Selecting Eucalyptus Clones Using Ultrasound Test on Standing Trees

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Abstract

The production of eucalyptus for the cellulose and paper industry is based on the cultivation of clones, which are obtained by crossing species with desirable characteristics. However, clones that were considered to have great potential have presented serious problems because of permanent bending and breakage, which are caused mainly by wind forces during the early years of growth. Wave propagation methods have shown great potential in applications related to predicting the stiffness of logs and lumber. Based on the premise that the stiffness of the stem is a major contributor to a tree's resistance to the wind, the objective of the present study was to determine whether an ultrasound wave propagation test performed directly on trees would have the sensitivity within a sample group to differentiate between clones and whether this differentiation would be consistent with the differences in stiffness between them. The stem was used to evaluate the stiffness of clones rather than logs, pieces of a structural size, or specimens. A cantilever static scheme and the application of a load near the top of the stem were intended to simulate field conditions. A total of 189 trees were tested from 21 different clones. To differentiate the clones, the ultrasound wave propagation velocity was obtained directly from the trees. The velocity differences among the trees were consistent with the results obtained using the stem stiffness of the same trees.

Eucalyptus production for the paper and cellulose industries is based on the cultivation of clones, which are obtained by crossing species with desirable characteristics, such as fast growth, disease resistance, higher productivity, and greater density. A substantial investment in terms of resources and effort has been made to produce clones with desirable characteristics.

In Brazil, many clones that were considered to have great potential have had serious problems due to permanent bending and breakage in their first 4 years of growth. The problems are primarily caused by wind forces. This problem is serious because it has systematically affected the productivity of forests and caused large losses. Therefore, companies often use clonal testing areas that are located in different regions to test the behavior of the clones for 4 to 5 years before using these clones in industrial production. This procedure is slow and is often ineffective because the absence of strong winds during this testing phase can lead to the acceptance of a clone that can break or develop permanent bending when subjected to high winds after having been planted industrially.

A logical assumption is that the response of a clone to the wind will largely depend on its stiffness (modulus of elasticity) and its resistance (modulus of rupture).

The modulus of elasticity, which is obtained during bending, has been the parameter that correlates most highly with the resistance of a tree to wind damage (Melo 2006). This result is as one might expect because bending is the type of effect that wind has on trees. Clones are evaluated before being introduced on a commercial scale; therefore, the use of a technique that could anticipate the stiffness characteristics of a clone could minimize the damage caused by the large-scale planting of clones that cannot endure wind effects during their first years of life.

Acoustic technologies are becoming accepted in the timber industry and forestry sector for quality control and for the classification of products, such as laminates, boards, veneer, and logs. This growing acceptance is because scientific studies have demonstrated a strong correlation between the wave propagation parameters (velocity and/or stiffness coefficient) obtained in structural lumber pieces

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and stiffness, which was determined from the modulus of elasticity measured by bending the same pieces (Ross and Pellerin 1988, Iijima et al. 1997, Ross et al. 1997, Gonçalves and Bartholomeu 2000, Huang et al. 2003, Arriaga et al. 2006, Bucur 2006, Bartholomeu and Gonçalves 2007, Brashaw et al. 2009).

Correlations between the ultrasonic wave propagation parameters (velocity and/or stiffness coefficient) in live trees and the stiffness properties of wood from these trees have been reported (Addis et al. 2000; Tsehaye et al. 2000; Wang et al. 2001, 2004, 2007; Lindström et al. 2002; Dyck 2003; Grabianowski et al. 2006; Amishev and Murphy 2008; Auty and Achim 2008; Gonçalves et al. 2011, 2013; Zhang et al. 2011) in many parts of the world and with different species. The cited authors used stress wave, ultrasound, or vibration as techniques and longitudinal waves in indirect measurements, with the transducer placed at 45°, applied at the stem of the standing trees.

These surveys showed that the correlations between the test results of wave propagation on standing trees and the properties of wood taken from these trees are lower than those obtained by the wave propagation tests performed on logs, even when they were freshly cut. The explanation for this result is that the wave propagation velocity obtained when testing trees is affected by several factors that cause the measured propagation velocity of the tree to differ from the propagation velocity value obtained from logs, even when they were freshly cut, or from pieces obtained from these trees (Tsehaye et al. 2000; Wang et al. 2001, 2004, 2007; Grabianowski et al. 2006; Gonçalves et al. 2011; Zhang et al. 2011). These studies showed that the wave dispersion caused by the type of test (indirect) and the stress state to which the tree was subjected are two prominent factors. Two other factors are related to the propagation area of the surface wave and to the static scheme of the tree (cantilever). Because the test is indirect, even if the transducer is placed at 45°, wave propagation will occur in the area of mature wood (outer wood), depending on the diameter and the age of the tree. In tests on logs and sawed pieces, the propagation has a more general coverage of the section. For young clones, this issue is not relevant because all of the wood is still juvenile.

Based on the presented problem (the breaking of clones younger than 4 years old), the theoretical basis and previous results for the relationship between wave propagation and wood stiffness and the previously reported results using this technique on trees, the goals of the present study were to verify whether an ultrasound wave propagation test, which was performed directly on live trees, could have the sensitivity to differentiate clones within a sample group and whether this difference would be consistent with the differences in stiffness between them.

Materials and Methods

In total, 189 eucalyptus trees belonging to a clonal test by the International Paper Company were used to carry out this research. The study involved 21 different clones that resulted from the crossing of the *Eucalyptus grandis* and *Eucalyptus urophylla* species. To reduce the interference of variables that were not intended for study but could affect the results, the sample set was composed of clones of the same age (3 y) that were planted with the same spacing (2.5 by 3.0 m). The trees came from the company's three clonal testing areas, and the 21 different clones were found in all of them. Three trees of each clone were removed from each clonal testing area, for a total of 63 trees per clonal testing. The sample consisted of trees taken from the inner zone of each lot, thus avoiding trees on the boundary, which resulted in a higher probability of taking reaction wood.

The wave propagation tests were performed on the trees using ultrasound equipment (USLab, Agricef, Brazil), and two exponential transducers with a frequency of 45 kHz, which were positioned at 45° on the same side of the trunk (indirect test) and at a distance of 1.2 m (Fig. 1). A 5-mm hole was drilled into the bark to attach the transducer to the tree stem. The propagation time (t), i.e., the amount of time that the wave took to traverse the distance between the transducers (L), was measured with the ultrasound equipment, and the wave propagation velocity for the stem of the tree was calculated (Vt).

The length corresponding to the distance between the transducers (1.20 m) should include the diameter at breast height (DBH; approximately 1.30 m from the soil). One sensor was placed at a height between 0.40 and 0.60 m above the ground (depending on ground conditions), and another was placed 1.20 m from the position of the first sensor. This procedure allowed the measurement to be comfortably carried out by the operator. The distance between the sensors was set according to the preliminary results of the team and also according to the methodologies proposed by other researchers.

The reading of the wave propagation time was acquired at two diametrically opposite positions on the stem with three replicates for each reading position, totaling six propagation velocity values per tree. The six velocity values per tree

Figure 1.—Ultrasonic test in a tree.

were used to determine the mean velocity (S_{Mean}) and the minimum velocity (S_{Min}).

After the ultrasound test, the trees were cut and taken to the laboratory without the branches or canopy. The cutting and transport to the laboratory was conducted in small lots; therefore, it was possible to perform the bending tests with the stem still in a saturated condition (moisture content greater than 30%).

To evaluate the stiffness of the clones while simulating the condition of live trees, a cantilever test was performed (Fig. 2). A bending load, which was controlled by a load cell, was applied 300 mm from the top of the stem by means of a hydrostatic drive. Offset measurements were performed during loading using two linear displacement transducers. One of the displacement transducers was positioned to measure the displacement at the point of the load application, and the other transducer was positioned 1 m from the first. This procedure was performed to correct for the length (L) of the stem corresponding to the section between the clamp and the point of load application, because when the stem is tilted, the load application point moves. Thus, this procedure was performed to ensure that the application point remained approximately perpendicular to the axis of the stem (Eq. 1). The linear displacement transducers were capable of measuring between 1,200 and 1,800 mm.

$$y = 1 - [\cos(\arcsin(f - f_1)] \tag{1}$$

where y is the displacement of the load application point, f is the displacement at the load application point, and f_1 is the displacement at 1 m from the application load point.

The stems showed large displacements during the bending test because the trees were still young. The laboratory space limited the rupture condition of many trees, which prevented a complete analysis of this parameter (modulus of rupture). Moreover, the modulus of elasticity assessment was performed by considering only the linear part of the stress–strain diagram, which is a nonadequate condition for the purposes of the present study because damage to the tree should occur only after exceeding the elastic regime. Thus, 800 mm was the value adopted in the present study as the load corresponding to a fixed displacement value in the rupture stress equation (Eq. 2). This displacement value was chosen because it was the largest deflection value that all of the clones reached without breaking, which allowed all of the trees to be analyzed under the same conditions.

The value obtained by Equation 2 was defined as the modulus of resistance (MR) because it is not the modulus of elasticity in the elastic section or the modulus of rupture.

$$\mathrm{MR} = \frac{32\pi^2 P(L - y)}{C^3} \tag{2}$$

where P is the load obtained for a deflection of 800 mm, L is the distance of the clamping section up to the point of application of the load, and C is the circumference of the stem at the clamping point.

The velocity test results (mean and minimum) obtained from live trees and the MR obtained from the cantilever test of the stems were statistically analyzed to determine whether groups of clones could be differentiated based on these results.

Results and Discussion

The frequency distributions of the velocities (minimum and mean) and the MR results for each clone were initially evaluated to establish which statistical tests should be used

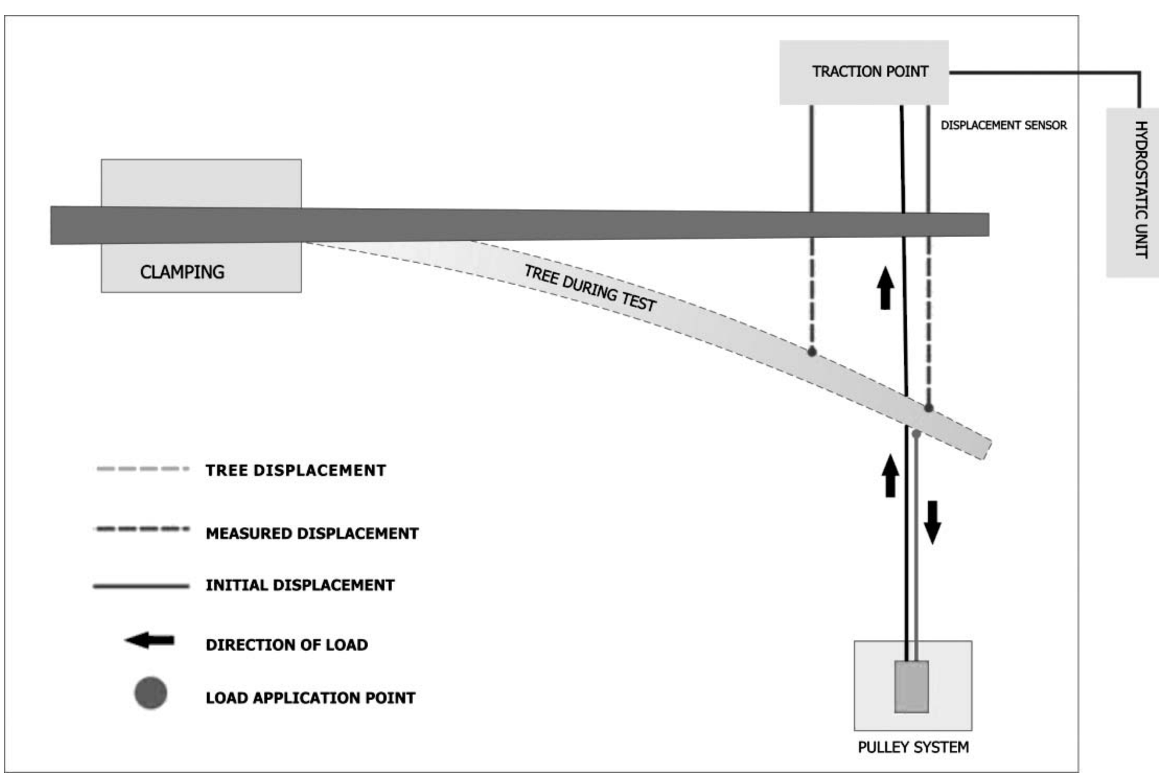

Figure 2.—Cantilever test scheme.

in the assessments. The kurtosis and asymmetry coefficients were used to verify the normality of the data. Values outside the range of –2 to +2 indicated a significant departure from normality. These tests also allowed verification of spurious data that could be excluded from the analysis because they likely represent problems in the test. After the normality of the data obtained for each clone was verified for the velocity and MR variables, parametric statistical tests were performed for the data analysis.

The minimum velocity, mean velocity, and MR results obtained for the 189 trees tested (9 trees tested from each of 21 clones) were used to assess whether these parameters enabled differentiation between clones. An analysis of variance was used for this assessment. For the purposes of this test, the observed parameter variance was separated into two components within the same clone and among the clones. By means of the multiple range test, the statistically equivalent groups of clones for each parameter (velocity or MR) could be determined.

The classification of the clones (in ascending order) was made using the mean and the minimum velocity (Figs. 3 and 4). We used statistical analysis to divide the clones into three homogeneous groups based on the three parameters (mean velocity, minimum velocity, and MR). Although the sequence of clone classification, based on the mean values of the parameters, was not identical, the extremes (best and worst values) were the same, regardless of the type of parameter considered. Clone 31 had the lowest velocities and the lowest MR, and clone 92 had the best results (Figs. 3 and 4). Results of the statistical analysis of both velocities (mean and minimum) and stiffness (MR) indicate that only clones 86 and 92 are different from the others.

For clones considered statistically equivalent, the differences in velocity and MR values are approximately 600 $m \cdot s^{-1}$ and 30 MPa, respectively. Lower velocity and MR differences were observed between clones that were considered significantly different. This result is due to the statistical analysis that was based on the variability of parameters, which determines an interval around each mean value and is based on Fischer's least significant difference procedure. In the multiple range test, this interval was used to determine which means were significantly different from the others.

In small and clear specimens, the variability of the ultrasound wave propagation velocity in the direction parallel to the fibers is small. For larger pieces, such as structural size beams, the variability is greater because singularities, such as knots and grain angles, cause changes in the velocity. Other important characteristics, associated with the wood structure (microfibril angle, density, fiber length, etc.), also have a strong influence on wood properties, affecting velocity of wave propagation (Huang et al. 2003). The coefficient of variation of the longitudinal velocity in structural beams obtained from 8-year-old *Pinus elliottii* trees was 12.6 percent under saturated conditions and 11.8 percent in 12 percent humidity (Gonçalves et al. 2013). Higher coefficients of variation have been obtained for trees. In fifty 8-year-old *Radiata pine* trees, the coefficient of variation of longitudinal velocity was 17 percent (Wang et al. 2007).

In the present study, the mean coefficient of variation of the velocities in each of the clones was 20.2 percent for the mean velocity and 23 percent for the minimum velocity. This variability, which is consistent with those obtained by other authors, is related to the influence of singularities such as knots and grain angles in the path of the wave and to the difference between clones due to the influence of the soil and temperature in the three different clonal testing areas from which each of the clones was removed. In 143 eucalyptus clones that were 6 years old and were grown in the same geographic region, the coefficient of variation of the velocity was only 4.2 percent (Gonçalves et al. 2011). For that sample group of eucalyptus clones, the coefficient of variation of DBH was 10.7 percent, whereas for some clones in the present study, it was greater than 30 percent, indicating the influence of the region in tree growth (Table 1).

In an evaluation of 15 eucalyptus clones that were between 5 and 6 years old, the modulus of elasticity obtained in the static bending of the specimens showed a

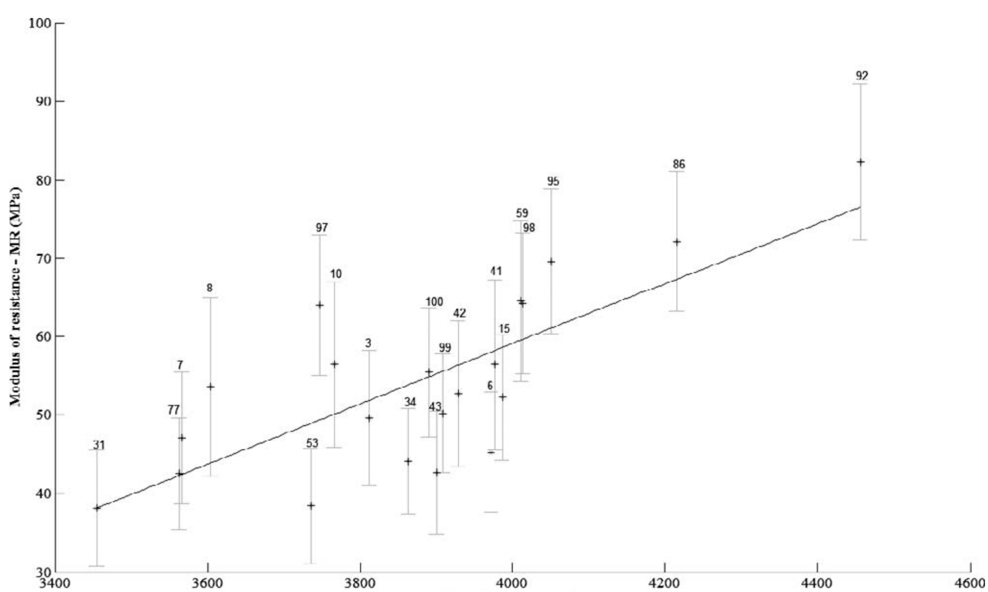

Figure 3.—Mean velocities and confidence intervals for the 21 clones and regression line.

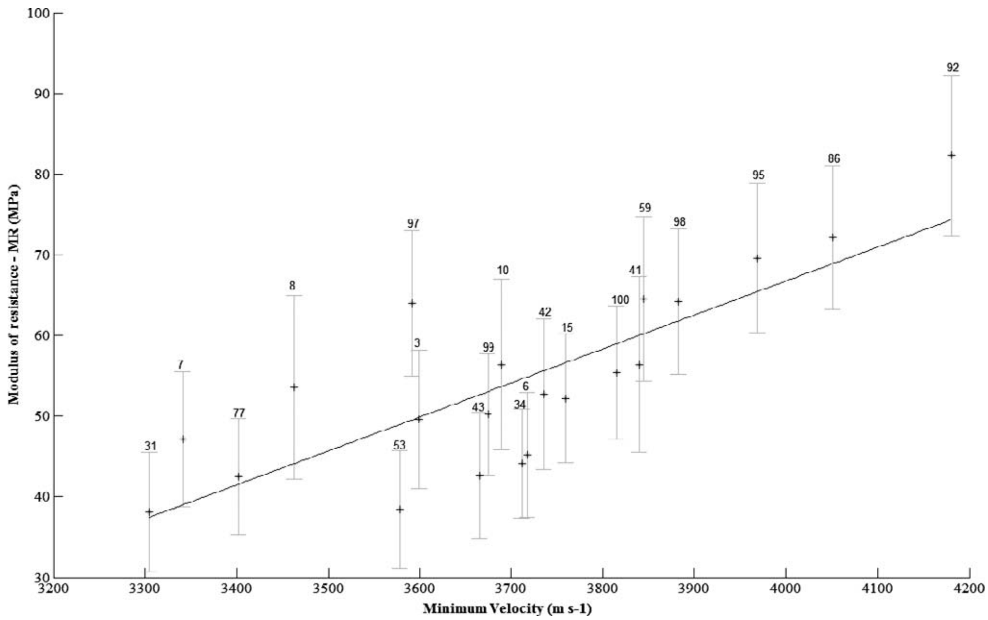

Figure 4.—Minimum velocities and confidence intervals for the 21 clones and regression line.

coefficient of variation of 14 percent (Trugilho et al. 2007). Similar to the velocity, the variability in the stiffness was expected to be greater for larger pieces or trees because there is a greater occurrence of singularities. In boards taken from 108 *Pinus radiata* trees that were 125 years old, the coefficient of variation was 31 percent (Tsehaye et al. 2000).

Ferreira et al. (2010) showed that the moment of rupture (compatible with MR in the present report) of four 2-year-old eucalyptus clones (three *E. grandis* × *E. urophylla* hybrids and one *Eucalyptus grandis*) from the same region ranged from 29.7 to 56.8 MPa, with a mean of 46.4 MPa and a coefficient of variation ranging from 6 to 31.3 percent for a tree test methodology similar to that performed in the present study. In our study, the mean MR value was 54.3 MPa, with a minimum value of 38.1 MPa and a maximum value of 82.3 MPa, and the coefficient of variation was 21.4 percent.

Although the statistical analysis only indicated differentiation between three groups of clones, one can observe, from the mean values of each clone, that there are variations in the parameters between clones. Thus, regressions were obtained based on the sample group represented by the mean parameters for each clone (Table 2; Figs. 3 and 4).

The mean and minimum velocities showed statistically significant correlations with the MR ($P < 0.05$), with a 95 percent confidence level (Table 2). Although the difference of the coefficient of determination was not large (8%), the minimum velocity was the parameter that explained the largest percentage of variability of the MR (65.3%). This result is most likely connected to the fact that the minimum velocity represents the region of the stem with a lower stiffness, whereas the mean represents the global stiffness. The significant correlations between the velocity and the MR (Table 2) explain the consistency of the results obtained in the separation of clones using these parameters.

In Figures 3 and 4 the variability of MR is also represented by the confidence interval for each clone. This variability could explain why the velocities (mean and minimum) separate the clones into only three different groups. For velocities higher than around 4,000 $m \cdot s^{-1}$ the clones began to show really significant differences in MR (Figs. 3 and 4). Below this value there is a tendency for the MR to increase with increase in velocity (regression line in Figs. 3 and 4), but because of the variability of the MR values to one value of velocity the clones cannot be differentiated.

The stress wave propagation technique, which was applied to a live tree, was used to evaluate the modulus of elasticity of the wood from two tree species (*Tsuga heterophylla* and *Picea sitchensis*) that were older than 15 years (Wang et al. 2001). After the stress wave propagation tests were conducted on live trees, 0.61-m pieces were removed from the trunks of 56 trees to perform the static bending tests. Regression analysis revealed significant models ($P = 0.010$) and correlation coefficients (R) of 0.91 between the stiffness coefficient ($C_{LL} = \rho V_{LL}^2$) obtained for the trees and the static modulus of elasticity obtained in the bending test (Wang et al. 2001).

The correlations obtained in this study were lower than those of the authors cited (Wang et al. 2001). However, direct comparisons are difficult because of the notable difference between their studies and this work, which was the use of the stiffness coefficient that involves density rather than the use of velocity alone. In addition, the

Table 1.—Mean diameters (ϕ) of the stem of the clones at the diameter at breast height.[a]

Clone	ϕ (mm)	Clone	ϕ (mm)	Clone	ϕ (mm)
3	139 (15.6)	34	107 (9.8)	86	107 (15.8)
6	131 (11.5)	41	124 (14.8)	92	129 (31.6)
7	142 (8.0)	42	130 (3.7)	95	126 (13.2)
8	124 (16.6)	43	118 (11.6)	97	132 (20.7)
10	128 (11.5)	53	132 (15.3)	98	128 (16.0)
15	114 (13.9)	59	121 (27.2)	99	131 (14.6)
31	135 (10.1)	77	139 (18.4)	100	120 (12.7)

[a] Values are means with coefficients of variation (%) presented in parentheses.

Table 2.—Models and parameters of a simple regression between the modulus of resistance (MR) obtained in a cantilever test and the mean (S_{Mean}) and the minimum (S_{Min}) velocities.[a]

Parameters	Model	P value	R	R^2 (%)
MR × S_{Min}	$\mathrm{MR} = -103 + 0.042 \times S_{\mathrm{Min}}$	0.0000	0.81	65.3
MR × S_{Mean}	$\mathrm{MR} = -94 + 0.038 \times S_{\mathrm{Mean}}$	0.0001	0.76	57.3

[a] MR is presented in megapascals and velocities are presented in meters per second.

determination of the modulus of elasticity was obtained from specimens in the elastic sections, in contrast with the tree stem test. The correlations between the stiffness coefficient, which were obtained by wave propagation methods, and the modulus of elasticity, which was obtained by static methods, are superior to direct correlations with velocity. However, the direct use of velocity is preferred by businesses because the results are easier and quicker to obtain with this method (Bucur 2006).

The correlation between the static and wave propagation methods was evaluated on seven 4-year-old *Pinus radiata* clones to select those with a higher modulus of elasticity (Lindström et al. 2002). Stress wave tests were conducted on the trees to separate seven clones with varying velocities for study, including two with a low velocity (mean of 1,600 $\mathrm{m \cdot s^{-1}}$), two with an intermediate velocity (mean of 1,900 $\mathrm{m \cdot s^{-1}}$), and three with a high velocity (mean of 2,200 $\mathrm{m \cdot s^{-1}}$). Logs from the bases and from the tops of these trees were obtained for further wave propagation testing (stress, ultrasound, and vibration waves). The specimens were removed from the logs for static testing of parallel compression and bending. The correlations between the static and wave propagation methods should not be compared with those obtained in this study because they were conducted via wave propagation testing on logs rather than on trees. Nevertheless, it was cited because of the results obtained by the authors indicating the possibility of using the velocity of wave propagation to separate different clones. In this case, the velocity in the tree was only used to separate the seven trees for testing. The moduli of elasticity obtained by the authors using wave propagation methods and static tests confirmed that there were differences between the seven clones that were identified by the wave propagation test on the trees.

Wave propagation tests using longitudinal vibration (Director ST300, Fibre-gen, New Zealand) were performed on 100 trees from two different forests of northern Scotland (Auty and Achim 2008). After the nondestructive tests, 1.5-m logs were taken from the trees, and specimens were obtained from these logs with the nominal dimensions of 20 by 20 by 300 mm for destructive testing. The specimens were removed from the area where the acoustic test was conducted. Using this procedure, the authors compared the wave propagation velocity values with the destructive testing values, obtaining correlations between the modulus of elasticity and velocity with $R = 0.73$ and between the modulus of rupture and velocity with $R = 0.77$, thereby concluding that the use of acoustic methods on a tree may be a tool for predicting the properties of the wood. In the article, the authors emphasized concern in extrapolating these findings to the entire stem of the tree because there may be variations in the mechanical properties along the trunk, and the results would not necessarily represent the condition of the whole tree because the tests were only carried out on specimens.

Notably, in the research cited, the interest of the authors was to correlate the nondestructive parameters obtained for the trees with the properties of their wood to have foreknowledge of these properties. This knowledge could then be used to direct the approach for processing the tree and, therefore, the application of the wood. The goal of the present study was to correlate the nondestructive parameters of the trees with stiffness properties of the tree itself and not pieces of it that had been removed. The results obtained demonstrate that the statistically significant correlations obtained between wave propagation tests on trees and static tests using structural parts or specimens can also be obtained by testing the entire stem of the tree.

The diameter of the tree may influence the ultrasound wave propagation velocity that is measured directly on the trees (Wang et al. 2004, 2007). Considering the findings of the present study (the results for the 189 trees from all of the clones), the diameter of the tree had a statistically significant influence with a significance level of 95 percent on the ultrasound wave propagation velocity obtained from the live tree ($P < 0.05$). The correlation and determination coefficients are not high, but the trend demonstrated by the model is that the velocity is reduced as the diameter of the tree increases (Table 3).

To assess whether the inclusion of diameter in the model would improve the correlation between the velocity and the MR, new regressions were determined (Table 4). Although the diameter is not a significant parameter in the regressions ($P > 0.05$), the coefficients of determination were slightly increased by 1.8 percent for the model as a function of the mean velocity and 4 percent for the minimum velocity. This result, combined with those of other authors showing the influence of the diameter on the ultrasound wave propagation velocity in live trees, suggests that this issue should be studied further. The result also suggests that this parameter should be associated with the velocity measurements

Table 3.—Statistical analysis of the variations in the mean and minimum velocities (S_{Mean} and S_{Min}) obtained for the live trees as a function of tree diameter (ϕ).[a]

Model	R	R^2 (%)	P value
$S_{\mathrm{Mean}} = 5{,}797 - 152.7 \times \phi$	−0.49	24	0.0000
$S_{\mathrm{Min}} = 5{,}788 - 165.6 \times \phi$	−0.49	24	0.0000

[a] Velocities are presented in meters per second and diameters are presented in millimeters.

Table 4.—Models and parameters of multiple regression between the modulus of resistance (MR) values obtained in the static bending test (cantilever), the mean (S_{Mean}) and minimum (S_{Min}) velocities, and the diameter of the tree (ϕ).[a]

Model	P value	R^2 (%)	P of parameters
$\mathrm{MR} = -163 + 0.049 \times S_{\mathrm{Min}} + 0.28 \times \phi$	0.0000	69.3	0.0000 (S_{Min}) 0.1462 (ϕ)
$\mathrm{MR} = -131 + 0.042 \times S_{\mathrm{Mean}} + 0.18 \times \phi$	0.0003	59.1	0.0001 (S_{Mean}) 0.3991 (ϕ)

[a] MR is presented in megapascals, velocities in meters per second, and diameters in millimeters.

because it does not hinder testing nor involve a large increase in the time required.

Conclusions

The measurements of the ultrasound wave propagation velocity, which was obtained directly from the trees, enabled the clones to be differentiated, and this differentiation was consistent with the results obtained using the stiffness of the same trees. Even with large variability of properties within a clone, high velocities (above near 4,000 $m \cdot s^{-1}$) appear to really identify the better clones and can be an important tool to identify clones with desirable characteristics to be commercially produced. The correlations between the stiffness (determined using a test that simulated field conditions with a cantilever test and a load on the upper part of the stem) and the ultrasound wave propagation velocity obtained from the live trees were statistically significant. Therefore, this technology may be an important tool for the selection of clones to be produced commercially or to be planted in areas with a history of strong winds.

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