_s = DB_s V_L^2 \quad \text{Equation 1}$$

The stiffness coefficient is, in general, determined using the apparent density. However, the use of the apparent density of saturated wood (in the case of seedlings) is not adequate, since it induces results contrary to those expected physically for stiffness (Sobue 1993, Mishiro 1996, Bucur 2006, Gonçalves and Leme da 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 length of the specimens was fixed as 150 mm to *Eucalyptus* clones and 120 mm to *Pinus pinaster*. This length allowed to insert the extensometer 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 using software it was possible to simultaneously receive the signals from the load cell and the extensometer. The speed was adopted considering the NBR 7190 (1997) procedures (10 MPa/min) 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 used in synthetic and natural fiber tests.

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

$$f_{ts} = \frac{F_{t,max}}{A} \quad \text{Equation 2}$$

$$E_{ts} = \frac{\sigma_{50\%} - \sigma_{10\%}}{\epsilon_{50\%} - \epsilon_{10\%}} \quad \text{Equation 3}$$

Where: $F_{t,max}$: maximum load [N]; A: cross-section area [mm²]; $\sigma_{50\%}$ and $\sigma_{10\%}$ is the range used to the calculus where: stress corresponding to 10% and 50% of f_{ts} ; and $\epsilon_{50\%}$ and $\epsilon_{10\%}$: specific deformation corresponding to $\sigma_{50\%}$ and $\sigma_{10\%}$.

Trials on trees

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

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 in the central section of the log. During the test, the load (P) and the vertical displacement (f) were measured simultaneously. The speed (mm.s⁻¹) of the test was used according to EN 408 (2010) and was 0.003 times the section high, which in this research was the diameter of the cross-section of the log under bark at the center point.

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

$$f_m = \frac{3F_{max}a}{bh^2} = \frac{3F_{max}a}{AD} \quad \text{Equation 4}$$

$$E_M = \frac{3aL^2 - 4a^3}{2bh^3 \left(2 \frac{f_{40\%} - f_{10\%}}{P_{40\%} - P_{10\%}} - \frac{6a}{5Gb} \right)} = \frac{3aL^2 - 4a^3}{48I \left(\frac{f_{40\%} - f_{10\%}}{P_{40\%} - P_{10\%}} \right)} \quad \text{Equation 5}$$

Where: F_{max} is the maximum load (N); $a = L/3$; L = span; A = transversal section area of the round timber $= \frac{\pi D^2}{4}$; D = diameter of the cross – section of the log at the center point under bark; $P_{40\%}$ and $P_{10\%}$ are the range used for the calculus where 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; and I = inertia of round timber $= \frac{\pi D^4}{64}$.

Data analysis

The statistical analysis put together both *Eucalyptus clones* and *Pinus pinaster* families. This design allowed having the necessary variability of the parameters involved in the analysis and also verify the consistence 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. So, if despite discrepancies it is possible to find significant correlations among properties measured in nursery seedlings and properties in forest trees at the same genetics units level (clone or progeny), the importance of very early measurements of mechanical, acoustic and physical properties in breeding program 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 statistic provided from the software (Statgraphics Centurion XV version 15.1.02), 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 6 variables obtained in the seedlings (independent), multiple regressions should contain only 4 of them, since the sampling was composed of 7 conditions (3 *Eucalyptus* clones and 4 *Pinus pinaster* progenies) (Table 1). To increase the possibility of using all the parameters measured in the seedlings, the analysis of the models also counted on the use of the stiffness coefficient (CLLs - Equation 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 ($E_t/s/f_t$) obtained in 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 multi-collinearity, which is undesirable in multiple correlation models.

The parameters considered not auto correlated 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

222 the lowest value of the Mallows Cp statistic, which is a measure of the deviation of the model
223 based on the comparison of the average total square error with the variance of the true error.
224 To analyze the regression models, besides the coefficient of correlation and the P-value, the
225 normality of the residuals was observed using the normal probability plot of the residuals.

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RESULTS AND DISCUSSION

The normality, tested by the parameters 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.

Tab. 2

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.s⁻¹ with a 10% average coefficient of variation for *Pinus* progenies and from 2000 to 2300 m.s⁻¹ with a 7.5% average coefficient of variation 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.s⁻¹ and coefficient of variation between 1.0% and 7.4%. Also, in 18-month-old *Pinus radiata*, Emms *et al.* (2013) obtained velocities of 1047 to 1172 m.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.s⁻¹, with coefficients of variation from 6.5% to 9.9%. Apiolaza *et al.* (2011b) using 18-month-old *Pinus radiata* obtained a velocity (in resonance test) of 1050 m.s⁻¹ (CV = 9.7%) for opposite wood (side opposite to compression wood) and 1230 m.s⁻¹ (CV = 7.28%) for compression wood. The differences between the two woods (reaction and opposite) were identified by wave propagation tests, indicating the usefulness of the test even in very young plants

(Apiolaza *et al.* 2011b). Lindström *et al.* (2002) obtained velocities (ultrasound, stress wave and resonance) between 1626 m.s⁻¹ and 2193 m.s⁻¹ in 48-month-old *Pinus radiata*. Sharma *et al.* (2016) obtained velocity values between 2520 m.s⁻¹ and 2810 m.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 velocities between 2243 and 2735 m.s⁻¹. For *Eucalyptus* wood, Gonçalves *et al.* (2013) obtained velocities varying from 3455 to 4456 m.s⁻¹ and coefficients of variation ranging from 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.* 2011a); 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 3.8%) for wood from 48-month-old trees (Lindström *et al.* 2002); and 344 kg.m⁻³ to 384 kg.m⁻³ (CV of 5.1% to 8.6%) for wood from 34-month-old trees (Sharma *et al.* 2016).

Tab. 3

For 72-month-old *Eucalyptus*, values of approximately 450 kg.m⁻³ were obtained for *E. grandis* and 500 kg.m⁻³ for *E. urophylla* (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 a coefficient of variation 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 a 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 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.* 2016). 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 10000 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, 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 the modulus of elasticity obtained in bending the logs from the base (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 parameter showed statistical significance with modulus of elasticity of the wood from trees (EM_t) - Table 3. Watt *et al.* (2010) evaluated the behavior of 13 clones (2 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 different age representative's growth rings. The authors obtained correlations between the MOE 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 EM_t with seedling parameters do not presenting 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 (V_{Ls}), basic density (BD_s) and diameter (D_s) (Table 3).

Strength prediction

For the bending strength obtained in the wood from trees (fm_t), 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.

Tab. 4

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 tress less than 15 years old, density has 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 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 *el 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 tress up to 6 years old, Watt *el 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 and Lassere *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).

Multi-collinearity analysis

Considering the 9 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 auto correlated ($R < 0,50$) are CLL_s (with no variable), ft_s with H_s/D_s and H_s with VL_s (Table 5).

Tab. 5

Multiple Regression

With the unrelated independent variables, the statistical software selected the most appropriate variables to be inserted in the multiple regression model. In no case was the C_{LLs} variable selected for the multiple regression models. It is important to remember that the calculation of C_{LLs} 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, apparent density is not appropriate to use because of the elevated grade of moisture content.

For the modulus of elasticity obtained in the wood from trees (EM_t), 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. Kijidani *et al.* (2014) conclude, in a study with *Chamaecyparis obtusa*, that the 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.* (2016), 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.

Tab. 6

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) note that, since the MOE is the criterion for which wood is classified, it is better for genetic selection to use this parameter and not the density or the 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 modulus of elasticity 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 ratio and minimum autumn temperature accounted for 96% of the variability in the modulus of elasticity. Our research shows that velocity of ultrasound wave propagation and height obtained in nursery seedlings could explain 98.5% of the modulus of elasticity of wood obtained from trees of the same genotype (*Eucalyptus* clones) or progeny (*Pinus pinaster*).

For the bending strength (fm_t) and basic density (BD_t) obtained in the wood of the tree, no multiple regression model involving independent variables not auto correlated 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 near 10%, but for modulus of elasticity, this variability was near 50%. A similar result was obtained by Lindström *et al.* (2002), who noted that density alone did not allow differentiate clones, but if associated with the microfibril angle, differentiation would be possible.

The 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),

401 representing very young ages of the tree. These results validating the good prediction results
402 obtained from nursery seedlings in this research, as well as future prospects of anticipation of
403 the knowledge of wood properties in very young trees.

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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 proposition 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 the height and the longitudinal velocity of ultrasonic waves along the grain direction of the seedlings stem was the most adequate for the prediction of the wood stiffness from trees. These two variables are very simple to be measured in seedlings or in young trees, so, increasing knowledge about the forest without implicate in hard or complex work.

To correlate the wood bending strength from trees, a simple regression model using the relationship between the modulus of elasticity and the strength obtained in the seedling tension test allowed a statistically significant result. These parameters are more complicate to be obtained by foresters, but it is easy from the academic point of view. So, the results can indicate a path for future researches aiming 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 researches in this area.

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Figure captions.

Table captions.

Table 1. Seedling and Tree sampling

Table 2. Average values (first row) and coefficient of variation (second row) of the parameters measured in seedlings: longitudinal velocity ($V_{L,s}$), diameter (D_s), height (H_s) and basic density (BD_s); wood properties obtained in the trees: Basic density (BD_t), modulus of elasticity (E_{Mt}), strength (f_{mt}) and relation between parameters measured in seedlings: stiffness coefficient ($C_{LL} = BD_s V_{L_s}^2$), H_s/D_s and E_{ts}/f_{ts} .

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 in the seedling: longitudinal velocity (V_{L_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 tension test, stiffness coefficient (CLL_s in MPa), relationship between height and diameter (H_s/D_s dimensionless) and between modulus of elasticity and strength (E_{ts} / f_{ts}).

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 in the seedling: longitudinal velocity (V_{L_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) obtained in 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})

Table 5. Correlations between the variables obtained in the seedlings (independent): longitudinal velocity (V_{Ls} 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 tension test, stiffness coefficient (CLL_s in MPa), relationship between height and diameter (H_s/D_s dimensionless) and relation between modulus of elasticity and strength (E_{ts}/f_{ts}).

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

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Table 1. Seedlings and trees sampling

Genotypes	Seedlings*	Trees†
<i>Eucalyptus</i> Clone 1	50	6
<i>Eucalyptus</i> Clone 2	20	6
<i>Eucalyptus</i> Clone 3	50	6
<i>Pinus pinaster</i> Progeny 15	30	8
<i>Pinus pinaster</i> Progeny 18	30	9
<i>Pinus pinaster</i> Progeny 19	30	8
<i>Pinus pinaster</i> Progeny 23	30	9
Total	240	52

*Seedling from clones 1, 2 and 3 were 3-months-old, and seedling from Progeny families 15, 18, 19 and 23 were 6-months-old.

†All the trees were 72-months-old

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Table 2. Average values (first row) and coefficient of variation (second row) of the parameters measured in seedlings: longitudinal velocity ($V_{L,s}$), diameter (D_s), height (H_s) and basic density (DB_s); wood properties obtained in the trees: Basic density (DB_t), modulus of elasticity (E_{Mt}), strength (f_{mt}) and relation between parameters measured in seedlings: stiffness coefficient ($C_{LL} = DB_s V_{L,s}^2$), H_s/D_s and E_{ts}/f_{ts} .

Genotypes	Seedlings (3* e 6 months)							Trees (72 months)				
	$V_{L,s}$	D_s	H_s	DB_s	f_{ts}	E_{ts}	C_{LLs}	H_s/D_s	E_{ts}/f_{ts}	DB_t	f_{mt}	E_{Mt}
	$m.s^{-1}$	mm	m	$kg.m^{-3}$	MPa	MPa	MPa			$kg.m^{-3}$	MPa	MPa
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
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
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
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
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
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
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

*Seedlings 1, 2 and 3 were 3-months-old, and seedlings 15, 18, 19 and 23 were 6-months-old.

**Clones: *Eucalyptus* and Progenies: *Pinus pinaster*

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 in the seedling: longitudinal velocity (V_{Ls} in $m.s^{-1}$), basic density (DB_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 tension test, stiffness coefficient (CLL_s in MPa), relationship 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*
VLs (Linear)	$E_{Mt} = -19671 + 12.6 V_{Ls}$	0.0025	86.3	0.93	1033
VLs (Double squared)	$E_{Mt} = \text{sqrt}(-1.02E8 + 34.3V_{Ls}^2)$	0.0017	88.2	0.94	1272
DBs (Linear)	$E_{Mt} = 18154 - 34.0 * DB_s$	0.0121	74.7	-0.86	1402
DBs (Reciprocal-Y squared-X)	$E_{Mt} = 1 / (-0.0000911 + 2.23E-9 * DB_s^2)$	0.0047	82.4	0.91	3422
Ds (Linear)	$E_{Mt} = 19278 - 4760 D_s$	0.0018	88.0	-0.94	964
Ds (Squared-Y reciprocal-X)	$E_{Mt} = \text{sqrt}(-1.18E8 + 4.5E8/D_s)$	0.0011	90.1	0.95	1154
Hs		ns	-	-	-
f _{ts} (Linear)	$E_{Mt} = -11439 + 871 f_{ts}$	0.05	57.1	0.76	1826
f _{ts} (square root-Y reciprocal-X)	$E_{Mt} = \text{sqrt}(2.32E8 - 3.77E9/f_{ts})$	0.033	63.4	-0.80	1608
E _{ts} (Linear)	$E_{Mt} = 2137 + 2.91 E_{ts}$	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	-	-	-
Hs/Ds (Linear)		ns	-	-	-
Hs/Ds (Squared-Y reciprocal-X)	$E_{Mt} = \text{sqrt}(2.12 E8 - 1.86 E7/Hs_Ds)$	0.012	74.8	-0.86	1490
E _{ts} / f _{ts} (Linear)	$E_{Mt} = 1667 + 68.1 * E_{ts}/f_{ts}$	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

*Standard error of estimative; The non-linear 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 to all correlations = 7 genetic units of 2 species (3 *Eucalyptus* clones and 4 *Pinus pinaster* progenies)

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 in the seedling: longitudinal velocity (V_{Ls} in $m.s^{-1}$), basic density (DB_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) obtained in 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})

Parameters	Model	P-value		R^2 (%)	R	Error*
		Regression	Intercept			
V_{Ls} (Linear)	$f_{mt} = 90.4 - 0.0207 * V_{Ls}$	0.0447	0.0019	58.6	-0.76	3.56
V_{Ls} (Double squared)	$f_{mt} = 1/(0.037 - 32.1/V_{Ls})$	0.0304	0.0012	64.2	-0.80	3.37
DB_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)	$f_{mt} = 54.8 - 0.0049 * E_{ts}$	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

*Standard error of estimative;

The non-linear 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 to all correlations = 7 genetics units of 2 species (3 *Eucalyptus* clones and 4 *Pinus pinaster* progenies)

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Table 5. Correlations between the variables obtained in the seedlings (independent): longitudinal velocity (V_{Ls} in $m.s^{-1}$), basic density (DB_s in $kg.m^{-3}$), diameter (Ds in mm), height (Hs in m), strength (f_{ts} in MPa) and modulus of elasticity (E_{ts} in MPa) in tension test, stiffness coefficient (CLL_s in MPa), relationship between height and diameter (H_s/D_s dimensionless) and relation between modulus of elasticity and strength (E_{ts}/f_{ts}).

	CLLs	DBs	Ds	Ets	Ets/fts	fts	Hs	Hs/Ds	VLs
CLLs		0.21	-0.042	0.34	0.36	0.21	0.20	0.16	0.46
DBs	0.21		0.90*	-0.69	-0.74	-0.51	0.55	-0.87*	-0.77*
Ds	-0.042	0.90*		-0.81	-0.85*	-0.63	0.71	-0.91*	-0.84*
Ets	0.34	-0.69	-0.81*		0.99*	0.93*	-0.70	0.65	0.84*
Ets/fts	0.36	-0.74	-0.85*	0.99*		0.87*	-0.66	0.73	0.90*
fts	0.21	-0.51	-0.63	0.93	0.87*		-0.78*	0.35	0.58
Hs	0.20	0.55	0.71	-0.70	-0.66	-0.78*		-0.36	-0.36
Hs/Ds	0.16	-0.87*	-0.91*	0.65	0.73	0.35	-0.36		0.90*
VLs	0.46	-0.77*	-0.84*	0.84	0.90*	0.58	-0.36	0.90*	

*P-value < 0.05

Sample size to all correlations = 7 genetics units of 2 species (3 *Eucalyptus* clones and 4 *Pinus pinaster* progenies)

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

Model	P-value						R^2	R^2 adjusted	Error**
	Regression	VLs	Hs	fts	Hs/Ds	CLLs*			
$E_{Mt} = -2504 + 10.8*VLs$ $- 42572*Hs$	0.0002	0.0003	0.0048			ns	98.5	97.7	384
$E_{Mt} = -18599 +$ $118.6*Hs/Ds +$ $595.4*fts$	0.0010			0.0054	0.0020	ns	96.9	95.3	549

*Stiffness coefficient of seedling ($CLL_s = DB_s * VL_s^2$) where, DB_s is the basic density obtained in the seedling;
“ns” non-significant variable in the model; **Standard error of estimative
Sample size to all correlations = 7 genetics units of 2 species (3 *Eucalyptus* clones and 4 *Pinus pinaster* progenies)

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