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ORIGINAL ARTICLE

Early prediction of basic density, shrinking, presence of growth stress, and dynamic elastic modulus based on the morphological tree parameters of *Tectona grandis*

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Abstract Significant efforts have been made to improve teak; however, evaluation in juvenile step is limited. The objective of this study was to conduct an early assessment of the wood properties of 4-year-old *Tectona grandis*. Samples of 36 clones were collected to determine their morphological tree parameters [diameter a breast height (DBH), diameter of the second log, tree height, and log quality]. Presence of growth stress, heartwood percentage, shrinkage (radial, tangential, and volumetric), basic density, and ultrasound velocity (USV) were determined for standing trees, logs, green lumber, and dry lumber. The results indicate that DBH and USV in standing trees can be used to predict elastic module (ED), mainly ED of the standing tree and dry lumber, as well as the possible presence of growth stress. Additionally, growth stress can be predicted by UVS in standing tree. Tangential and volumetric shrinkage were not predicted by tree morphology, but radial shrinkage was predicted by diameter and UVS was not affected by any shrinkage. Basic density was predicted by DBH and UVS measured in log.

Keywords Early assessment · Phenotypic correlation · Costa Rica · Clonal trial

Introduction

Teak is a tropical species planted on large extensions of land and of great commercial value in Costa Rica, as well as in other countries with tropical climate [1]. It is currently considered a species with the potential to produce high quality wood [2, 3] because of its good properties and color [4], which make commercialization easy [5, 6]. In the case of clone plantations, wood quality in relation to good physical and mechanical properties and the presence of growth stresses are determined by intensity of management and correct selection of clone phenotypic characteristics (height, diameter, and morphology) [1].

The selection of individuals for cloning with higher growth rates allows the use of younger-age trees and reduces the cutting cycle of the plantation [3, 7]; however, a greater production of juvenile wood within the tree constitutes an inconvenience [3]. Juvenile wood is anatomically different and structurally inferior to mature wood. Investigation in recent years has focused on predicting the properties of mature trees based on the properties of juvenile wood [8, 9].

On the other hand, the morphological tree parameters, such as diameter and total height, have traditionally been used as the main predictors of an individual's internal characteristics [10, 11]. The assessment of plantation wood properties has generally been conducted in trees that have undergone their first thinning or in trees of sufficient diameter from which planks can be obtained [12]. However, research on the properties of wood in early-age trees is scarce [5, 11, 13]. Additionally, these studies use non-destructive methods in order to ensure the growth of these trees [8, 14–16]. Particularly, some researches had determined wood properties in *Tectona grandis* using non-destructive methods [17, 18], however, they were determined in older trees. In other tropical species, there is little research on the early assessment of wood properties, their correlation with morphological tree parameters, and their impact on wood use [19]. An example of an early-age study is the one conducted in fast-growth families of *Calycophyllum spruceanum* in Peru [8].

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This article presents the results of an assessment of wood properties of 4-year-old *Tectona grandis* L. clones from fast-growth plantations. Using non-destructive methods, the stiffness (ED) and several physical properties (shrinkage and basic density), such as presence of growth stress and presence of heartwood were determined. Ultrasonic velocity (USV) was measured in standing tree, in log after fell tree, in green lumber after sawn log, and in dried lumber. The wood properties were rationed with tree morphological tree parameters (diameter, height, and diameter/height relationship) to predict wood quality.

Materials and methods

Plantation localization

Wood samples were taken from two trials located in Costa Rica's northern region. Both sites belong to Grupo Ecodirecta Sociedad Anonima. The first trial is situated in the district of Los Chiles, in the village of Combate (N10°57′36″ and W84°35′30″). There is no well-defined dry season. The soil is of ultisol-type, with an umbric epipedon and argillic horizon and a moderate to high acidity with an acid saturation greater than 30 % and a slope of less than 3 %. The second trial is located in the district of Pocosol, in the village of San Cristobal (N10°49′47″ and W84°27′54″). There is no well-defined dry season. The soil is of ultisol-type, with an argillic horizon and acidity varying slightly between acidic and neutral. The topography is irregular with slope variations ranging between 15 and 30 %. Both sites have an average annual rainfall of 2592.5 mm and a mean annual temperature of 25.3 °C.

Trial characteristics

Clonal trial age was 4 years. This age is commonly applied to the first genetic thinning. Sample trees were cut based on low value genotype, because they will not produce certified, genetically superior seed [20]. Trials were established according to a randomized complete block design 3 blocks of 684 trees each; each block was made up of 36 clones, one witness and a mix of clones. Each clone was repeated 18 times with a 3 × 3 m spacing between trees (38 clones × 18 repetitions × 3 blocks = 2052 trees) in each block. The study was conducted with all 36 clones and did not include the witness and mix of clones.

Sampling

Six trees were selected for each clone (1 tree × 3 blocks × 2 sites) for a total of 216 trees. Of the trees marked for thinning, the tree with highest diameter was selected. Trees felled had a straight trunk, normal branching, and no disease or pest symptoms. Before the tree was felled, the diameter at breast height (DBH), total height (h), and tree quality were measured and they were called as morphological tree parameters. Transverse and longitudinal ultrasound velocities were measured too. The tree quality was evaluated according with Murillo and Camacho methodology [20]. This methodology classifies trees into 3 categories: quality 1: tree with excellent shape, small branches and straight tree without damage by fungus or insects, quality 2: acceptable quality, moderated branch diameters, inclination and damage by fungus or insects, 3: bad, big branch, severe inclination and some damage are presented. The tree was then cut to obtain a first log between the tree base and a height of 230 cm, and then at this height (from 2.25 to 4.00 m) a second log was obtained measuring 175 cm long. A 3-cm thick cross section was extracted from the lower portion of each log; the log length was 225 cm for first log and 170 cm for second log. The diameter of the 3-cm thick cross section was measured and named d_2.

Determining time of ultrasound velocity

The ultrasound velocity (USV) was first determined in a standing tree in two directions at breast height: longitudinal and radial. After the tree was felled and two logs were extracted, USV was measured in the first log. The log was sawn and USV was measured again, and then USV was measured again in dry lumber. Measurements were taken using SYLVATESTDUO ultrasound equipment with 22-kHz transductors (CBS-CBT, Switzerland). This device was set to four readings per measurement.

Standing trees

Before trees were felled, their north-facing side was marked and times of ultrasound pulse propagation in longitudinal and transversal direction were obtained. The time of ultrasound pulse propagation in longitudinal direction was determined on the north- and south-facing sides of the tree and was measured on a 130-cm long section, 30 cm above ground level and at a height of 160 cm (Fig. 1a). Perforations of the bark angled at 45° were made at these two heights in order to expose the xylem and place the ultrasound transductors (Fig. 1a). The transversal of ultrasound pulse propagation was measured at DBH in north–south and west–east directions (Fig. 1b). Once again, the bark was removed during transversal measurement of time. Two measuring of time ultrasound pulse propagation in longitudinal direction (north and south facing side of the tree) were average. And two measuring of time of ultrasound pulse propagation in transversal direction were average too.

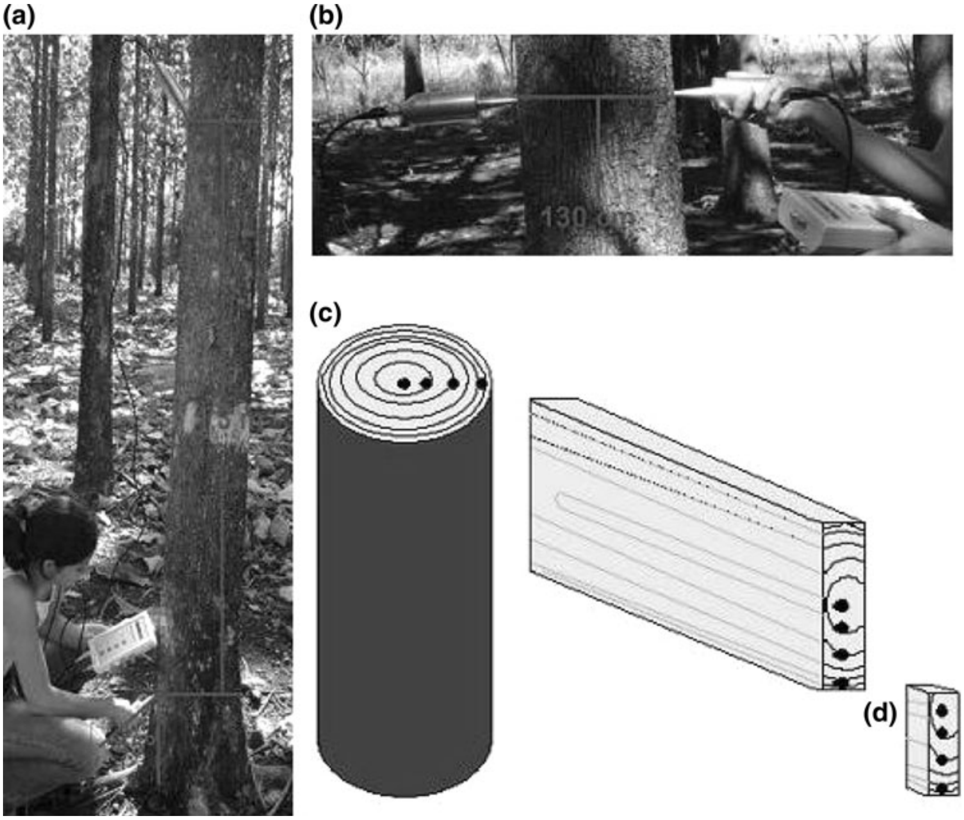

Fig. 1 Measurement of ultrasound time in longitudinal (**a**) and transversal direction (**b**) in standing tree, log (**c**), and lumber (**d**) with SilvaTest Duo in young trees of *Tectona grandis*

Measuring time of ultrasound pulse propagation in logs

The time of ultrasound pulse propagation in longitudinal direction of the first log was measured at three radial distances in a transverse section (from base to a height of 2.25 m) and they were averaged. The three distances from pith to bark (at a 10, 50, and 95 % distance between pith and bark) were marked on the north side of the log (Fig. 1c).

Measuring time of ultrasound pulse propagation in lumber

The middle portion of the first log was sawn to obtain a 3-cm wide plank that contained the same points of measurement for time of ultrasound as those in the log (Fig. 1d). The time of ultrasound pulse propagation was determined immediately after obtaining the lumber and therefore, corresponds to green wood.

Measuring time of ultrasound pulse propagation in dry wood

The lumbers were conditioned at 22 °C and 60 % relative humidity for 6 weeks until they reached 11–12 % moisture content. The planks were then taken out of the kiln and left to rest for 24 h so that measurements could be obtained at room temperature. The points of measurement were the same as those used in logs and green wood.

Determining ultrasound velocity and ED

Equation 1 was used to calculate USV and Eq. 2 to calculate the longitudinal and transversal dynamic elastic modulus in standing tree (ED_T and ED_L, respectively), dynamic elastic modulus in log (ED_{log}), dynamic elastic modulus in green lumber (ED_{lumber}) and dynamic elastic modulus in dry lumber (ED_{dried}). The determination of wood density differed according to the different stages of log processing. A 2 × 2 × 2 cm wood sample was taken from the cross section of boards after sawing (Fig. 1d). And weight and volume were determined for this sample using the water displacement method specified by standard ASTM D-2395 [21]. Density of green wood (mass/volume, both in green condition) was determined and it was used for determining USV in standing trees, logs and green lumber. Wood density was calculated considering the density of green wood (mass/volume, both in green condition). After drying process, a new 2 × 2 × 2 cm wood sample was extracted from dried wood. Then, air-dried wood density was determined according to ASTM D-2395 standard [21].

$$V = \frac{L}{T} \quad (1)$$

$$\mathrm{ED} = V^2 \times d \times 10^{-6} \quad (2)$$

where V is the ultrasound velocity in m s^{-1}, L the sample length in m, T the time required by ultrasound pulse propagation to travel from one end of board to the other in µs, ED the dynamic stiffness in GPa and d is the wood density at testing in kg m^{-3}.

Presence of growth stress

The second log was submitted to the procedure followed by Chauhan and Entwistle [22] in order to determine the presence of distortions due to growth stress (GS). The log was cut longitudinally along the middle, from end to end (Fig. 2a). This was done with a band saw (blade width = 1 cm; flywheel diameter = 90 mm). After sawing, the two halves were re-assembled to reconstruct the log and clamped together at the mid-point along the length. When split into two halves, the relaxation of inherent growth stresses (compressive stresses at the core and tensile stresses at the periphery) results in the two half rounds to bend apart from each other. The outward bending of two half rounds is called log opening. These openings at both ends of the log were measured using a digital caliper (Fig. 2a). The log opening data were used to estimate the presence of growth stress using Eq. 3, as proposed by Chauhan and Entwistle [22].

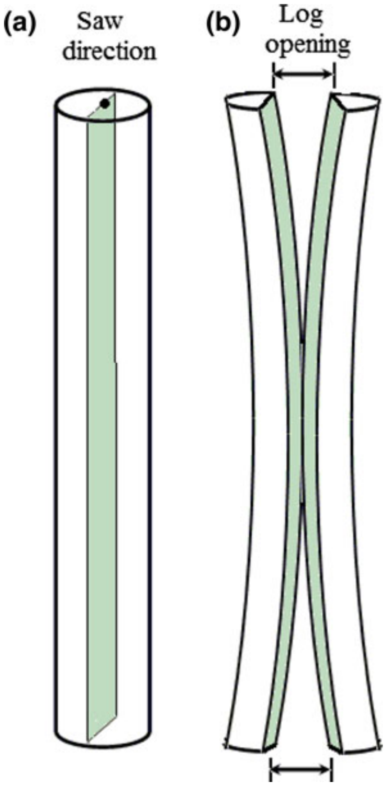

Fig. 2 Log sawn (**a**) and growth stress (**b**) measurement from young trees of *Tectona grandis*

$$\mathrm{GS} = \frac{\mathrm{Yu} \times R_{\mathrm{avg}}}{0.87 \times L^2} \quad (3)$$

where GS is the presence of growth stress, Yu the free end deflection, R_{avg} the average diameter between the smallest and largest diameter, L the length log and 0.87 is the constant value derived from bending moments of a semi-circular cross section beam (see Chauhan and Entwistle [22]).

Determining heartwood percentage and physical properties of the wood

Heartwood percentage (HWP) was determined in a cross section from the base of the tree and therefore, total disk diameter (with bark) was measured as well as heartwood diameter in two directions (north–south and east–west). *HWP* was calculated using total heartwood area in relation to the total disk area expressed as a percentage.

Total radial shrinkage (RS), total tangential shrinkage (TS), total volumetric shrinkage (VS), and basic density (BD) were determined in a cross section from the lower portion of the second log (height of 2.25 m). A 3-cm wide block was cut along the center, from north–south (including the pith), of each disc and divided into two subsamples (cut into half). The east and west sides of the disk were used to measure RS and TS (refer to Figure 1 of Moya and Pérez [4] for details regarding type of sample cut). The weight and volume of both diametral subsamples were determined when green according to standard ASTM D-2395 [21] and they were kept under room conditions in a uniform moisture content of approximately 12 % for 3 weeks and finally they were kiln dried at 105 °C for 24 h to determine the weight and volume. BD was calculated from the relation between over-dried weight and green volume. VS was calculated by differences in dimensions between green and over-dried condition/volume in green conditions. Sample dimensions for RS and TS complied with standard ASTM D-143 [23].

Statistical analysis

Average values were obtained for the variables measured and then data was tested for normal distribution using the SAS System PROC UNIVARIATE procedure Version 8.1 for Windows (SAS Institute Inc., Cary, NC, USA). Before the analysis, normality distribution and homogeneity of variances of data were revised and some transformations were applied to some variables. Logarithmic transformations were applied to DBH, TS and V_L. In the case of BD and $V_{\log}$, an x^2 transformation was required; an inverse transformation (1/*x*) was used for RS and growth stress; VS was transformed with $x^{-1.5}$; and V_{dried} with $x^{1.5}$.

Afterwards a correlation analysis (Pearson correlation matrix) was conducted for all properties and the PROC CORR of SAS procedure for Windows 8.1 was used here to demonstrate the possible prediction of wood properties using the morphological tree parameters. Finally, forward stepwise regression analysis was carried out for defining the priority morphological tree parameters affecting the wood properties the most and all coefficients of adjust regression were presented. PROC REG analysis of SAS procedure was used. Wood properties prediction (BD, HWP, GS, VS, TS and RS) was calculated using USV and morphological tree parameters, but dynamic module elasticity in different stages was utilized as the only morphological tree parameter of plantation.

Results and discussion

Morphologic characteristics

The morphological tree parameters (DBH, d_2 and h) for average and two different sites are shown in Table 1. The trees from site 2 presented higher DBH, d_2 and h than site 1. However, these trees had highest coefficient of variation for these morphology parameters.

Presence of growth stress and physical properties

The average of GS of the second log after sawing was 1003×10^{-6}, with a 17.60 % coefficient of variation (CV). GS in site 1 was lower than site 2. In general, teak trees exhibit an intermediate amount of GS. In fact, when comparing GS results with other species exhibiting a high amount of GS, such as *Eucalyptus nitens* [22], the GS in logs cut from teak trees at heights between 2.25 and 4.0 m was lower than that in logs extracted from *E. nitens* at heights between 1.6 and 3.6 m, averaging 855×10^{-6} mm [22]. However, this comparison with other studies should be considered carefully because GS would depend on log diameter and log length [24].

GS is related to opening when sawing logs [22, 24]. Therefore, based on the results obtained, we can assert that lumber extracted from these logs will exhibit moderate warping, less than that occurring in *Eucalyptus* lumber. GS was also applied to the second log only and GS in the top portion of the trunk was greater than that in the bottom portion of the tree [24]. Therefore, GS in lumber obtained from the bottom portion of trees will be less than that in lumber from the top.

The average values for BD, TS, RS and VS for average and two sites are shown in Table 1. In general, wood shrinkage values are higher, with *RS* being the highest (42.23 %) and VS exhibiting the least variation (13.38 %). Additionally, the CV of BD was the lowest of all properties measured. Trees from two sites presented similar RS, but BD, TS, and VS slightly differed. Average values for BD and shrinkage are lower and higher, respectively, than those reported by different authors in 5- to 17-year-old teak plantations [12–14]. This difference can be explained by the fact that these properties are being measured on juvenile wood. Recent investigations with teak trees from fast-growth plantations have determined that shrinkage and BD increase with tree age; however, between the ages of 4–8 these properties experience a decrease [13, 14]. These

Table 1 Statistics descriptive for some wood properties of 4-year-old *Tectona grandis* trees from two site ($N = 216$)

Wood properties	Average (CV)	Site 1	Site 2
DBH	12.56 (18.25)	11.53 (14.12)	13.58 (17.68)
d_2	10.80 (18.85)	10.12 (17.12)	11.49 (18.22)
h	12.49 (16.51)	11.45 (10.99)	13.53 (16.17)
GS (10^{-6})	1003.00 (17.60)	999.75 (17.87)	1007.98 (17.19)
BD	0.46 (6.87)	0.45 (7.24)	0.47 (5.82)
Green density (g/cm^3)	1.03 (6.00)	1.02 (6.02)	1.04 (5.87)
Air-dried density (g/cm^3)	0.52 (6.85)	0.51 (7.25)	0.53 (5.88)
Radial shrinking (%)	3.29 (40.52)	3.29 (38.95)	3.28 (42.23)
Tangential shrinking (%)	5.36 (21.71)	5.48 (23.18)	5.24 (19.80)
Volume shrinking (%)	10.42 (14.81)	10.62 (13.38)	10.22 (16.03)
Heartwood proportions (%)	12.84 (72.09)	9.01 (79.24)	16.67 (57.42)
ED_T (GPa)	6.86 (41.90)	6.16 (44.42)	6.80 (37.68)
ED_L (GPa)	4.88 (46.80)	4.59 (28.75)	5.83 (50.99)
ED_{log} (GPa)	7.32 (19.84)	8.39 (11.96)	7.32 (19.84)
ED_{lumber} (GPa)	10.87 (10.97)	11.11 (9.51)	10.63 (12.00)
ED_{dried} (GPa)	13.69 (12.18)	14.00 (9.56)	13.30 (13.24)

The values in parenthesis represent standard deviations

DBH diameter at breast height, d_2 log from 2.25 and 4 m, h total height of tree, *CV* coefficients of variation, *GS* presence of growth stress, *BD* basic density, ED_T transversal dynamic elastic modulus in standing tree, ED_L longitudinal dynamic elastic modulus in standing tree, ED_{log} dynamic elastic modulus in log, ED_{lumber} dynamic elastic modulus in green lumber, ED_{dried} dynamic elastic modulus in dry lumber studies serve as basis to establish that the transition phase between the formation of juvenile wood and mature wood probably starts within this age range and therefore, confirm that trees sampled for this study (4 years old) contain juvenile wood. This type of wood is characterized by low *BD* resulting from a thin cell wall, as well as a high angle of inclination of microfibers in the S_2 layer, which affects wood shrinkage.

Average HWP was 12.84 %; however, CV was high (72.09 %) in comparison to other properties. Trees from site 1 have higher *HWP* than site 2 (Table 1). Pérez and Kanninen [1] and Moya and Pérez [4] also report higher CV in HWP with trees from 7 to 45 years and 7 to 15 years, respectively. However, the high variation is due to the fact that this study uses very young trees (4 years old) and this wood property increases with tree age [1].

Dynamic elastic modulus

The lowest average values of ED found were for ED_L, ED_T and ED_{log}, with values ranging between 4.88 and 8.39 GPa, while values for ED_{lumber} and ED_{dried} were 10.63 and 14.00 GPa, respectively (Table 1). Some difference in ED values between site 1 and site 2 was observed (Table 1). The values for ED_{lumber} and ED_{dried} are in the 2–10 GPa range reported in 3-year-old *T. grandis* trees growing in Ivory Coast [20] with range values reported by Rujinirum et al. [17]. Teak lumber is used to build musical instruments in India. Nevertheless, Schimleck et al. [8] report an average 15.1 GPa in *T. grandis* trees from Myanmar, which exceeds the average value found in this study; these authors do not mention the age of the trees sampled.

An important aspect to highlight in relation to this mechanical parameter of wood is that ED_L and ED_T exhibit lower values and the greatest in CV values in comparison to ED_{log}, ED_{lumber} and ED_{dried} (Table 1). A possible cause for this variation may have been the method of measurement used, which was indirect. Both ultrasound transducers were located at a 45° angle in log for measuring ultrasound wave time. This is an indirect measurement of ED and lower values than transducers were located parallel to the fiber [17]. Variations in transducer inclination or depth affect wave transmission through the trunk, since energy flows through the anisotropic plane and decreases as it passes through the growth rings [25]. In the case of ED_T, this measurement was taken precisely at the center of the tree and therefore, the pith might affect this measurement. In teak wood, pith diameter is greater than 1 cm and is usually made up of very soft tissue [26], which decreases ultrasound velocity.

When comparing ED in standing trees, there were differences in the longitudinal (ED_L) and transversal (ED_T) dynamic elastic modulus. ED_T was higher than ED_L (Table 1). The difference in the variability of data is due to the location of the anatomical elements of the tree. Ultrasound waves travel slower in longitudinal direction than in transversal direction because waves disperse along the fiber length. The contrary occurs in transversal direction, where the ultrasound spreads easily across fiber cell wall [27]. Bucur [25] mentions that speed in longitudinal direction is one-fifth or one-third of the speed in perpendicular-to-grain direction, which is why the dynamic elastic modulus is smaller in longitudinal direction as was determined in the teak trees.

When comparing longitudinal ED measured in different wood types (standing tree, log, green lumber, and dry lumber), it was observed that ED parameter increased throughout wood processing (Table 1) and was therefore lowest in a standing tree and highest in dry lumber. It is important to highlight the differences found between ED_{log} and ED_{lumber}. These measurements were taken at the same points and in the same direction; however, ED_{lumber} was statistically higher than ED_{log} (Table 1). This difference can be explained by the fact that logs contain elements that disperse ultrasound waves, such as water, knots, fiber or pith inclination, and ultrasound waves take longer time to go from one end to the other and therefore; USV has lower values and so ED has lower values too [25]. Whereas in green lumber, some of these wave-dissipating elements disappear and the wave travels faster from one end to another resulting in greater resistance.

Finally, ED is highest in dry lumber (Table 1). Brashaw et al. [28] attribute this increase in ED to the little amount of water present in dry lumber and, therefore, there is a relationship between wave propagation and wood moisture. In logs, fibers are saturated with water leading to a slowing of the wave passage through the material, unlike dry lumber where moisture content is much lower. Therefore, USV increases as wood loses moisture resulting in less resistance in green lumber and greater resistance in dry lumber.

Predicting wood properties using the morphological parameters and USV of trees

Table 2 shows Pearson correlation coefficients between wood properties and morphological tree parameters. The correlation coefficients, for significant relationships, between the morphological tree parameters and wood properties ranged between 0.14 and 0.71 (Table 2). However, some of them are not logical that is, the statistical correlation between HWP and V_{log} and V_{lumber}. This is probably the result of a collinearity effect of a variable influencing heartwood. HWP as well as V_L, V_{lumber}, and GS are statistically related to DBH (Table 2) and this latter variable is probably responsible for the collinearity effect.

When correlating USV with morphological tree parameters, only V_{dried} was not affected by tree conditions; whereas V_{T}, V_{L}, V_{log}, and V_{dried} correlated with several morphological parameters (Table 2). DBH and d_2 was negatively correlated with V_{L}, V_{T}, V_{log} and V_{lumber} with values ranging between −0.14 and −0.44, while *h* only correlated with V_{log} and V_{lumber}.

Many studies have focused on the relationship between speed of sound and DBH [17]. Sotelo et al. [8] studied 39-month-old clonal assays of *Calycophyllum spruce* and found significant correlations between V_{dried}, *h* and DBH (−0.28 and −0.27, respectively); these values disagreed with those obtained in our study. Moya and Marin [14] studied 10-year-old *T. grandis* trees and found a negative correlation between V_{dried}, *h* and DBH. The relation between V_{dried} and d_2 was negatively correlated, as Moya and Marin [14]; however, no significant relationship was obtained between V_{dried}, *h* and DBH.

The correlation found between morphological tree parameters (DBH, d_2, *h* and tree quality) and USV, which indicate wood mechanical resistance, in young trees can be used to predict stiffness of wood. However, forward stepwise regression analysis (Table 3) shows that coefficient of determination is low ($R^2 < 0.2$) for $\mathrm{ED_T}$, $\mathrm{ED_L}$, $\mathrm{ED_{log}}$ and $\mathrm{ED_{dried}}$ and the $\mathrm{ED_{lumber}}$ cannot be predicted by morphological tree parameters. According to these results, wood mechanical resistance is slightly predicted by morphological tree parameters.

With regard to the DBH, diameter of second log (d_2), and tree height (*h*), it was found that they were related to V_{L}, V_{log} and V_{dried} (using USV). They exhibited a significant correlation coefficient ranging between −0.24 and −0.71. And the correlation coefficient between GS and V_{L}, V_{log} and V_{dried} are 0.26, 0.18 and 0.19, respectively. But, forward stepwise regression analysis shows that d_2 is a main variable related to $\mathrm{ED_L}$, following DBH, V_{L} and V_{T} (Table 3). Morphology tree parameters (DBH, d_2 and *h*) showed correlation with GS (Table 2). An increase in these morphological tree parameters (DBH and d_2) leads to a decrease in GS, but an increase in V_{L} leads to an increase in GS. Figure 3a, b shows how GS increases with increase in tree diameter and decrease in log diameter. The relationship of GS with tree height is typical of performance in the trees. GS decreased with increase in tree height [24].

TS and VS were not affected by morphological tree parameters, except TS with d_2, which was not significant. Whereas, RS was affected by DBH, d_2 and *h*. The UVS was not affected any shrinkage (Table 2). The regression analysis shows that it is not possible to predict RS and TS using morphological tree parameters or USV. While VS can be predicted with clone, however, the determination coefficient (R^2) was low (Table 3).

BD is positively affected by DBH, d_2 and V_{log} (Table 2). The regression analysis determined that d_2 is the predictor of this wood property and block treatments can be predicted too. However, low R^2 was found (Table 3). In

Table 2 Phenotypic Pearson correlations among morphological tree parameters, wood properties and stiffness in 4-year-old *Tectona grandis* trees from two sites in Costa Rica ($N = 216$)

	DBH	d_2	h	HWP	BD	RS	TS	VS	GS	V_{T}	V_{L}	V_{log}	V_{lumber}	V_{dried}
BHD	1.00													
d_2	0.89**	1.00												
h	0.68**	0.59**	1.00											
HWP	0.59*	0.54**	–	1.00										
BD	0.16*	0.17*	–	–	1.00									
RS	−0.21**	−0.24**	−0.18**	–	–	1.00								
TS	–	−0.18**	–	–	–	–	1.00							
VS	–	–	–	–	−0.15*	–	0.22**	1.00						
GS	−0.69**	−0.71**	−0.52**	−0.41**	–	0.21**	0.21**	–	1.00					
V_{T}	−0.14*	−0.19*	–	–	–	–	–	–	–	1.00				
V_{L}	−0.24**	−0.25**	–	–	–	–	–	–	0.26**	0.40**	1.00			
V_{log}	−0.44**	−0.34	−0.36**	−0.32**	0.17**	–	–	–	0.18**	–	–	1.00		
V_{lumber}	–	–	−0.16*	−0.19*	–	–	–	–	–	–	–	0.52**	1.00	
V_{dried}	–	−0.30**	–	−0.20**	–	–	–	–	0.19**	–	0.25*	0.23**	0.61**	1.00

V_T ultrasound velocity in transversal direction, V_L ultrasound velocity in longitudinal direction, V_{log} ultrasound velocity in longitudinal direction in log, V_{lumber} ultrasound velocity in longitudinal direction in green lumber, V_{dried} ultrasound velocity in longitudinal direction in dried lumber. See legend of Table 1 for other abbreviations

– Correlation not significant ($P < 0.05$) and the values were not written

* Statistically significant at 95 %, ** statistically significant at 99 %

Table 3 Multiple correlation analysis for the relationship between wood properties and morphology tree parameters of *Tectona grandis* plantations

Wood properties	Regression	F value	R^2
GS (10^{-6})	$47.17^{**} - 1.31 \times d_2^{**} - 0.44 \times \text{DBH}^{**} - 0.002 \times V_\text{T}^{**} + 0.001 \times V_\text{L}^{**} - 0.31 \times h$ $(R^2 = 0.50)$ $(R^2 = 0.018)$ $(R^2 = 0.008)$ $(R^2 = 0.017)$ $(R^2 = 0.007)$	38.00**	0.53
BD	$388^{**} + 8.67 \times \text{block}^{**} + 3.31 \times d_2^{**} + 0.01 \times \text{VT}^{\text{NS}} + 0.006 \times \text{VL}^{\text{NS}}$ $(R^2 = 0.014)$ $(R^2 = 0.014)$ $(R^2 = 0.014)$ $(R^2 = 0.010)$	4.77*	0.08
RS (%)	$4.79^{**} - 0.15 \times d_2^{**} + 0.0005 \times \text{clone}^{\text{NS}}$ $(R^2 = 0.07)$ $(R^2 = 0.01)$	7.82^{NS}	0.07
TS (%)	$6.28^{**} - 0.09 \times d_2^{**} + 0.0004 \times \text{clone}^{\text{NS}}$ $(R^2 = 0.03)$ $(R^2 = 0.01)$	4.59^{NS}	0.04
VS (%)	$10.18^{**} + 0.0012 \times \text{clone}^{\text{NS}}$ $(R^2 = 0.04)$	2.47*	0.07
HWP (%)	$-22.66^{**} + 0.0048 \times \text{Clone}^{**} + 1.94 \times \text{DBH}^{**} + 0.81 \times h^{*}$ $(R^2 = 0.35)$ $(R^2 = 0.02)$ $(R^2 = 0.02)$	45.02**	0.39
ED_T (GPa)	$8956^{**} - 536 \times \text{block}^{**} - 196 \times d_2^{**} + 138 \times \text{DBH}^{*} - 0.37 \times \text{clone}^{\text{NS}}$ $(R^2 = 0.17)$ $(R^2 = 0.01)$ $(R^2 = 0.016)$ $(R^2 = 0.009)$	43.01**	0.20
ED_L (GPa)	$9768^{**} - 597 \times \text{block}^{**} - 191 \times d_2^{**}$ $(R^2 = 0.07)$ $(R^2 = 0.04)$	12.39**	0.11
ED_log (GPa)	$10473^{**} - 265 \times \text{DBH}^{**} + 200 \times d_2^{*} - 92 \times h^{\text{NS}}$ $(R^2 = 0.10)$ $(R^2 = 0.02)$ $(R^2 = 0.01)$	10.63**	0.13
ED_lumber (GPa)	$12397^{**} - 61 \times \text{DBH}^{\text{NS}} - 309 \times \text{tree quality}^{\text{NS}}$ $(R^2 = 0.01)$ $(R^2 = 0.01)$	2.86^{NS}	0.02
ED_dried (GPa)	$16578^{**} - 262 \times \text{DBH}^{**} + 202 \times \text{block}^{\text{NS}}$ $(R^2 = 0.12)$ $(R^2 = 0.01)$	30.43**	0.13

Number among parenthesis bellow variable represent contribution of the parameter to the coefficient of determination (R^2)

See Tables 1 and 2 for abbreviations

* Statistically significant at 95 %, ** statistically significant at 99 %, and *NS* no significance at 95 %

4-year-old *T. grandis* trees, BD increases as tree diameter increases. This result contradicts what occurs in older teak trees, where basic density is lower in trees with a greater growth rate [29]. Tree quality, which was evaluated by shape, branches and straightness and damage by fungus or insects, was not correlated with wood physical properties or GS in the 4-year-old trees (Table 3), with an exception of ED_lumber. Therefore, it is not a good parameter to determine wood properties at an early age. Though BD is a good predictor of the mechanical resistance of wood [5], it is logical to assume that an increase in BD will increase the mechanical resistance of wood; however, this relationship does not occur in green or dry lumber. Green and dry lumber are probably being affected by other factors that have not been considered in this study. We have highlighted that the trees in this study are only 4 years old and therefore, are characterized by the presence of juvenile wood, with a high incidence of log defects (such as knots and high fiber inclinations) and these parameters in turn affect the resistance to ultrasound waves [25].

HWP is significantly affected by DBH and d_2, but UVS does not affect these parameters (Table 2). The regression analysis shows that clone effect is the main parameter of variability of HWP ($R^2 = 0.35$) and morphological tree parameters are secondary effects (Table 3). Pérez and Kaninnen [29] agree with this result. HWP in teak trees from fast-growth plantations increases exponentially with tree diameter and therefore, tree diameter is a predictor of this wood property.

Predicting dynamic module elasticity in dried lumber from log and green lumber

There was a strong correlation between V_log, V_lumber and V_dried (Table 2); therefore, we can expect that there are strong relationships between ED_log, ED_lumber and ED_dried (Fig. 3). However, data distribution is only able to predict 24 % in both cases (Fig. 3c, d) and therefore, ED_log offers little precision as a predictor of the resistance of wood that has undergone some degree of processing. In teak, the low correlation between ED_log and ED_lumber and ED_dried is probably due to data variation, measured using CV (Table 1).

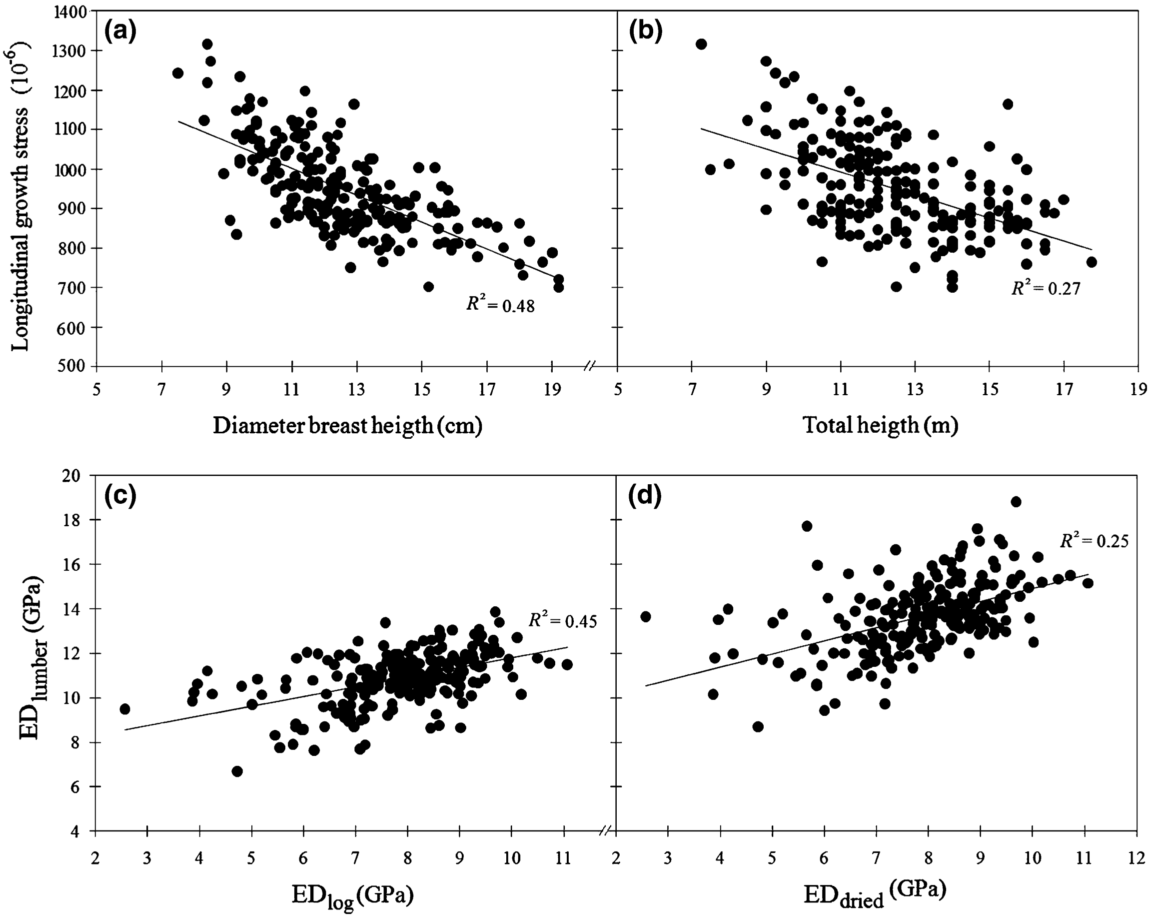

Fig. 3 Variation between presence of growth stress in relation to diameter at breast height (**a**) and tree height (**b**) and the relationship of dynamic elastic modulus measured in green lumber log (**c**) and stiffness measured in log and dried lumber (**d**) in young trees of *Tectona grandis*

Several studies have examined the relationships between acoustic measurements on standing trees and ED of lumber [30]. Controversial results have been found. These results and weak correlation found in *Tectona grandis* can explain that the ultra sound used on standing trees are considered less accurate than resonance tools, now commonly used for sorting logs [30]. Thus, acoustic velocity derived from ultra sound readings must be interpreted differently when assessing wood stiffness in standing trees [31]. Andrews [30] concluded that squaring the USV will seriously overestimate wood stiffness in standing trees. Furthermore in most studies involving the evaluation of standing trees, the inherent differences between static and dynamic estimates of wood stiffness have been overlooked, thereby producing a bias in the relationship between predicted and observed MOE values [31].

The highest correlation coefficients were found between V_{lumber} and V_{dried} (0.61). Strong correlation was found between $\mathrm{ED}_{\mathrm{lumber}}$ and $\mathrm{ED}_{\mathrm{dried}}$ too (Fig. 3d). This significant correlation in the same plank (green and dry) is logical since the only thing that changes is the percentage of moisture content. Therefore, $\mathrm{ED}_{\log}$ is a good indicator of resistance in dry teak lumber.

Conclusion

The assessment of wood properties such as basic density, shrinkage or growth stress of 4-year-old *Tectona grandis* trees can be done at a very early age (under 4 years old) based on morphological tree parameters (tree diameter or height), or using non-destructive methods such as ultrasound velocity and without having to completely destroy the tree, which tends to be the norm when determining wood properties. Additionally, though we have been able to establish significant relationships between wood properties and morphological tree parameters or wood parameters, it is necessary to establish whether the inherited wood properties measured in this study manifest themselves at an early or later age in order to include these results in reforestation programs with this species.

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