Evolution of Acoustical, Geometrical, Physical, and Mechanical Parameters from Seedling to Cutting Age in *Eucalyptus* Clones Used in the Pulp and Paper Industries in Brazil

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Abstract

Wood-processing industries must be able to estimate the properties of wood to properly manage the wood production chain. For this estimation, changes in certain characteristics over time must be identified so that they can be used to rapidly differentiate a clone or species. Of interest are acoustical, geometrical, physical, and mechanical properties, all measurable in seedlings. Thus, the objective of this research was to analyze the evolution of the ultrasonic wave propagation velocity, diameter, height, basic density, strength, and stiffness starting in nursery seedlings at 3 months of age to trees at 6 years of age, which is the cutting age used by the pulp and paper industry in Brazil. The experiment was conducted in 121 seedlings and 270 trees of three *Eucalyptus* clones. Within the age range analyzed, the results indicated that all parameters have the potential to be used in a predictive model to estimate the future quality of clones, although the predictive value of these parameters varies. The ultrasonic wave propagation velocity was the only property that maintained the coherent differences among clones from the seedling to the cutting age (6 yr old). The strength, stiffness, diameter, and height maintained coherence from 12 months to the cutting age, whereas the basic density was maintained from the age of 24 months to the cutting age. We hope that these results will contribute to improving the methods to select clones.

The quality of the raw materials evaluated in the forest will determine the future of the forest industry. The increased competitiveness of the timber sector will be dependent on technological modernization, which will allow for the evaluation of wood quality from standing trees. Better estimates of this characterization will lead to greater gains in productivity and quality.

The effectiveness of wave propagation techniques for the selection of wood according to the stiffness has been evaluated by many authors, who have applied these techniques to standing trees and freshly felled logs (Grabianowski et al. 2006; Wang et al. 2007a, 2007b; Gonçalves et al. 2011, 2013; Lenz et al. 2013; Sharma et al. 2016). In the more advanced programs of genetic improvement, the velocity of wave propagation obtained in measurements in standing trees has been considered efficient for the selection of trees by stiffness (Lindström et al. 2002, Gapare et al. 2009) and the determination of juvenile wood quality (Wielinga et al. 2009). According to Apiolaza et al. (2013), for structural uses, selecting wood early on the basis of stiffness is more appropriate than selecting on the basis of density.

However, any parameter included in this type of analysis, especially in young trees, requires knowledge of the parameter's behavior during tree growth or its ability to

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Forest Prod. J. 69(1):5–16.
doi:10.13073/FPJ-D-17-00013

propagate with age. In this sense, results in the literature have indicated that the acoustic wave propagation velocity increases with age, especially until the transition period from juvenile to adult wood (Grabianowski et al. 2006, Innes 2007, Gonçalves et al. 2012). The results of these surveys (Thomas et al. 2009, Gonçalves et al. 2013) indicate a positive trend between an increase in age and an increase in bending properties (strength and stiffness). Apiolaza et al. (2013) did not use seedlings and instead started their research in young trees (2 yr), which is closer to the objective of this research, and they indicated that foresters believed that tree selection would be performed at approximately 10 years old to provide accurate results. However, the authors (Apiolaza et al. 2013) commented that tree selection should be performed at 2 years old because for conifers, the microfibril angle (MFA) decreases from 50° to 30° in the first 2 years. Huang et al. (2003) also indicated that 2-year-old trees could be analyzed by nondestructive methods and suggested that trees with a MFA $> 35°$ could be used to predict a low quality of wood in the future. The early selection of conifer and hardwood trees with wood with smaller MFA indicates a better quality of wood in the future (Apiolaza et al. 2013).

The basic density of wood was the first variable used as a parameter for the selection of wood quality in genetic improvement programs almost 30 years ago (Merlo et al. 2008, Santaclara et al. 2011) because it is highly correlated with other properties of interest and presents a high degree of genetic propagation (Merlo et al. 2008, Santaclara et al. 2011). Padua (2006) reported on different parameters of quality selection and included density because of its inheritance and correlations with several properties. Apiolaza (2009) suggested that the correlation between the basic density of juvenile and adult wood makes it an important parameter for early selection in genetic improvement programs. In certain conifers, the genetic correlation (R) between the density measured at 3 years old and the final density is 0.83, and this value increases to 0.96 using the 10th growth ring (Kumar et al. 2002). This result shows that this parameter can be used to select trees for future quality.

The basic density usually increases abruptly in the juvenile period, more slowly during the transition period, and remains more or less constant at maturity. However, researchers have obtained another pattern in which uniform variation occurs, with the density increasing or decreasing over the life of the tree or decreasing during the juvenile period and then increasing at maturity (Haygreen and Bowyer 1982, Lorensani et al. 2015). These discrepant results show that density does not present a definite or consolidated pattern of variations with tree growth.

The height of trees and their diameter at breast height (DBH) present a gradual increase with age and are influenced by several factors, such as the spacing between individuals (Simões et al. 1980, Alves Ferreira et al. 2014), geographic localization (Bhat et al. 1987), and clonal differences (Neves et al. 2013), thus demonstrating the high sensitivity of these traits to changes in the environment.

Although a large number of studies have been conducted on the progression of mechanical properties with age, few authors have analyzed several parameters in the same study and initiated the investigations at such young ages as those used in this research. Considering the aforementioned aspects and the goal of estimating wood selection, the objective of this research was to verify whether seedlings should be judged on the basis of diameter, height, basic density, strength, or stiffness tension and determine whether the velocity of ultrasonic wave propagation remains consistent with tree growth until 6 years of age (cutting age used by the pulp and paper companies in Brazil).

Materials and Methods

Material

The samples in this study were composed of three clones: A, B, and C (Table 1). The number of nursery seedlings and trees at each age was determined according to the availability and logistics of the company that was the partner in this research (International Paper). For all clones, nursery seedlings at 3 months old could be obtained, whereas the available ages of trees were 12, 24, 48, and 72 months.

Clone C was randomly adopted from the beginning of the research as validation material, and its tests were performed only in the nursery seedlings (3 mo old) and in trees at the cutting age (72 mo old). From each site and each age, 30 trees were chosen randomly, and trees at the edge were avoided because they were more likely to contain reaction wood. All seedlings and trees (Table 1) were submitted to ultrasonic and tension tests as well as basic density calculations and diameter and height measurements. After the ultrasound tests, the 30 trees from each site were graded using the following tree groups for ultrasonic velocity: extreme velocities (major and minor) and intermediate velocities. From each group, at least two trees were chosen to compose the sample of trees to be cut to obtain logs for the static bending tests (Table 1).

For density determination, specimens from 30 to 50 mm long were obtained from the seedling stems, which were approximately 150 mm long, and these samples were used for the basic density determination. In the case of the trees, an increment borer was used at breast height to obtain cylindrical samples that were 6 mm in diameter. Each sample was packed in a plastic bag and refrigerated to maintain moisture for subsequent laboratory measurements.

The trees from the three clones at different ages were planted in different sites of the company. All sites presented the same type of soil and altitude, and the average annual temperatures and average annual precipitation were similar (Table 2). The altitude presented the greatest variation among the sites (coefficient of variation [CV] of 9% for clone A and 5% for clone B; Table 1). However, according

Table 1.—Sampling of seedlings, trees, and logs used for ultrasound, basic density, tension, and bending tests for three different clones from 3 to 72 months of age.

	Age (mo)					
Clone	3	12	24	48	72	Total
Sampling of seedlings and trees						
A	51	30	30	30	30	171
B	20	30	30	30	30	140
C	50	—	—	—	30	80
Total	121	60	60	60	90	391
Sampling for mechanical evaluation						
A	35	6	10	10	6	32
B	10	10	10	10	6	36
C	40	—	—	—	6	6
Total	85	16	20	20	18	74

Table 2.—Characteristics of altitude (m), temperature (°C), and precipitation (mm) of the planting sites of clones A, B, and C.[a]

	Age (mo)					Coefficient of variation
Clone	12	24	48	72	Average	(%)
A						
Altitude	610	680	750	650	673	9
Temperature	20.2	20.3	20.3	20.3	20.3	0
Precipitation	1,305	1,305	1,305	1,344	1,315	1
B						
Altitude	676	730	748	684	710	5
Temperature	20.0	20.3	20.3	20.6	20.3	1
Precipitation	1,299	1,305	1,305	1,273	1,296	1
C						
Altitude				684		
Temperature				20.6		
Precipitation				1,273		

[a] Altitude, temperature, and precipitation data provided by International Paper Company.

to Kiaei and Samariha (2011) and Topaloglu et al. (2016), in the range of altitudes from 610 to 750 m, property variations should not occur.

Experimental procedures

Measurements of height and diameter.—To measure the height of the nursery seedlings, the stem was considered to extend from the ground level to its extremities in the region where budding occurred, with extreme leaves disregarded. The diameter was measured at the ground level.

For the trees (from 12 mo onward), the height was measured with a hypsometer (Vertex IV; Haglöf, Switzerland).

The diameter of the nursery seedlings was measured at the ground line, whereas the DBH was measured at 1.30 m from the ground using calipers.

Ultrasound testing.—Ultrasound equipment (USLab; Agricef, Brazil) with 45-kHz-frequency exponential transducer tips were used in the tests. The transducer tips are interchangeable, thus allowing the seedlings tests to be performed with needle tips and the tree tests with 3-mm rounded tips. The needle tips were designed and manufactured by the research group.

For the test in the nursery seedlings, a wooden support was constructed to position the probes within a distance of 150 mm for all measurements. The distance between the probes (wave propagation length) was previously established to include at least three wavelengths (λ = velocity of wave propagation/transducer frequency), and wave disturbance was avoided. The seedlings were tested indirectly by ultrasound, with the transducers positioned at 45° from the stem axis (Fig. 1a). The indirect test allowed the nursery seedlings to be tested alive, and this methodology was also applied for the trees.

As in the case of nursery seedlings, the ultrasound test on trees was performed indirectly, with the transducers positioned at 45° from the trunk axis (Fig. 1b). In trees, the distance between the transducers was 0.7 m, and they were located 0.35 m above and below the breast height (1.3 m from the ground line). The ultrasound test on each tree was repeated on two opposite sides of the trunk.

The wave propagation time and distance between the transducers were used to calculate the velocities for both the nursery seedlings and trees (sample detailed in Table 1).

Strength and stiffness.—In the case of the 3-month-old seedlings, the strength and stiffness were determined using the sample detailed in Table 1 via the tension parallel to the fiber test, which was performed using a universal machine (DL30000, EMIC, Brazil; Fig. 2a). The seedlings were clamped using tensile test strips. As there are no standards for this specific test, the loading rate used was that proposed in the Brazilian Standard (Associação Brasiliera de Normas Tecnicas [ABNT] 1997) tension test in small and clear wood specimens (10 MPa/min). The load and the deformation were obtained simultaneously by the software of the machine that receives the signals from the load cell and the extensometer.

In trees, strength and stiffness were obtained using the log samples detailed in Table 1 via static bending tests in 3.5-m-length saturated base logs. The tests were performed on a servo-hydraulic load frame using an eight-channel data acquisition system (Quantun; HBM, Germany) in which the load cell and the electronic linear position transducer with 0.001-mm resolution (PC-M-0300; Gefran, Italy) were coupled, thus allowing for the automatic reading of load and vertical displacement during the test. The application of the load (two symmetrical points) was performed according to the European standard EN 408 (European Committee for Standardization [CEN] 2010; Fig. 2b).

Brazilian standard (ABNT 1997) equations used in the specimen tension tests (Eqs. 1 and 2) were also used to determine the strength (f_t) and modulus of elasticity (E_t) of the seedling stems in tension.

$$f_t = \frac{F_{t,max}}{A} \tag{1}$$

where $F_{t,max}$ is the maximum load applied during the test and A is the transversal section area at the central part of the stem.

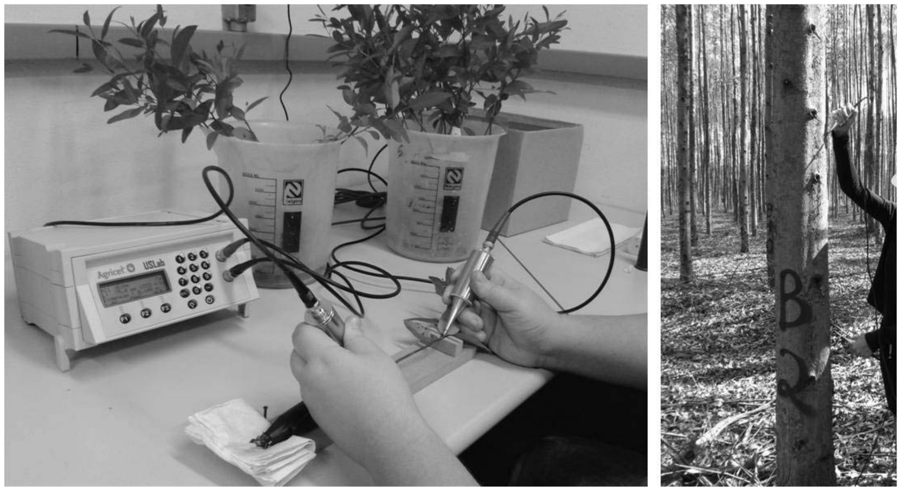
$$E_t = \frac{\sigma_{50\%} - \sigma_{10\%}}{\varepsilon_{50\%} - \varepsilon_{10\%}} \tag{2}$$

where $\sigma_{10\%}$ and $\sigma_{50\%}$ are the tension stresses corresponding to 10 and 50 percent of the tension strength, respectively, and $\varepsilon_{10\%}$ and $\varepsilon_{50\%}$ are the specific strains measured on the central part of the stem corresponding to $\sigma_{10\%}$ and $\sigma_{50\%}$, respectively.

For the static bending tests on the tree logs, the modulus of elasticity (E_M) was calculated using Equation 3 (global modulus from EN 408; CEN 2010), with the shear modulus (G) considered an infinite value (simplification allowed by EN 408; CEN 2010).

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

where $P_{40\%}$ and $P_{10\%}$ are 40 and 10 percent of the maximum load applied to the log during the bending tests, respectively; $f_{40\%}$ and $f_{10\%}$ are the vertical displacements corresponding to the loads $P_{40\%}$ and $P_{10\%}$, respectively; L is the span; a is $L/3$; I is the inertia of round timber and the value is $\frac{\pi D^4}{64}$; and D is the diameter of the cross-section of the log at the center point under the bark.



a b

Figure 1.—Indirect ultrasound test in seedlings (a) and in trees (b).

The bending strength was also calculated according to EN 408 (CEN 2010) using Equation 4.

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

where f_M is the bending strength, $F_{\max}$ is the maximum load (N), D is the diameter of the cross-section of the log at the center point under the bark, and A represents the transversal section area of the round timber and the value is $\frac{\pi D^2}{4}$.

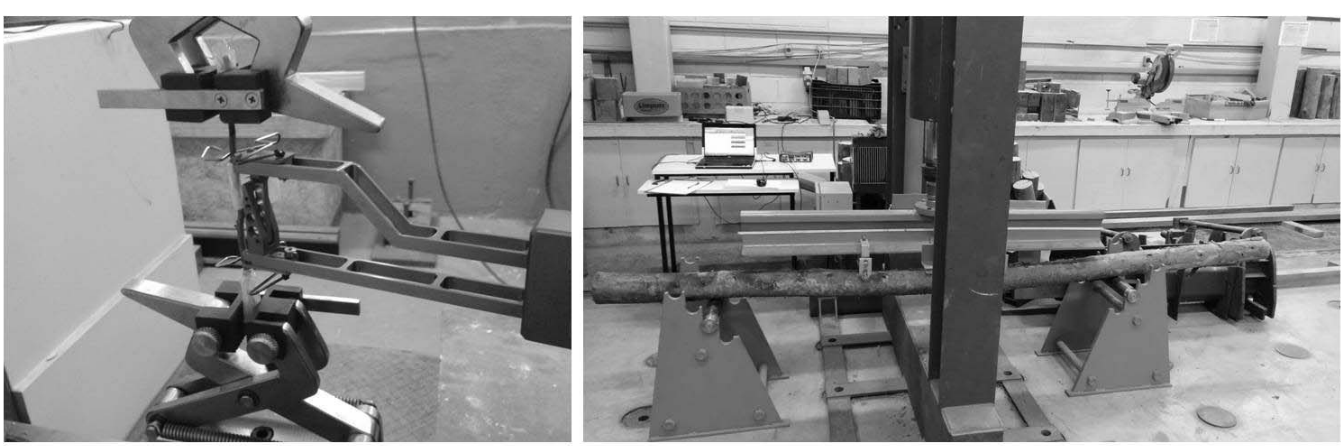
Basic density.—The volume of the specimens (from seedlings and trees) was obtained in the saturated condition, and then the specimens were dried in an oven at 103°C ± 2°C until a constant mass was achieved (ovendry condition), and the weights were then determined. The ovendry mass and saturated volume were used to determine the basic density (Eq. 5).

$$\mathrm{BD} = \frac{m_s}{V_s} \tag{5}$$

where BD is the basic wood density, m_s is the ovendry mass (103°C ± 2°C), and V_s is the saturated volume of the specimen.

Nondestructive techniques can be used to determine the wood density directly from trees because the trees do not need to be cut to remove discs for evaluation in the laboratory; thus, these techniques are more economical and agile. In addition to the increment borer method, studies have also reported the use of penetration resistance (Pilodyn) and drilling resistance (Resistograph; Isik and Li 2003, Padua 2006, Lima et al. 2007, Couto et al. 2013, Sotomayor 2013). Downes et al. (1993), who were cited by Padua (2006), stated that density determined using a single tree disk consumes five times as much time and is five times more expensive than the density obtained using a motorized increment borer. Downes et al. (1993; cited by Padua 2006) warned that seven trees would be required to obtain the same accuracy as the motorized increment borer. In this research, 30 trees of each clone and each age were used to calculate the density (Table 1).

Data analysis.—First, the parameters (diameter, height, velocity, strength, stiffness, and basic density) were analyzed for normality to verify the feasibility of applying parametric analyses.



a b

Figure 2.—Tension test in seedling (a) and bending test in log (b).

For each parameter, the central tendency (average data) and its deviation were summarized. Additionally, for each parameter, the statistical differences in the ages for the same clone and among clones were verified. To statistically test the differences among ages, we used a one-way analysis of variance (ANOVA), with the parameter under analysis the dependent variable and age the independent factor (five levels: 3, 12, 24, 48, and 72 mo old). On the basis of this procedure, the software constructs different tests to compare the mean values of the parameter for the five different levels (ages). The *F* test in the ANOVA table tests whether significant differences occur among the means, and the multiple range test is used to determine the means that are significantly different from the others. To test for differences among the clones, we compared the means using two tests: 95% CI for the mean and the *t* test.

Finally, the actual average values in each age were subjected to a regression analysis (parameters under analysis by age) to verify the behavior of the parameter over time. The regression models were also used to analyze whether the differences among clones observed in the nursery seedlings were maintained until the cutting age.

Results and Discussion

Diameter and height

The rates of increase in the diameter and height are dependent on the site (Alves Ferreira et al. 2014) and species. Downes et al. (1993) found a 1.24-m average height increment for fast-growing *Pinus radiata* from 13 to 24 months of age. Even for clones, the CV of the diameter (from 7.2% to 16.1%) and height (from 2.6% to 14.9%) were high (Table 3). These values were higher than the ranges obtained by Simões et al. (1980) and Neves et al. (2013), whose studies considered trees growing in the same sites. Similar to this research, Bhat et al. (1987) tested trees from different ages planted (DAP) in different sites and obtained CV values (13% to 21% for height and 19% to 27% for DAP) that were higher than those obtained by Simões et al. (1980) and Neves et al. (2013).

The rate of increase in diameter from 12 to 72 months of age was higher for clone A (3.23%/mo) than for clone B (1.8%/mo). Alves Ferreira et al. (2014) obtained an intermediate value for a *Eucalyptus urophylla* × *E. grandis* clone (2.03%/mo) on the basis of close spacing (3.0 by 2.5 m for Alves Ferreira et al. [2014] and 3.0 by 3.0 m in this research). Ikeda et al. (2015) showed large differences in diameter with age (60% by year and 19% by year) in Japanese cedar trees grown at different sites. As expected, the seedling growth from 3 to 9 months of age was much more significant than the tree growth for both clones and was higher for clone B (161%/mo) than for clone A (144%/mo).

The diameter presented significant differences at all ages in both clones (Table 3), and significant differences between clones were also observed at different ages (Table 3). Clone B was significantly different from clones A and C and presented a larger average diameter. At the cutting age, the three clones differed statistically; however, an inversion was then observed, with clone A presenting the largest average diameter (Table 3).

The rate of increase in height was greater for clone A (4.48%/mo) than for clone B (2.52%/mo) in the trees from 12 to 72 months of age, although the results were reversed

Table 3.—Average values of diameter[a] (mm), height (m), and basic density (kg m^{-3}); coefficient of variation (CV, %) of clones A, B, and C at different ages (mo); and analysis of statistical differences between ages (lowercase letters in the rows) and between clones (numbers in the columns); different letters and numbers indicate statistically different values.

		Age (mo)				
Clone	Parameters	3	12	24	48	72
Diameter						
A	Average	2.5	64.7	110.6	124.5	190.1
	CV	7.2	7.6	14.3	9.2	8.9
	Statistical	a 1	b 1	c 1	d 1	e 3
B	Average	2.8	81.2	119.9	143.0	168.7
	CV	12.5	16.1	12.2	9.1	6.4
	Statistical	a 2	b 2	c 2	d 2	e 2
C	Average	2.5				139.5
	CV	10.1				12.4
	Statistical	a 1				b 1
Height						
A	Average	0.31	7.78	16.12	17.52	28.72
	CV	9.3	13.7	2.8	2.6	3.6
	Statistical	a 1–2	b 1	c 1	d 1	e 3
B	Average	0.28	10.66	16.47	20.87	26.75
	CV	7.5	5.8	14.9	3.0	2.6
	Statistical	a 1	b 2	c 1	d 2	e 2
C	Average	0.31				20.45
	CV	10.1				5.7
	Statistical	a 2				b 1
Basic density						
A	Average	350	430	480	470	480
	CV	17.8	5.2	6.8	3.8	4.6
	Statistical	a 1	b 1	c 1	c 1	c 1
B	Average	360	460	470	460	460
	CV	15.7	4.1	10.0	5.8	5.0
	Statistical	a 1	b 2	b 1	b 1	b 2
C	Average	270				470
	CV	17.0				4.8
	Statistical	a 2				b 2

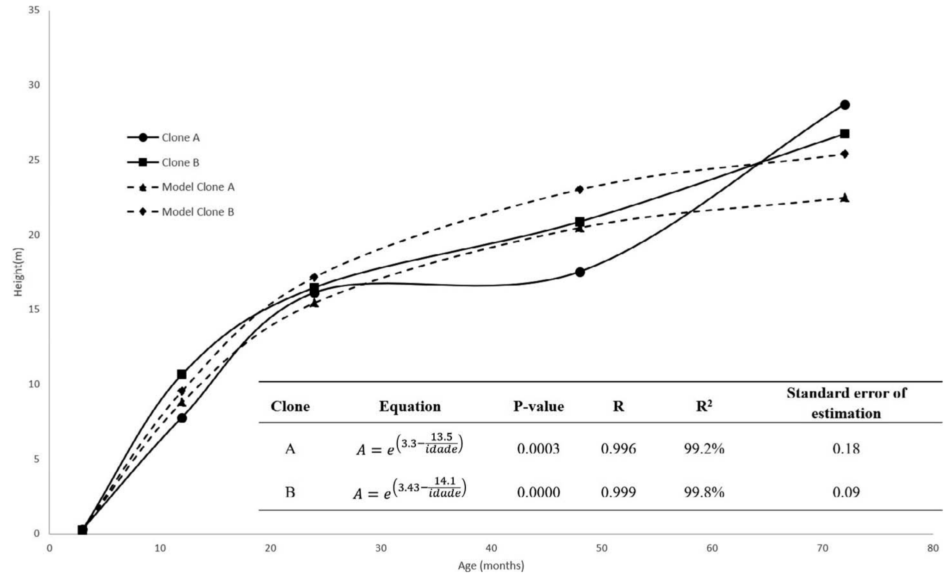
[a] In the case of trees, corresponds to the diameter at breast height.

for the rate of increase in height of seedlings from 3 to 12 months old (212%/mo for clone B and 139%/mo for clone A). As for diameter growth, Alves Ferreira (2014) obtained intermediate values (3.7%/mo) for clones from 3 to 6 years of age. Ikeda et al. (2015) showed large differences in height with age (33% by year and 16% by year) in Japanese cedar trees grown at different sites.

Significant differences in height were observed for all ages and clones, although differences among the clones were not observed for all ages (Table 3). In addition, differences in the nursery seedlings were not significant, although over time, the order of the differences was not maintained, with an inversion occurring at 72 months (Table 3).

The behavior of height with age and diameter with age can be statistically represented by the S-curve model (Figs. 3 and 4). On the basis of the regression models, the clones presented differences in diameter and height at 12 months of age.

As previously discussed, the values reported here are the averages among the trees and do not represent values reported in the same trees at different ages, which might explain the variation observed between the actual behavior and the model results, particularly for the height, diameter,



Clone	Equation	P-value	R	R^2	Standard error of estimation
A	$A = e^{\left(3.3-\frac{13.5}{idade}\right)}$	0.0003	0.996	99.2%	0.18
B	$A = e^{\left(3.43-\frac{14.1}{idade}\right)}$	0.0000	0.999	99.8%	0.09

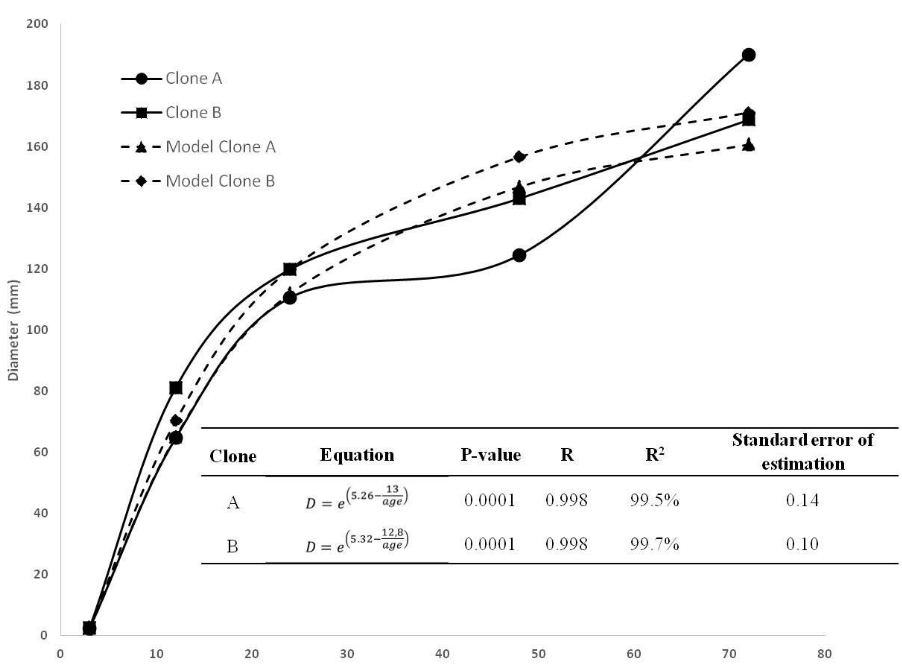
Figure 3.—Actual behavior and model of variation of height with age of clones.

strength and E_M. This aspect of our study design represents a source of error, and if the same plants were tested during growth, the model would likely fit better with the actual results. However, such a process would extend the time of the research. Another source of error was related to the different edaphoclimatic conditions of the sites for the clones planted at different times. Although the differences among sites were not significant, as previously discussed, certain parameters might have been more affected than others by the sites. Although the ideal conditions for the research are known, the ideal conditions must be adjusted to actual conditions provided by the partner company.

Density

The CV of the basic densities varied from 3.8 to 17.8 percent for the different clones at the different ages of measurement (Table 3). These values were within the ranges reported in the literature (Downes et al. 1993, Padua 2006, Stackpole et al. 2011, Sharma et al. 2016). Similar to the case of strength and stiffness, the highest CV values for the basic density were found for the nursery seedlings.

The basic density is expected to increase with age, although this parameter is variable within and between trees up to 3 years of age (Raymond 2002 in Padua et al. 2006). Different studies using *Eucalyptus* obtained incompatible results concerning the density variation with age, with



Clone	Equation	P-value	R	R^2	Standard error of estimation
A	$D = e^{\left(5.26-\frac{13}{age}\right)}$	0.0001	0.998	99.5%	0.14
B	$D = e^{\left(5.32-\frac{12,8}{age}\right)}$	0.0001	0.998	99.7%	0.10

Figure 4.—Actual behavior and model of variation of diameter with age of clones.

certain authors indicating that density decreased with age (Ferreira 1972, Padua et al. 2006), increased with age (Sturion et al. 1987, Shimoyama and Barrichelo 1991), initially increased and then decreased with age (Manfredi 1985, Purnell 1988, Wilkins and Horne 1991, Lima et al. 1992, Lausberg et al. 1995, Gominho et al. 2001, McKenzie et al. 2003, Alzate et al. 2005, Oliveira et al. 2005), initially decreased and then increased with age (Brasil et al. 1977, Rosado 1982, Oliveira et al. 2006), and showed no variation with age (Teixeira and Vargas Filho 1994).

The multiple-comparison test indicated that the basic densities of clone A at 3 and 12 months old were significantly different, and the values were also different from the densities at the other ages (Table 3); however, only the density of clone B at 3 months presented variations from the density at other ages (Table 3).

Similar to the strength and stiffness, age-density variations can be statistically represented by a double reciprocal model (Fig. 5). Numerically, both the experimental data and those obtained by the regression model indicate that the densities at 3 months (seedling) and 12 months (tree) were not consistent with the density at the cutting age (Fig. 5). After 24 months, clone A presented higher density than clone B until the cutting age. Wu et al. (2007) used two mature genetic trials of *P. radiata* planted in two different sites (A and B) with thinning (one with no thinning and the other thinned three times). Using only the trend of wood density from 1 to 28 years of age (not a statistical analysis), Wu et al. (2007) showed that the density of wood from the A and B sites was equal at 1 year, the wood density from site A was slightly greater than that of site B from 2 to 5 years, the wood density from site B was greater than that from site A from 6 to 13 years, but the wood density from site A was again greater than that of site B from 14 years until the final age of analysis (28 yr of age).

Ultrasound

The CV of the velocities ranged from 5.9 to 16.7 percent for the different clones at different measurement ages (Table 4). These values were compatible with those referenced in the literature (Wang et al. 2007a; Emms et al. 2012; Chauhan et al. 2013; Gonçalves et al. 2011, 2013; Sharma et al. 2016), which reported CV values from 1.0 to 17 percent.

Direct comparisons of the velocity values of trees obtained by different authors should be performed with caution because this parameter varies with the species and growth conditions. However, the mean values in trees at different ages (from 2,697 to 4,654 m s^{-1}) obtained in this work (Table 4) show the same order of magnitude as those obtained by different authors (Grabianowski et al. 2006; Johnson and Gartner 2006; Wang et al. 2007a, 2007b; Cherry et al. 2008; Moore and Lyon 2008; Santaclara 2010; Apiolaza et al. 2011, 2013; Gonçalves et al. 2011; Vikran et al. 2011; Merlo and Santaclara 2012; Sharma et al. 2016), who obtained velocities varying from 1,260 to 4,800 m s^{-1} in trees with ages close to those analyzed in this study. These results indicate that for both the CV and velocity, the values reported here are consistent with those obtained in the literature.

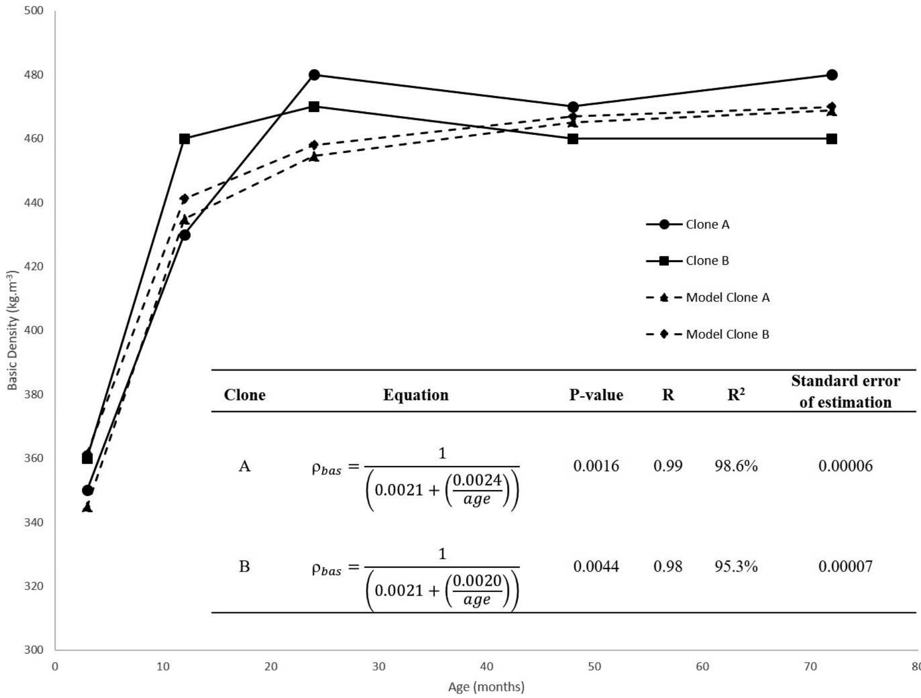
The velocity is expected to increase with the age of the tree until maturity. The maturity of the tree depends on the species, although it generally occurs above 6 years of age, which was the maximum age evaluated in this research. For *Pinus elliotti,* Gonçalves et al. (2012) reported a growth of approximately 50 percent in the wave propagation velocity in trees from 8 to 15 years old, whereas this growth was only

Table 4.—Average values of velocity of ultrasound wave propagation (m s^{-1}), strength in seedling stem (3 mo; f_t, MPa) and in wood from trees (f_m, MPa), average values of modulus of elasticity in seedlings stem (E_t, MPa) and in wood from trees (E_M, MPa); coefficient of variation (CV, %); and analysis of statistical difference between ages (lowercase letters in rows) and between clones (numbers in columns); different letters and numbers indicate statistically different values.

		Age (mo)				
Clone	Parameter	3	12	24	48	72
Velocity of ultrasound wave propagation						
A	Average	2,249	2,697	3,130	3,811	4,654
	CV	10.1	7.7	16.7	9.2	8.1
	Statistical	a 1	b 1	c 1	d 1	e 1
B	Average	2,048	2,475	2,835	3,133	3,852
	CV	4.7	5.6	10.5	12.3	9.6
	Statistical	a 2	b 2	c 2	d 2	e 2
C	Average	2,095				3,954
	CV	7.7				5.9
	Statistical	a 2				b 2
Strength						
A	Average	19.8	31.7	42.5	57.9	46.0
	CV	27.3	20.8	13.1	9.4	12.0
	Statistical	a 1	b 1	d 1	d 1	c 1
B	Average	23.2	30.6	40.7	51.4	44.2
	CV	44,9	20.7	9.3	8.2	16.0
	Statistical	a 2	a 1	b 2	cd 2	bc 1
C	Average	19.0				47.7
	CV	36.5				5.7
	Statistical	a 1				b 1
Modulus of elasticity						
A	Average	1,822	5,858	9,704	9,772	8,257
	CV	58.2	25.6	11.8	14.8	18.3
	Statistical	a 1	b 1	de 1	e 1	cd 1
B	Average	2,241	5,440	6,283	5,843	7,346
	CV	60.1	12.2	14.7	11.5	8.6
	Statistical	a 1	b 1	bc 2	b 2	cd 1
C	Average	1,256				7,295
	CV	59.1				30.6
	Statistical	a 2				b 1

3 percent in trees from 15 to 23 years old. For *Pinus taeda*, Ballarin and Lara Palma (2003) concluded that juvenile wood was present up to the 14th ring. In this study (Table 4), the velocity growth from the nursery seedling age (3 mo) to the trees at cutting age (72 mo) was similar for the three clones (107% for clone A, 88% for clone B, and 89% for clone C). In clones A and B, we obtained velocities at different ages, and the results indicated that the average velocity (obtained at each age) increased linearly with age (Fig. 6) and the velocity order of magnitude obtained at the seedling age (velocities in clones, B $<$ A) was consistent with that at the cutting age (Table 4). The slope of the linear regression model (Fig. 6) showed that variations in velocity with age in clone A were approximately 6 percent higher than that of clone B. Ikeda et al. (2015) performed tests on Japanese cedar trees grown in different sites and found a 25 percent increase in stress-wave velocity propagation measured from 2 to 6 years of age and a 14 percent increase in trees measured from 4 to 7 years of age.

A statistical analysis using all the data obtained at each age (Table 1) instead of just the average values (Table 4) showed that the velocities not only increased but were



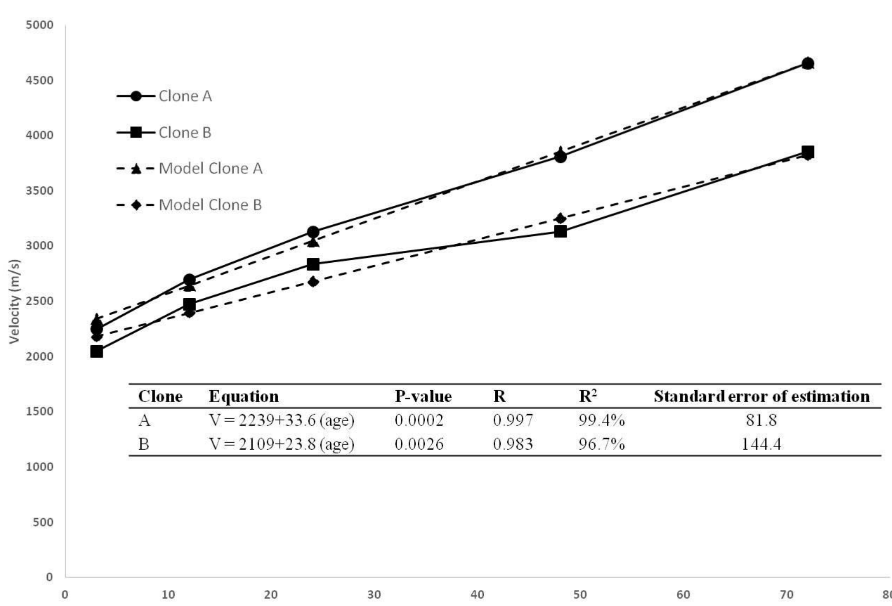
Clone	Equation	P-value	R	R^2	Standard error of estimation
A	$\rho_{bas} = \dfrac{1}{\left(0.0021 + \left(\dfrac{0.0024}{age}\right)\right)}$	0.0016	0.99	98.6%	0.00006
B	$\rho_{bas} = \dfrac{1}{\left(0.0021 + \left(\dfrac{0.0020}{age}\right)\right)}$	0.0044	0.98	95.3%	0.00007

Figure 5.—Behavior of actual values and values from regression model for density-age variation.

significantly different at different ages (Table 4). Moreover, for clones A and B, the velocities obtained at the same age were significantly different in all age ranges (Table 4), indicating the potential of the tool to differentiate properties among clones.

The nursery seedlings of clones B and C presented statistically equivalent velocities, which were both lower (on average by 9%) than that of clone A (Table 4). This same behavior was repeated at the cutting age (Table 4), although at this age, the difference increased to approximately 20 percent, showing that the grading of nursery seedling clones by velocities remained until the cutting age. This same result was obtained by analyzing the velocities in clones A and B at 12, 24, and 48 months, which showed that at these ages, the clones could also be graded by velocity.

Although it was not the focus of this research, Huang et al. (2003) noted that positive and statistically significant correlations ($R = 0.92$) occurred between wave propagation velocity and fiber length. Because fiber length is an important parameter for paper and pulp companies, the early screening of clones by velocity may also be interesting for estimating fiber length.

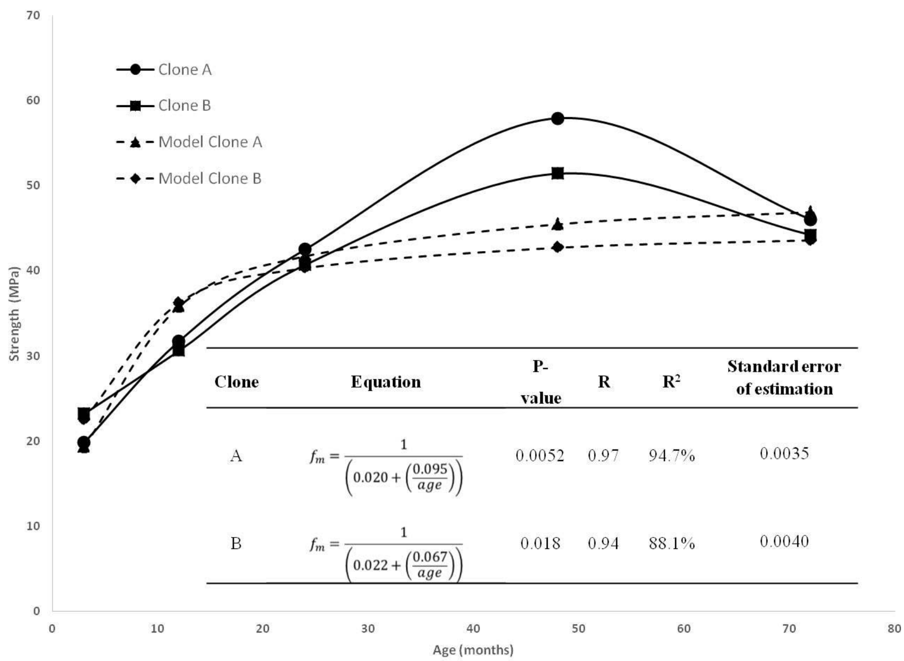


Clone	Equation	P-value	R	R^2	Standard error of estimation
A	V = 2239+33.6 (age)	0.0002	0.997	99.4%	81.8
B	V = 2109+23.8 (age)	0.0026	0.983	96.7%	144.4

Figure 6.—Behavior of actual values and values from regression model for velocity variation with age.

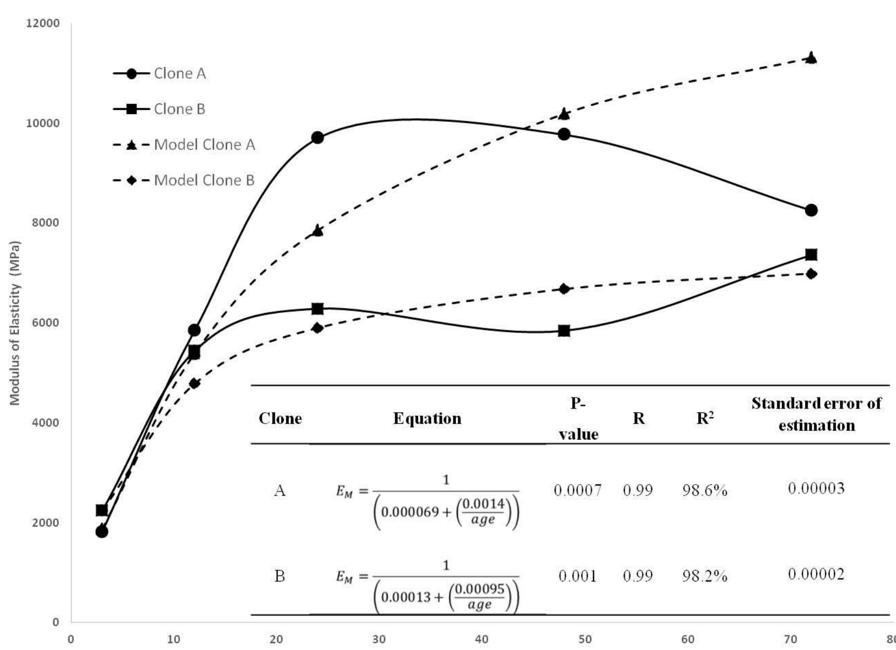
Strength and stiffness

The variability in the strength and stiffness, which was measured by the CV (Table 4), was high for the seedlings. At other ages, the CV was within the order of magnitude observed in the literature for *Eucalyptus* roundwood, although the trees were older (McKinley et al. 2002, Christoforo et al. 2011, Ziangiácomo et al. 2013, Ruy 2016). For other species and purposes, Zhu et al. (2012) also performed tests on young plants (2 mo old) and obtained the tension strength (20 $\pm$ 9 MPa and 17 $\pm$ 6 MPa) for two species with the same order of magnitude as those obtained in this study (19.8 $\pm$ 1.86 for clone A and 33.2 $\pm$ 12.5 for clone B) but with greater variability. Zhu et al. (2012) commented that the variability is generally high in young plants for all properties, including the MFA and density. Downes et al. (1993) obtained lower stiffness values (mean $E_M = 530$ MPa) and similar strength values (mean $f_m = 15$ MPa) on logs of 2-year-old *P. radiata* using the same methodology in roundwood bending tests. The CVs of E_M



Clone	Equation	P-value	R	R^2	Standard error of estimation
A	$f_m = \frac{1}{\left(0.020 + \left(\frac{0.095}{age}\right)\right)}$	0.0052	0.97	94.7%	0.0035
B	$f_m = \frac{1}{\left(0.022 + \left(\frac{0.067}{age}\right)\right)}$	0.018	0.94	88.1%	0.0040

Figure 7.—Behavior of actual values and values from regression model for strength–age variation.



Clone	Equation	P-value	R	R^2	Standard error of estimation
A	$E_M = \frac{1}{\left(0.000069 + \left(\frac{0.0014}{age}\right)\right)}$	0.0007	0.99	98.6%	0.00003
B	$E_M = \frac{1}{\left(0.00013 + \left(\frac{0.00095}{age}\right)\right)}$	0.001	0.99	98.2%	0.00002

Figure 8.—Behavior of actual values and values from regression model for modulus of elasticity–age variation.

and f_m obtained by Downes et al. (1993) were inferior (mean 11% and 6.5%, respectively) to the ones obtained in this research (Table 4).

Despite the oscillations observed in the average properties at 24, 48, and 72 months, the increased strength and stiffness with age (Table 4) can be statistically represented by a double reciprocal model (Figs. 7 and 8). In general, the mean mechanical properties obtained in the tests decreased at 72 months (Table 4), which was not expected. However, the values represent the average and do not represent the values obtained in the same trees at different ages. Thus, this behavior suggests that the mechanical parameters of the clones presented limited changes with age in this period (24, 48, and 72 mo).

Moreover, the significant differences in the strength and stiffness of the nursery seedlings (f_m: A = C < B and E_M: A = B > C in Table 4) were not maintained until the cutting age, at which all clones presented similar values (Table 4). However, the regression model of the mechanical properties (Figs. 7 and 8) showed that after 12 months, the differences in these values between clones A and B (A > B) were maintained up to cutting age. This result indicates that differences in the mechanical properties between these clones at 12 or 24 months could be estimated, which represents a significant finding for forest companies.

Wu et al. (2007) used two mature genetic trials of *P. radiata* planted in two very different sites (named here A and B) and performed thinning (one with no thinning and the other thinned three times). Using only the trend of the E_M from 1 to 28 years of age (not a statistical analysis), Wu et al. (2007) showed that wood from site B had a greater E_M from 1 to 13 years of age. Wu et al. (2007) showed that the data from 14 to 28 years of age presented an inversion trend, with site A presenting wood stiffness slightly greater than that of site B.

Conclusions

In this work, changes in certain wood properties that occur from the seedling to cutting age were analyzed to determine whether these properties can be used to estimate the future quality of clones. The results indicate that the ultrasound wave propagation velocity can be used to distinguish the clones at the nursery seedling age and the differentiation order is coherently maintained up to the cutting age. The ultrasound wave velocity was used as a tool to grade clones at 12 or 24 months old and presents the same behavior, thus indicating that clones could be differentiated by acoustic methods at these ages.

The age-related mechanical properties indicated that after 12 months of age, the distinction between the clones was maintained, showing that the quality could be estimated at 12 or 24 months of age, which is a significant finding for forestry companies.

The age-related density was consistent with the statistical regression model for age-related mechanical properties after 24 months of age, with the differentiation among the clones maintained from this age up to the cutting age.

The age-related height and diameter were represented by the same statistical regression model, and the clones could be differentiated at 12 months of age.

In general, the results indicate that all parameters have the potential to be used in a predictive model to estimate the quality of clones, although the predictive value of the parameters varies.

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