Influence of Measurement Position, Tree Diameter, and Bulk Wood Density on Models that Predict Wave Propagation Velocity in Logs According to the Velocity in Trees

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Abstract

The propagation velocity of ultrasonic waves from measurements in trees is numerically different from the velocity obtained from measurements in logs, even in freshly felled logs, and the latter velocity is better correlated with the quality of the wood. The differences can be explained by the basic and fundamental aspects of wave propagation; however, these aspects are difficult to consider in practical applications. Thus, the present study examined parameters that are more easily obtained in the field and considered to provide an equivalent log velocity based on living tree velocities. The results indicate that base logs are better correlated with the velocities measured in trees, because the measurement in trees is performed at the stem base. However, the inclusion of the diameter at breast height (DBH) can produce a model with the same prediction accuracy as that of logs obtained from the whole tree. The inclusion of the green density does not improve estimations of the velocity of logs using the velocity obtained for the tree. Considering that DBH is a parameter often used in forest management, this result can be useful for improving the accuracy of wood-quality predictions from acoustic trials in standing forests.

The forestry sector has specific requirements for wood quality, and many of these requirements involve costly processes (e.g., sawing and drying). Often, the entire process is completed before grading methods are applied and the producer determines that the wood does not meet the required specifications. In such cases, the unsatisfactory wood can be directed to less profitable purposes that might not produce a return on the investments or justify the removal of trees (because of the high benefits they yield as part of the forest). Thus, the prediction of wood properties from in-forest trees provides knowledge that improves the use of natural resources and increases profitability in a sustainable manner.

Wave propagation and other methodologies (e.g., X-ray, gamma radiation, and nuclear magnetic resonance) applied to logs have been long studied to predict the subsequent wood quality (Johansson 1985; Ross et al. 1996; Andrews 2000; Booker et al. 2000; Hauffe and Mahler 2000; Tsehaye et al. 2000a, 2000b; Dyck 2003; Huang et al. 2003; Lyon et al. 2007; Wang et al. 2007a; Yin et al. 2010; Gonçalves et al. 2011; Wang et al. 2013). Such methods allow targeted wood-processing improvements by following a plan for utilization, but they do not prevent the unnecessary removal of trees or allow use of the technique in monitoring procedures aimed at forest management.

To provide additional knowledge of wood properties while the wood is still in the forest, wave propagation tests must be applied directly to trees. Research has revealed that the velocity of the tree is not numerically equal to the velocity obtained in the log, even if the test is applied immediately after tree felling (Curtu et al. 1996, Wang et al. 2004, Chauhan and Walker 2006, Grabianowski et al. 2006, Lasserre et al. 2007, Wang et al. 2007b, Mora et al. 2009, Yin et al. 2010, Gonçalves et al. 2011).

Wang (2013) presents a consistent revision on the causes of tree-log differences in velocity. Although that author focused on acoustic technologies (stress waves on trees and

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resonance on logs), which is different from our own research (ultrasound for both trees and logs), the fundamental causes of the deviation are the same. In standing trees, there is no access to the ends of the stem, so acoustic waves are introduced from the side surface. In this case, the one-dimensional wave equation (independent of Poisson's ratio) is no longer valid, especially for large tree diameters (Wang et al. 2007b). Additionally, the wave propagation occurs in the outerwood of the tree stems, which is the stiffer wood zone. Thus, the higher velocity consistently found in trees compared with logs during previous research is coherent, because the velocity is stiffness dependent and the dilatational wave velocities of trees are greater than the one-dimensional wave velocity of logs (Wang 2013).

Acoustoelasticity might be another cause of the tree-log velocity differences. This phenomenon is related to variations in the velocity based on loading conditions (Sasaki et al. 1998, Hasegawa et al. 2000). Because the living tree is subjected to loads from the weight of the stem and crown and the log is free of charge, their velocities are expected to be different. This phenomenon is not fully understood, because there are many variations among species and levels of charging.

In addition to the numerical differences in velocity (tree/log), the correlations between velocity and properties of stiffness and strength are better for the acoustic results obtained from logs than for those obtained from trees (Merlo et al. 2009, Bertoldo 2011, Wang 2013). This behavior can also be explained by fundamental concepts of wave propagation. Although standing trees and logs are neither homogeneous nor isotropic (hypothesis for the wave propagation equations), the one-dimension wave equation is a better fit for logs (Wang et al. 2004), so the modulus of elasticity predicted using this equation has a higher accuracy (Wang 2013). Thus, if the velocity obtained from the tree can be used to predict the expected velocity for the log using a correlation model, it will be possible to predict wood quality based on tree measurements. In addition, better correlation models increase the accuracy of predictions for wood quality from tree measurements.

Despite the importance of knowing the basic and fundamental aspects of wave propagation, certain parameters, such as Poisson's ratio or acoustoelasticity, are difficult to consider in practical applications. Consequently, models should include parameters that are more easily obtained in the field to achieve the equivalent log velocity from living tree velocities.

The aims of the present study were to (1) examine whether tree measurements taken at the stem base can be correlated to log measurements taken from the whole tree and (2) determine whether including the diameter at breast height (DBH) and bulk green density (ρ) improves the predictions of log velocity based on tree velocity.

Materials and Methods

Considering the research goals, trees from different species (providing a range of densities) with different ages (providing a range of diameters) were used. Age was not the object of investigation in the present study and was only used to increase the variability of the diameters.

The research material consisted of 139 logs (Table 1) obtained from 40 trees representing eight species. *Eucalyptus* trees came from forests in the Brazilian state of São Paulo, *Pinus elliottii* trees from forests in the Brazilian state of Santa Catarina, and *Pinus pinaster* trees from a forest located in Galicia, Spain.

The two parameters used to assess the fit of the model for predicting the log velocity based on the tree velocity were DBH and ρ (Table 2). The coefficients of variation (COV) of these two parameters considering all of the trees were 33.3 percent (from 0.20 to 0.80 m) for DBH and 21.1 percent (from 600 to 1,300 kg/m^3) for ρ.

The ultrasonic tests in the trees were performed using ultrasound equipment (USLab; AGRICEF, Brazil) with a 45-kHz dry point contact transducer positioned on the side of the tree (indirect measurement). The vertical distance between the transducers was 0.70 m, which included the breast height (~1.3 m above the ground). To ensure adequate contact between the transducer and the trunk, small holes were drilled at the measurement points using a power drill. The transducers were inserted into the holes at an angle (~45°) that favored wave propagation in the longitudinal direction (Fig. 1). The ultrasonic wave propagation time and distance between the transducers (0.70 m) from the test were used to calculate the wave propagation velocity in the tree.

The number of logs collected from each tree ranged from one to six, depending on the diameter of the tree. A log cut at the base (hereafter referred to as ''base log'') was always present in the sample, but logs taken from higher positions were also used. Immediately after tree cutting, ultrasonic tests were performed in the logs longitudinally with transducers positioned at the ends (direct measurements). The wave propagation time was measured at three different points of the cross section: one positioned close to the bark, another close to the pith, and the third at an intermediate point. The mean value from the log readings was used in the calculations and analyses. The COV of the three measure-

Table 1.—Species, number of trees, and number of logs.

Species	No. of trees	No. of logs
Eucalyptus grandis	7	21
E. citriodora	2	6
E. pellita	2	6
E. cloesiana	5	26
E. maculata	4	23
E. resinifera	5	23
Pinus pinaster	3	6
P. elliottii	12	28
Total	40	139

Table 2.—Mean value and coefficient of variation (COV) of the diameter at breast height (DBH) and bulk density (ρ) of wood in the green condition.

	DBH		ρ	
Species	Mean (m)	COV (%)	Mean (kg/m^3)	COV (%)
Eucalyptus grandis	0.47	39.4	768	8.1
E. citriodora	0.24	8.0	953	1.1
E. pellita	0.42	11.0	1,123	4.2
E. cloesiana	0.36	11.2	1,217	7.5
E. maculata	0.48	15.8	1,205	0.9
E. resinifera	0.41	12.5	1,299	2.2
Pinus pinaster	0.42	8.0	632	5.3
P. elliottii	0.26	26.7	960	4.9

ment points was used to verify if there was any differentiated velocity zone in the log that would indicate the presence of a defect (e.g., knots). The wave propagation velocity in the log was calculated from the length of the log and mean wave propagation time.

The bulk green densities were calculated using freshly sawn wood taken from the logs. The logs were sawed into beams with a 0.05 by 0.10-m nominal transversal section and lengths equal to the length of the logs. The values used in the evaluations were the mean green densities of all of the sawn wood (beams) taken from each log. Using specimens obtained from this freshly sawn wood, we determined the moisture content based on the difference in the weights under the fresh condition and the dry condition. The moisture varied from 47 to 60 percent for *Eucalyptus* species and from 100 to 150 percent for *Pinus* species.

The statistical comparison of the tree and log velocities were based on the t test, which does not reject the hypothesis of equality of the means (with 95% confidence level) if the P value is greater than 0.05. In the analysis of the correlation models between the tree and log velocities, the P value was used to determine the statistical significance of each parameter in the regression as well as the statistical significance (fit) of the generated model, with all determinations at a 95 percent confidence level.

Results and Discussion

The numerical ratio between the velocities (tree/log) varied among the tree species (Fig. 2) for the average velocity of the logs removed from the whole tree and average velocity of just the base logs. Because the tree measurements are only taken at the stem base, only the velocity of the base log includes the measurement zone on the tree.

In the present study, the tree and log velocities were numerically different, and the average tree velocity was higher than the average log velocity (Fig. 2) when the velocities from all logs (mean ratio = 1.07 for all species) were considered and when only the base log velocity (mean ratio = 1.07 for all species) was considered. The only exceptions were *P. elliottii* trees with the smallest diameters (184 to 242 mm). Sasaki et al. (1998) found that in some species of softwood, the velocity tends to decrease with a loading increase. In trees with small diameters for which the one-dimensional wave equation is more accurate (Wang 2013), the tree/log velocities ratio is smaller, and the acoustoelastic phenomenon may overcome other effects. The presence of excessive branches near breast height can also explain the reduced velocities in trees obtained for this species. The same result was obtained by Chauhan and Walker (2006), which was reported in the review by Wang (2013).

Wang et al. (2007b) evaluated 352 trees from five different species and removed a 3.66-m log from the base of each tree. The authors obtained an average for the ratio between the tree and log velocity of 1.20 based on all of the species, with the lowest ratio value for the velocities of *Pinus radiata* (1.07) and greatest value for *Pinus ponderosa* (1.36). Gonçalves et al. (2011) obtained a mean value of 1.11 for the ratio between the ultrasonic velocity obtained in the tree and the ultrasonic velocity obtained in saturated logs; the minimum ratio was obtained for *P. elliottii* (0.90) and the maximum for *Eucalyptus* clones and *Eucalyptus grandis* (1.15). These values were obtained by those authors based on the evaluation of four different species (*Eucalyptus*

Figure 1.—Placement of transducers for ultrasonic testing of trees.

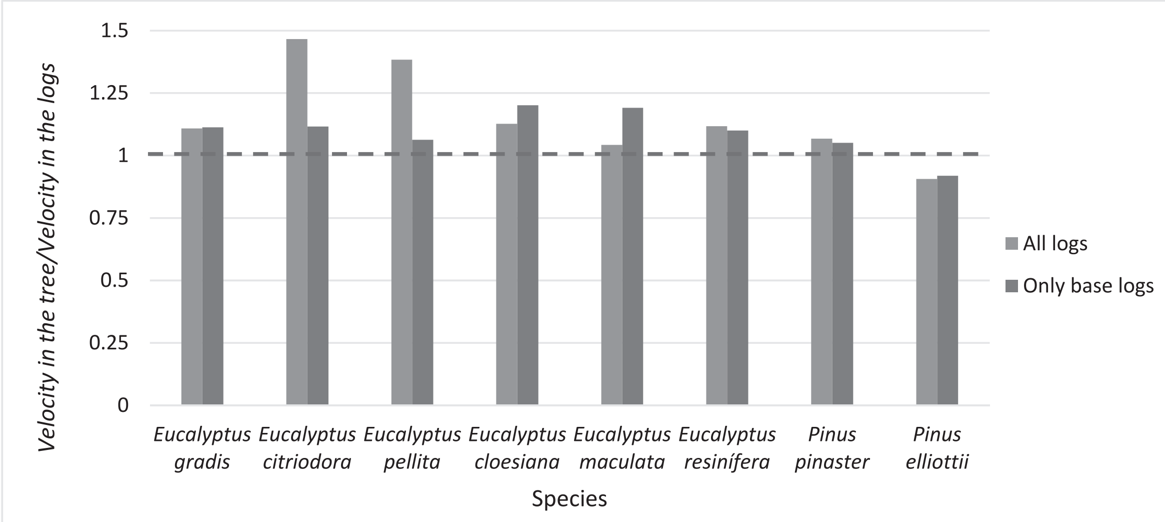

Figure 2.—Mean relationship for each species between the tree and log velocity considering all of the logs removed from the tree or only the base logs.

clones, *E. grandis*, *P. elliottii,* and *Toona ciliata*). Wang (2013) presented a review of results obtained by several authors who reported differences between tree and log velocities varying from 1.07 to 1.35.

The tree measurements were obtained at the stem base; however, in practical applications of this method, knowledge of the properties of the whole wood from a tree, not just wood from the base, is desired. The results from the present study indicate that the log position coinciding with the tree measurement position only reduced the numerical difference of the velocities (tree/log) for approximately half of the trees. This result apparently indicates that the coincident measurement zone on trees and logs (stem base) has a randomized effect on the differences between the velocities of trees and logs. This result was shown statistically, because no significant difference (95% confidence interval) was obtained (P value of the t test = 0.52) for the tree/log velocity differences. If the acoustoelastic phenomenon has an influence on the tree velocity, we would expect that the differences between the velocities in the trees and logs would be larger for the base log, because this is the most charged log on the tree. However, the magnitude of the charge depends on the height and crown of the tree. These characteristics are highly variable among species and among trees from the same species, thus randomizing this effect.

The statistical analysis revealed significant differences between the velocities obtained in trees and in logs from whole trees (P value of the t test = 0.003). The same statistical result was obtained using velocities in trees and in base logs only (P value of the t test = 0.002).

Although the tree velocities and log velocities were not numerically (Fig. 2) or statistically equivalent, the linear correlation between these parameters was statistically significant (P value = 0.00) when all the logs were considered and when only the base logs are considered (Fig. 3). The coefficient of correlation for logs from the whole tree ($R = 0.89$) was inferior to that obtained for base logs ($R = 0.92$). The standard error of estimation using the whole tree (428 m/s) was slightly superior to that using only base logs (415 m/s).

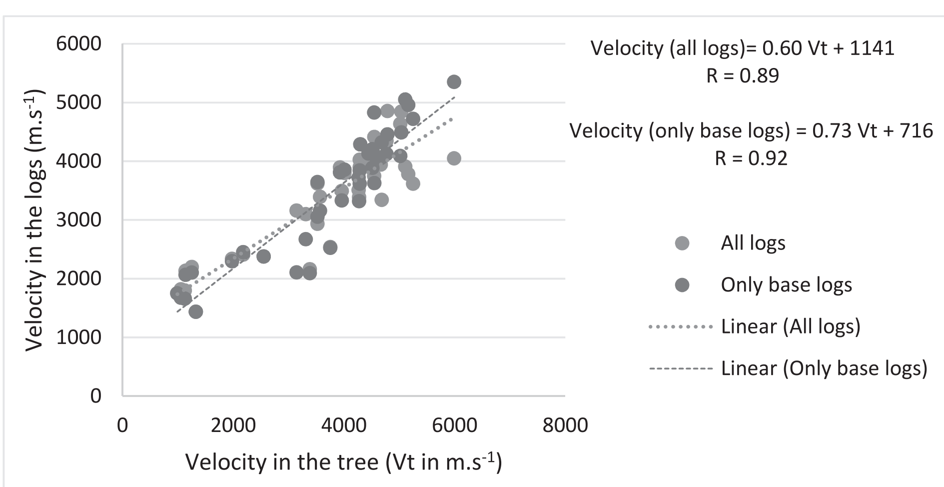

Figure 3.—Models to predict the log velocity from the tree velocities (Vt).

Wang et al. (2007b) presented a linear regression model to correlate the tree and log velocities and found that *R* ranged between 0.84 and 0.97. The value of *R* obtained by Bertoldo (2011) for the tree and log velocity regression was 0.91. Gonçalves et al. (2011) obtained a value for *R* of 0.93 for the linear models between the ultrasonic velocity in the tree and log.

For the results obtained in the present study, the tree velocity accounted for 79 percent of the variation in the log velocity using the whole tree and 85 percent of the variation using only the values obtained from the base logs (Fig. 3). The results from several authors presented in a review by Wang (2013) demonstrate coefficients of determination (R^2) ranging from 71 to 93 percent. Because the tree velocity does not explain 100 percent of the variability of the log velocity, other parameters must influence the wave propagation in the two types of material (trees and logs) and account for the different velocity results.

For logs from the whole tree, all of the generated models were significant at a 5 percent level (Table 3). Including the DBH in the models was significant; this parameter increased the R^2 value and decreased the regression errors (Table 3). The value of ρ, however, was not significant in any of the models, and its inclusion did not have a positive effect on the R^2 value or on the standard error of estimation (Table 3).

When only the base log was considered in the regression, the tree velocity was the most significant single parameter for the model (Table 4). Both DBH and ρ were not significant in any model, and including these parameters in isolation did not improve R^2, which remained at 85 percent (Table 4). Considering the full model (with the inclusion of both the DBH and ρ), the standard error of estimation was only slightly lower (1%; Table 4). In this case (logs from the base), the result for the DBH is expected, because these data were obtained from the stem base and coincided with those of the log base.

The adjusted velocity (model involving tree velocity and DBH) was correlated with the experimental velocities in all of the logs (Fig. 4). The regression indicated that the adjusted velocity accounted for 85 percent of the experi-

Table 3.—Models to predict the velocity in the log (Vlm) using the independent variables tree velocity (Vt), bulk green density (ρ) of wood, and diameter at breast height (DBH), and the corresponding regression analysis parameters.

Independent variables	Model	P value					
		Vt (m/s)	ρ (kg/m^3)	DBH (m)	Model	R^2 (%)	Error (m/s)
Vt	Vlm = 1,141 + 0.60 × Vt	—	—	—	0.00	79	428
Vt and DBH	Vlm = 671 + 0.46 × Vt + 27.6 × DBH	0.00	—	0.00	0.00	85	365
Vt and ρ	Vlm = 1,476 + 0.56 × Vt – 0.17 × ρ	0.00	0.52	—	0.00	79	431
Vt, ρ, and DBH	Vlm = 972 + 0.50 × Vt – 0.26 × ρ + 21.6 × DBH	0.00	0.35	0.00	0.00	85	366

Table 4.—Models to predict the velocity in the base log (Vlb) using the independent variables tree velocity (Vt), bulk green density (ρ) of wood, and diameter at breast height (DBH) and the corresponding regression analysis parameters.

Independent variables	Model	P value					
		Vt (m/s)	ρ (kg/m^3)	DBH (m)	Model	R^2 (%)	Error (m/s)
Vt	Vlb = 716 + 0.73 × Vt	—	—	—	0.00	85	415
Vt and DBH	Vlb = 787 + 0.66 × Vt + 4.65 × DBH	0.00	—	0.29	0.00	85	414
Vt and ρ	Vlb = 1,447 + 0.67 × Vt – 0.51 × ρ	0.00	0.24	—	0.00	85	413
Vt, ρ, and DBH	Vlb = 1,349 + 0.64 × Vt – 0.54 × ρ + 5.57 × DBH	0.00	0.26	0.32	0.00	85	412

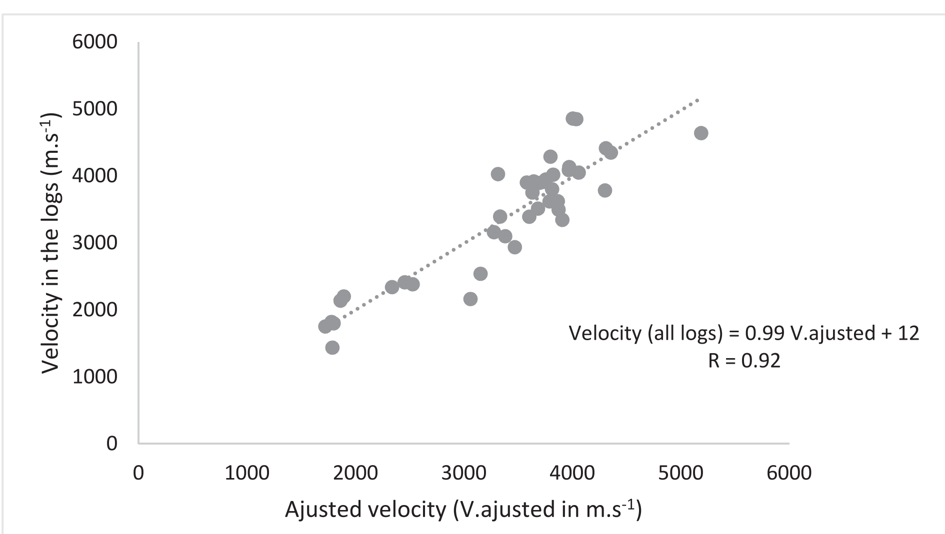

Figure 4.—Models to predict the log velocity based on the adjusted velocity.

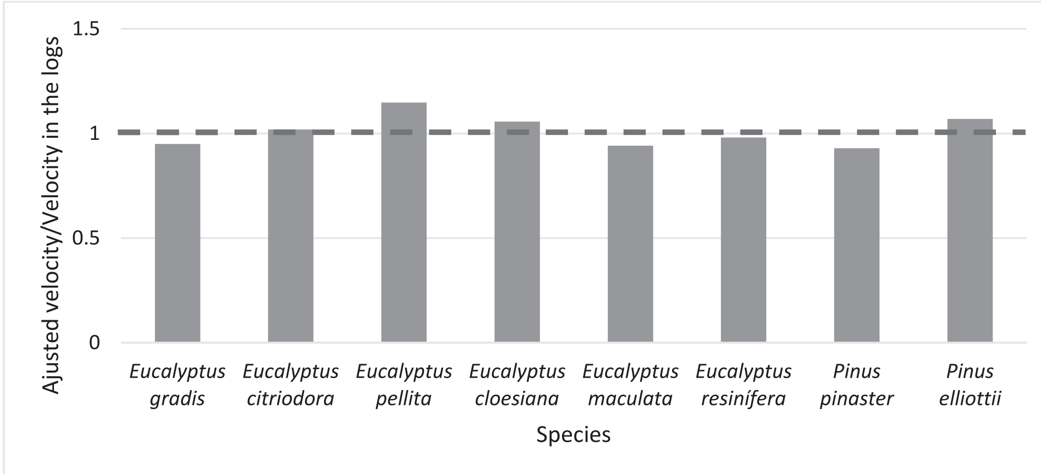

Figure 5.—Average ratio according to species between the adjusted tree velocity and log velocity considering the logs from whole trees.

mental velocity. This result indicated that by including DBH in the model to predict the equivalent log velocity, the value of *R* was equal to that obtained using only base logs. The remainder of the variability in the log velocity that was not explained by the tree velocity is related to other parameters (discussed earlier) that were not studied in the present research.

Using the adjusted velocity, the difference between the predicted average velocity for the logs and the average experimental velocity (Fig. 5) was reduced from 1.07 to 1.02. This result confirms that using the tree velocity associated with information on DBH improves predictions of log velocity and, therefore, predictions of the wood properties of trees.

Conclusions

The wave propagation velocities in the tree and log are significantly different, but there is a significant correlation between these values. The velocities obtained for the base logs are better correlated with the velocities measured for the trees than those for the logs from the whole tree; however, the inclusion of DBH allows the production of a model with the same prediction accuracy as that for logs obtained from the whole tree.

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