An Acad Bras Cienc (2023) 95(2): e20200809 DOI 10.1590/0001-3765202320200809
Anais da Academia Brasileira de Ciências | *Annals of the Brazilian Academy of Sciences*
Printed ISSN 0001-3765 I Online ISSN 1678-2690
www.scielo.br/aabc | www.fb.com/aabcjournal

FORESTRY SCIENCE

Influence of juvenile wood proportion on density and modulus of elasticity in softwood boards for structural use: a preliminary study

TALITHA O. ROSA, SETSUO IWAKIRI, ROSILANI TRIANOSKI, RODRIGO F. TEREZO & JOÃO L.B. RIGHEZ

Abstract: Juvenile wood (JW) can influence the performance of structural boards since it presents lower physical and mechanical properties. This study aimed evaluate the influence of JW proportion on density and modulus of elasticity (MOE) on boards for structural use. Pinus taeda logs 30 years old, had growth rings manually counted (on the pith to bark direction), and the first six rings were painted with color red (0-6), followed by blue (6.1-12), orange (12.1-18), green (18.1-24), and yellow (over 24.1), successively, and cut into boards. The proportion of each color was obtained by analysis of the transversal areas of boards with software. MOE was obtained by a nondestructive test. Multiple linear regression models were applied with 5% of significance. The estimated MOE indicates that boards with at least 57% of orange and green colors (between 12.1 – 24 years old) can achieve the minimum MOE value for using as structural as well as boards without red color but with the presence of green and yellow can have MOE bigger than 7000 MPa. The study indicates a behavior tendency about which proportion and mixed colors can affect the MOE of the board to be classified as structural.

Key words: Structural wood products, Cross-laminated timber, glued laminated timber, non-destructive tests, fast grown forests.

INTRODUCTION

Advances in timber products and consumption of those materials for construction have increased the demand for wood. For this reason, plantation forestry focused on improving the growth rates to supply wood to the market, but this model often emphasizes only maximizing the volume of wood. However, these improvements in growth rates result in a higher proportion of juvenile wood (JW) (Moore & Cown 2017, Schimleck et al. 2018).

JW can be defined as wood formed in the first years of tree growth and under the hormonal influence of the apical meristem by young cambium initials while trees are exposed to lateral forces such as winds (Barnett & Bonham 2004). Growth rates in the first years are higher than in the ultimate years of the rotation, and it results in a higher proportion of JW in relation to the total area of the log. Moreover, the physical and mechanical properties of JW are inferior to those found in adult wood (AW). A high proportion of juvenile wood within a tree can be a critical determinant in the quality of solid wood products (Zobel & Sprague 1998, Moore et al. 2012, Wessels et al. 2011, Rais et al. 2014), and it leads to a negative effect on wood quality, which is particularly problematic for structural timber use (Lasserre et al. 2009).

As manufacturing structural timber products sometimes requires boards with larger widths and thicknesses, due to the variation within trees, these boards usually present different mechanical properties. For this, understanding the potential of softwood from fast-growth plantations is advantageous to optimize the competitiveness in the market of wood-based structural products.

Simultaneously, the production of wood-based structural products in the world follows standards which consider specific classifications of wood. In the European Standard EN 338 (2016), the minimum value of modulus of elasticity (MOE) to a softwood classified as structural timber is 7000 MPa. This standard allows to categorize timber by bending test and provides the possible values of density for each one of the strength classes. However, as reported by Moore et al. (2013), it is the nature of the grading system that one of the properties will limit and constrain timber to a grade and in their study, they showed stiffness was the limiting property.

Even so, some structural products such as laminated veneer lumber, glued laminated timber, and cross-laminated timber can accommodate JW in their middle layers without substantial impacts on the product performance. But these wood products must achieve a certain minimum characteristic value to compete with other materials. For this, models that can link internal wood property distributions to the end product's performance are important to help the wood processing sector understand what the next challenges will be to improve the quality of produced wood (Moore & Cown 2017).

One of the most produced woods in Brazil is *Pinus taeda*, which have the second biggest area of commercially planted forests, and around 27.9 million m^3 was consumed as lumber in 2018. Such forests have an annual average growth rate of 30 $m^3 \cdot ha^{-1} \cdot year^{-1}$ (Ibá 2019), and this growth results in a high proportion of JW in the wood, a low density and poorer mechanical properties. However, after the fifteenth year, *Pinus taeda* starts to produce AW (Ballarin & Palma 2003). AW has features of smaller ring widths, higher densities and better mechanical properties (Moore et al. 2012, Erasmus et al. 2018). For the importance of the species on the economy, as well as the minimum requirements needed for structural timber, studies should understand how JW proportion influences the boards.

In light of the fast growth rates in plantation forestry of *Pinus taeda* in southern Brazil and the different mechanical properties of JW formed in these trees, this study aims to evaluate what is the JW proportion influence on longitudinal MOE, and density, to classify softwood boards for structural purposes according to the EN 338 standard.

MATERIALS AND METHODS

Logs (n=5) of *Pinus taeda* wood were randomly chosen at a sawmill yard in Capão Alto city, Santa Catarina, Brazil. A commercial company supplied the logs to the sawmill. The planting forests were located at Campo Belo do Sul region, Santa Catarina, Brazil, latitude 27°53'55" S and longitude 50°45'26" W, Köppen classification Cfb, and annual precipitation average of 1406 mm. The average diameter of logs was between 350-450 mm, with 3060 mm in length, and the trees were 30 years old. In order to obtain the average diameter, the circumferences (small-end and big-end) were measured on all the logs, and by the reason between the circumference and number pi the average diameters were obtained.

Material preparation started with counting manually the growth rings, on the pith to bark direction, and separating each six growth years with an ink mark. Next, with spray ink, the total area corresponding to the first six years of growth was painted in red (R) color. The same process for the other years was made, being blue (B) for the corresponding growth rings interval between 6.1-12; orange (O) to rings between 12.1-18; green (G) to 18.1-24 and yellow (Y) to 24.1-30 years (Figure 1a). The choice of six years was to facilitate evaluation by means of visualization of colored areas and to facilitate the painting of colors around the transversal area since the log had a diameter of around 350-450 mm. This distribution also facilitated the application of green and yellow colors, due to the ring width being closer to the outer area of the log. The sequence of colors was chosen to avoid mixing colors, as red and orange are considered warm colors, by this reason, the sequence was one warm color and one cold. All logs were painted one day before the sawing to dry the inks.

The pattern for sawing wood was according to the commercial measurements of the sawmill company, these dimensions were 25 x 150 x 3060 mm and 25 x 100 x 3060 mm (thickness, width, length). The pattern had as a goal to obtain a greater yield of boards, for this reason, boards have 150 mm width, and most of the boards from edges have 100 mm. Because of sawing pattern, most of the boards had a radial distribution (Figure 1b). Logs were numbered, and after sawing, they (n=113) were marked with a sequence of letters and numbers to allow separate each board according to the corresponding log. After that step, the boards followed to a kiln to dry until achieving a moisture content of 10%. The kiln drying program followed the steps used by the sawmill. In order to keep track of the progress of the lumber drying, eight pairs of stainless-steel electrodes were nailed to the lumber until the desired moisture content was achieved.

Then, boards from each log were separated in an ascending order to take photographs of transversal areas for posterior image analysis. The sequence of boards was always ascending (board 1 to board i) to aim have not errors. A scale with a known measure was positioned with the boards to help calibrate the scale of the software (Figure 2a).

To calculate the proportion of colors on each board by image analysis the software ImageJ (opened to the public) was used. The proceeding to calculate the area followed the steps: (a) one photograph for each log was taken;

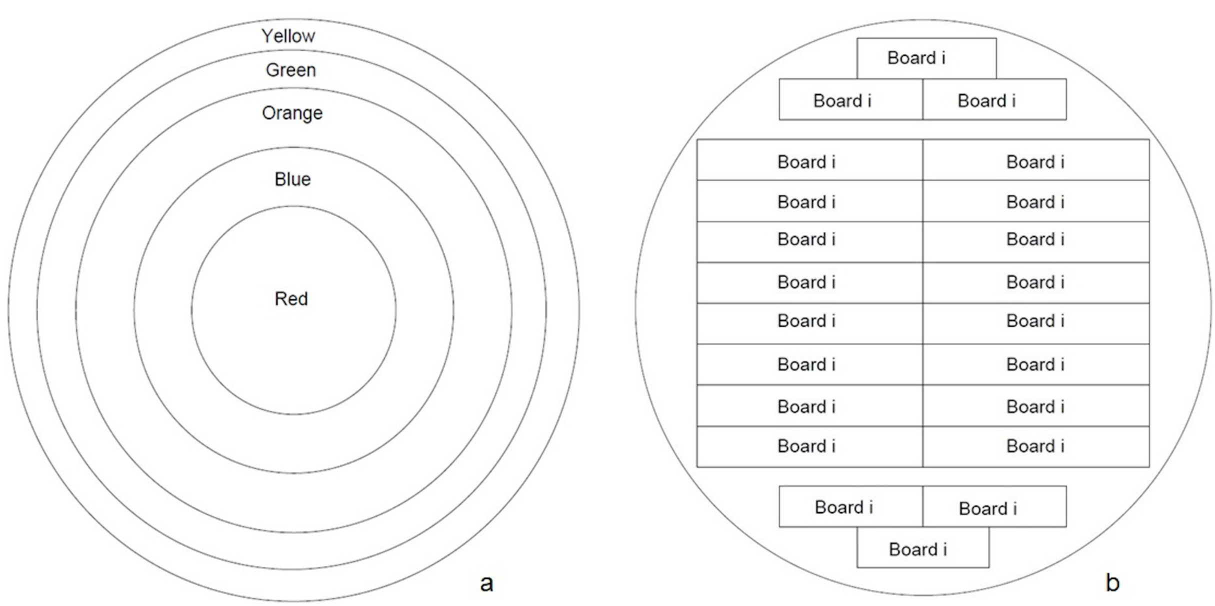

Figure 1. Colors distribution on the transversal area of logs for each 6 growth ring years of the tree (a) and distribution of boards within a log (b).

(b) the scale was calibrated on each picture to avoid errors; (c) the cross-sectional total area of the board was selected manually and calculated by the software; (d) cross-sectional areas of each color were manually selected and after also calculated by the software; (e) by a simple rule of three the percentage of each color in each board was determined. In the Figure 2b the interface of a board marked by its area and the window for area calculus made by the software is illustrated. The possible color combinations for the boards were: RBO, RBOG, RBOGY, BOGY, BOG, BO, OG and GY.

Then, all boards were measured in the three directions and weighed on an electronic balance to obtain the apparent density. The conditioning of the boards (from drying up to apparent density measurement) lasted around 90 days with an average temperature of 25°C and moisture content of 65%.

Preliminary bending tests were performed on ten boards using the automatic displacement transducer. In doing so, it was guaranteed that the displacement to be measured in the other pieces was always within the elastic limits. The results of the preliminary tests indicated that should be used a maximum load (force) of 90 N for the boards with 150 mm width and a load of 80 N for the boards with 100 mm width. Since the mean length of the boards is 3060 mm, a constant span of 2720 mm was used between the support of the end boards. The procedure to measure the displacement follows the order described by Rosa et al. (2019): an inductive transducer was positioned at the central point of the span (with the board without any load), then, a load was applied; then MOE was calculated.

The statistical data analysis followed the next steps: (a) all boards (n = 113) were classified by the MOE within each stiffness class as recommended by EN 338 (2016). Next, according to the number of boards the percentage of the representativeness of each stiffness class was calculated; (b) aiming to identify the MOE value that JW proportion starts to increase in relation to the AW, a dispersion plot of the data with the intersection between JW and AW tendency lines was made; (c) Pearson's correlation among all color variables versus MOE and versus density was run with 5% of significance; (d) before linear regression models, all data was processed by an analysis graph to identify possible outliers, which did not occur; (e) multiple linear regression model with all colors was tested (Eq.

Figure 2. Example of wood Pinus taeda boards positioned by numbers (a) to marking and calculating of area by image analysis at software ImageJ (b).

1), and after, two different new models were separated, one with all possible colors from AW (Eq. 2) and second with all colors corresponding to the JW (Eq. 3). For comparison, the models were run twice, first with the colors described as qualitative and second as quantitative. Qualitative means the presence or absence of the colors on the board, and quantitative the percentage of each color present on a board. The presence of a color assumed a value of 1, and the absence assumed a value of 0. To the variables with more than one color in a board, presence only was considered when all the colors were present, e.g., a board with colors red, blue and orange is considered present in the variable RBO. (f) After an analysis of residual plots was made and Kolmogorov-Smirnov test was run with 5% of significance.

The same steps for the estimation of density linear regression models were conducted. Equation 1 originated the models 1 and 2 for MOE and 7 and 8 for density; Eq 2 models 3 and 4 for MOE and 9 and 10 density and Eq 3 originated the models 5 and 6 and 11 and 12 for MOE and density, respectively (Table I).

RESULTS

The grading of the boards according to the EN 338 (2016) is in Table II. The grading in relation to the MOE indicated that 42.48% of the boards achieved the minimum values to be structural. Most of the boards graded as structural are in class C14 and C16, whose MOE interval is between 7000 to 9000 MPa. When we observe the density, most of the boards have presented higher density values. These boards (92.92%) were placed in the higher classes C50 and C45, and none board was placed below C27.

Figure 3 has the intersection among the wood proportions with the point that indicates the corresponding MOE value. When the portion of JW starts to be less than 50%, at that point, the MOE is around 7000 MPa. It is also possible to observe that the type of wood proportions varies according to the MOE value. When MOE is lower the proportion of JW is higher, but the behavior is inverse when the MOE is greater, and it means the proportion of AW is higher. For density, this point is around 540 $kg \cdot m^{-3}$, the behavior of decreasing JW proportion while density increases were equal as observed for MOE.

In Table III, Pearson's correlations indicated that the red and blue colors had a negative

Table I. Models for estimation of Modulus of Elasticity (MOE) and apparent density based on the general equations.

	Models (type of variables)	
Equations	**MOE**	**Density**
Eq. 1 *y= bo + b1 RBO + b2 RBOG + b3 RBOGY + b4 BOGY + b5 BOG + b6 BO + B7 OG*	1 (qualitative) 2 (quantitative)	7 (qualitative) 8 (quantitative)
Eq. 2 *y = bo + b1 OG + b2 OGY + b3 GY*	3 (qualitative) 4 (quantitative)	9 (qualitative) 10 (quantitative)
Eq. 3 *y = bo + b1 RBO+ b2 BO*	5 (qualitative) 6 (quantitative)	11 (qualitative) 12 (quantitative)

correlation with MOE. The behavior is the opposite when the colors orange, green and yellow are considered. When more than one color is present, the presence of red color indicated a negative correlation with MOE, as observed at variables RBO and RBOG. The RBOGY, BOGY, BOG, OG, OGY and GY presented positive correlations with the MOE. It was observed that for RBOGY the presence of red color did not give a negative correlation. The density results are followed by the same behavior tendency as MOE.

In Table IV are the linear multiple regression models results, which had the ANOVA test statistically significant to the principal models. Model 2 to estimate MOE with color proportion was not statistically significant for variables RBO, RBOG, RBOGY, BOGY, BOG, and BO, with p-values of 0.4873, 0.4880, 0.2991, 0.3071, 0.4874, and 0.4874, respectively. In light of this result, four new models with AW variables (models 3 and 4) and JW variables (models 5 and 6) were made, separately. Model 3 (using AW) has had a weak R^2 (0.2927) for the presence/absence of color variables and 0.3447 for the color percentage variables. To JW variables (Model 5 and 6) resulted in a simple linear regression with the RBO variable, for both presence/absence and color percentage. To predict density by the presence/absence of color, model 7 had all significant variables. In model 8, with the proportion of color, all variables: RBO (p-value: 0.6599), RBOG (0.6586), RBOGY (0.0988), BOGY (0.4394), BOG (0.6588), BO (0.6593), and OG (0.7250) were rejected. The model 9 and 10, even with a weak R^2 (0.21 and 0.30, respectively), presented all the variables statistically significant to predict density. Models 11 and 12 that considered the JW colors only model 12 had a good predictor of density since model 11 rejected the BO variable (p-value: 0.7844).

Models 1, 4 and 6 had the Ho hypothesis validated since their residuals have a normal data distribution (p-value>0.05). In addition, Model 4 presented a smaller scatter of the points, and better results to predict MOE when compared with Models 1 and 6. Model 3 did not have a good distribution of residuals since it uses qualitative variables (presence or absence of color).

For density, models 7, 10 and 12 had p-value>0.05, also validating the Ho hypothesis. However, the residual plots of all models indicated that they had tendentiousness

Table II. Grading of *Pinus taeda* boards according to the requirements of MOE and ρ (density) from EN 338 (2016) for logs of 350-450 mm diameter.

Stiffness Classes													
MOE (MPa)	N.S < 7000	C14 7000	C16 8000	C18 9000	C20 9500	C22 10000	C24 11000	C27 11500	C30 12000	C35 13000	C40 14000	C45 15000	C50 16000
n	65	20	10	3	4	6	2	1	1	1	-	-	-
%	57.52	17.70	8.85	2.65	3.54	5.31	1.77	0.88	0.88	0.88	-	-	-
Density Classes													
ρ (kg.m-3)	< 350	350	370	380	400	410	420	430	460	470	480	490	520
n	-	-	-	-	-	-	-	1	1	2	4	27	78
%	-	-	-	-	-	-	-	0.88	0.88	1.77	3.54	23.89	69.03

N.S. – Non-structural class. n – number of samples. All references values for MOE and ρ (density) are in accordance with the EN 338 (2016).

of overestimated the higher densities and underestimate the lower density values.

In general, models with color percentage had higher values of R^2 than models with presence/ absence colors and had a residual plot better adjusted. However, models 1 and 7, with only the presence or absence of color, had better results in estimating the values, instead of models 2 and 8, which used the proportion of colors as independent variables.

Applying models 1 and 4 was possible to have some prediction of MOE according to the presence and percentage of colors. To Model 1, boards with RBO would have an estimated MOE of 5527 MPa; RBOG of 6951 MPa; RBOGY 6119 MPa; BOGY 7408 MPa; BOG 7501 MPa; BO 5959 MPa and OG of 7977 MPa. When the percentage of AW colors is considered (Model 4), these results are achieved with 57.83% of a minimum percentage of OG in a board to achieve 7000 MPa; to OGY the minimum percentage would be 74.18% and GY 30.18%. To estimate density by model 12, the maximum percentage of RBO colors present in a board would be 59.34% to obtain a density of 540 $kg\cdot m^{-3}$.

DISCUSSION

Table II indicated only a few boards of *Pinus taeda* that can be classified inside the bigger stiffness grades. These low values of the MOE are similar to the values of *Pinus taeda* grown in Brazilian forests as shown by other studies (Ballarin & Palma 2003, Cunha & Matos 2010, Lucena et al. 2019). Probably, it indicates that most *Pinus taeda* forests in Brazil have the same feature of fast-growing during the rotation, which leads to a lower stiffness wood. On the other hand, density indicated an opposite behavior for the same boards. It is interesting to notice this result because in the literature many studies point out that usually density is correlated with many mechanical properties (Panshin & Zeeuw 1980, Fiorelli et al. 2009, Niklas & Spatz 2012). Typically, wood stiffness increases with wood density since stiffness is correlated positively with density (Moore et al. 2015). This relation does not indicate that Brazilian *Pinus taeda* will be classified as structural grade only because the density of boards is greater. It is noticeable in this study that even achieving higher densities, the property cannot be used to classify timber as structural boards. It may also indicate that, as observed by Moore et al. (2013), it is the nature of the grading system that one of the mechanical properties will

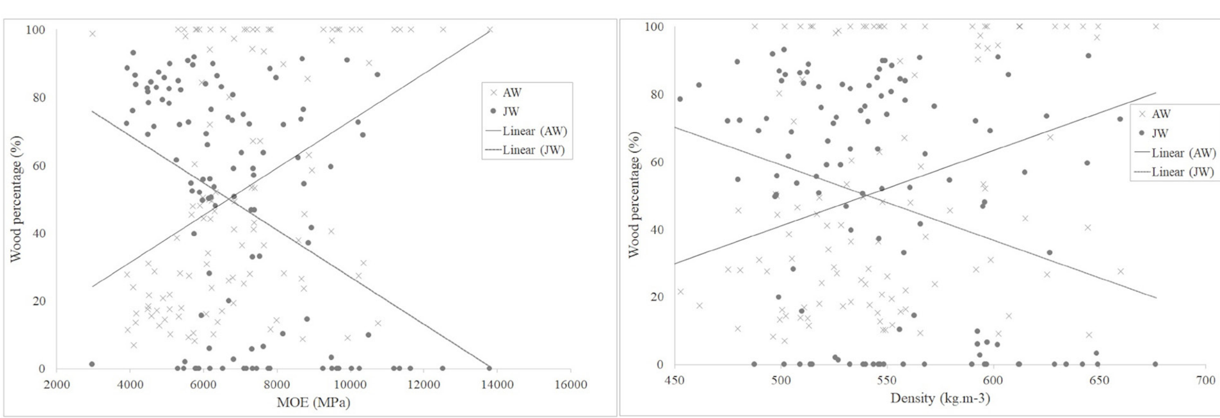

Figure 3. Influence of juvenile and adult wood proportion on stiffness and density of Pinus taeda boards from logs of 350-450 mm diameter.

limit and constrain timber to a grade. In this study, the same tendency of stiffness being the limiting property was found, which means that constrains boards to lower classes, C14 up to C24, instead of density that allows the classification on the upper classes, C45 until C50. These constraints might occur due to the presence of knots and/or different grains that can affect some of the mechanical properties, such as MOE (Kretschmann 2010, Hossein et al. 2011), this is also evidenced in Figure 3, where the scatter of points observed might be related to the natural defects of wood. Although the natural defects were not assessed in this study, it was observed that only three boards did not have any knot or other defect (clear lumber). The effect of knots on the mechanical properties, as stated by Hossein et al. (2011), depends on the proportion of wood occupied by the knots. In addition, growth sites and silvicultural management can also affect the proportion to the knots and width of the growth rings, wherein the increase or decrease of one of these properties can influence the stiffness of the boards.

Further, JW tends to present lower stiffness when compared to AW (Figure 3), which could mean that stiffness will increase as the proportion of AW rises. In the opposite behavior, the stiffness will be lower when the proportion of the JW in the board is higher. The increase of stiffness from JW to AW is consistent with findings from other studies covering a variety

Table III. Pearson correlations of color proportion variable with MOE and density of boards from log 350-450 mm diameter.

			MOE		
	RED	BLUE	ORANGE	GREEN	YELLOW
MOE (p-value)	-0.4019 0.0000	-0.4643 0.0000	0.2069 0.0286	0.4651 0.0000	0.3828 0.0000
	RBO	RBOG	RBOGY	BO	BOG
MOE (p-value)	-0.5255 0.0000	-0.3828 0.0000	0.3850 0.0000	-0.2243 0.0174	0.1396 0.1422
	BOGY	OG	OGY	GY	
MOE (p-value)	0.0749 0.4326	0.4354 0.0000	0.4321 0.0000	0.4799 0.0000	
			Density		
	RED	BLUE	ORANGE	GREEN	YELLOW
Density (p-value)	-0.4782 0.0000	-0.3307 0.0004	0.1367 0.1508	0.4711 0.4711	0.3986 0.3985
	RBO	RBOG	RBOGY	BO	BOG
Density (p-value)	-0.5382 0.0000	-0.3986 0.0000	0.3366 0.0003	-0.1690 0.0749	0.2032 0.0316
	BOGY	OG	OGY	GY	
Density (p-value)	0.0940 0.3242	0.3898 0.0000	0.4019 0.0000	0.4608 0.0000	

of softwood and hardwood species since the boards closer to the core wood will have a lower stiffness (Bao et al. 2001, Koponen et al. 2005, Moore et al. 2012).

It is highlighted that EN 338 uses destructive tests to classify timber, and in this study, non-destructive techniques for classifications were used. Previous studies using different non-destructive methods present strong correlations when correlating MOE from non-destructive methods with MOE from destructive methods (Ballarin & Nogueira 2005, Stangerlin et al. 2008, Ballarin & Palma 2009), those models could answer an average of 85% of static MOE. In other words, the MOE from non-destructive tests seems to be 15% higher than the MOE from destructive tests. Nevertheless, in this study, it can have occurred differences in the classification of boards in the strength classes from EN 338, due to the non-destructive method applied. For this reason, in future studies, it is indicated that destructive techniques be applied to validate if there is a significant difference in classification for Brazilian *Pinus taeda* on strength classes.

Pearson's correlations indicated that red and blue color had a negative correlation with MOE and density. This evidence supports the fact that JW presents lower stiffness, since the microfibril angle has a bigger influence on MOE, due to its lower angle in the first years of growth. This result highlights the increase of MOE in the radial direction of the tree (Moore et al. 2012).

However, as a board hardly will have the presence of only one color, results for mixed

Table IV. Linear multiple regression models for two different dependent variables, (MOE) and density.

MOE			
Presence/Absence of color		**%**	
Model	R^2 / R^2_{adj}	Model	R^2 / R^2_{adj}
MOE= 9542.34-4015.43RBO-2590.65RBOG-3422.94RBOGY-2134.23BOGY-2040.45BOG-3583.31BO-1564.64OG*	0.40 / 0.36	(2) Rejected variables: RBO; RBOG, RBOGY, BOGY, BOG and BO ^{NS}	-
(3) MOE=6425.61+1552.10OG+2887.00OGY+3576.19 GY*	0.29 / 0.27	(4) MOE=5446.57+26.86OG-20.94OGY+51.47GY*	0.34 / 0.33
(5) MOE=7627.51-2100.59RBO Rejected: BO (0.0767) ^{NS}	0.22 / 0.21	(6) MOE=9752.26-46.69RBO*	0.30 / 0.28
Density			
Presence of color		%	
Model	R^2 / R^2_{adj}	**Model**	R^2 / R^2_{adj}
(7) ρ=620.69-95.46RBO-55.84BO-90.85RBOG-98.72RBOGY-58.67BOGY-56.73BOG-48.72OG*	0.32 / 0.26	(8) Rejected variables: all ^{NS}	-
(9) ρ=538.73+33.23OG+46.36OGY+81.95GY*	0.21 / 0.19	(10) ρ=517.01+0.5651OG-0.5223OGY+1.2279GY*	0.31 / 0.29
(11) ρ=558.47–33.26RBO+6.37BO ^{NS} Rejected: BO (0.7844)	0.10 / 0.09	(12) ρ=612.4-1.22RBO+0.5522BO*	0.34 / 0.33

colors are interesting. MOE have a negative correlation with mixed colors with the presence of red, except RBOGY. Due to the presence of yellow, a balance between the properties of red and yellow seems to occur, creating a higher MOE value. As RBOG did not present a positive correlation, only the presence of green is not enough to balance the variability of red. This behavior is similar to the mixed colors BO, as blue is a JW wood, orange seems to be the transition wood (wood between JW and AW) and correlations are negative when orange is associated with red or blue color. The correlation becomes positive when orange is associated with green and yellow. In light of this, red and blue color seem to indicate a poorer MOE, but if these colors are present with green and yellow, a balance is created, allowing the use of this JW in a board to classify as structural.

These results are in accordance with other studies about JW. For many species, the inner region of wood, which corresponds to JW, had shown lower MOE, especially when the logs are harvested at young ages (Moore et al. 2012, Wessels et al. 2011, Rais et al. 2014, Erasmus et al. 2018). This lower MOE is correlated to the microfibril angle (MFA) since the young trees require more flexibility to avoid fractures on wind-loading exposures. The MFA is lower and results in poorer stiffness (Lasserre et al. 2009).

The estimation of colors, only by the presence or the absence, was possible when the multiple linear regression was analyzed in Model 1. This model presents seven possibilities of mixed colors that could be within a board. However, due to the high variation of properties, within and between trees, using only the colors proportion (Model 2) was not statistically enough to estimate MOE. It might mean that more variables must be considered, such as the growth ring width, since this characteristic can affect the individual properties of boards. Due to the sawmilling patterns seems that some rings of outer wood are cut away, while the rings of young age (closer to the pith) are present in a higher percentage in the boards. Erasmus et al. (2018) stated that the ring's width could affect the geometry of patterns due to sawmilling, despite that, in this study, statistical significance was not obtained when the geometry (radial or tangential rings) of the boards were considered. It can indicate that only the geometry of the boards will not affect the prediction of MOE, but maybe in association with the width of rings, both could be used to estimate the MOE in a more accurate result.

Model 4, with color percentage variables that correspond to AW, had a better estimation of MOE since the variation in this area of wood (after the 12th growth year) seems to be stabilized. Some studies point out that after this age the competition in the planting sites is higher, especially if spacing among trees is lower, and these conditions result in higher MOE (Clark et al. 2008, Moore et al. 2015, Froneman & Wessels 2017, Erasmus et al. 2018). These conditions create a smaller rate of growth in the trees, influencing mainly the MFA, whose angle tends to increase resulting in a higher stiffness of boards. This situation is also due to the fact that trees need to reach higher heights to capture sunlight, and consequently, they need more rigidity to bear their own height (Lasserre et al. 2009, Watt et al. 2009, Schimleck et al. 2018).

Differences in the radial direction of wood also are due to a large amount of variation in the mechanical properties within and between trees (Moore et al. 2013). The presence of this variation is reported by Erasmus et al. (2018) as an influence on the planting space of trees. The authors mentioned that on closely planted trees the MFA tends to decrease and as a result, MOE increases, while the trees that grow in higher planting spacing seemed to be a lower MOE.

Although the density of *Pinus taeda* can be estimated significantly by the Models presented here, its behavior is variable within and between trees, which leads to tendentiousness to overestimate the higher and underestimate the lowers densities. Density seems that also would be predicted by adding the widths of the rings to the models. After all, density is correlated with early and latewood, since the cells of latewood tend to have bigger cell walls which result in higher densities (Erasmus et al. 2018).

Due to the variations that occur within and between trees, even in the same species, the option would be grading the logs before sawmilling, avoiding the work and the loss of resources for boards that will not be classified as structural. However, if it is not possible, changing the pattern of sawmilling, with lower stiffness (red and blue colors) discarded, could be an option to decrease outgoing on this grading process. The patterns of sawmilling and ring width are also important since it seems to affect the geometry of sawing and the individual lumber properties (Erasmus et al. 2018).

This study has yielded a considerable amount of information on the proportion of JW variation in wood density and stiffness within *Pinus taeda* trees and some impact of these difference proportions on the properties of structural timber. This information can impact forest management and grading timber, not only in decisions about rotation length but also in different decisions around forest planting space and sawmilling process options.

In conclusion, JW and AW seem to have a relation with the stiffness of timber. This study can point out that high densities are not enough to grade a board as structural, because MOE does not perform proportionally. Boards up to the first 12 years old do not present a minimum value of MOE, and they cannot be graded as structural. However, radial boards with the presence of JW (up to the first 6 years old) can be classified as structural if, at the same board, there is a minimum of 30% of AW over 18 years old. Considering this, a new sawmilling pattern that prioritizes boards of edges should be developed. Since boards of edges present higher percentages of AW and consequently, higher MOE values.

Due to the differences caused by variation within trees which impacts MOE, studies models to predict JW proportion should try to understand if there are other features that could influence MOE, such as width growth rings. In summary, this study can help sawmill managers and wood companies to understand how to work in a better rational way the wood and avoid waste. This kind of study should continue to expand the knowledge about JW proportion and its influence on boards, as well as the relationship of visual defects to stiffness and juvenile and adult woods, aiming the structural use, since their information maybe helps to advance its potential and better use of fast grown Brazilian Pinus trees.

Acknowledgments

We thank Mr. Gentil Righez from Righez Madeireiras for donating all the logs wood used in this study, as well as, the space at the sawmill to work with the material. We also thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for the financial contributions (grant number: 88882.382813/2019-01).

REFERENCES

BALLARIN AW & NOGUEIRA M. 2005. Determinação do módulo de elasticidade da madeira juvenil e adulta de *Pinus taeda* por ultra-som. Eng Agríc 25(1): 19-28. https://doi.org/10.1590/S0100-69162005000100003.

BALLARIN AW & PALMA HAL. 2003. Propriedades de resistência e rigidez da madeira juvenil e adulta de *Pinus taeda* L. Árvore 27(3): 371-380. https://doi.org/10.1590/S0100-67622003000300014.

BALLARIN AW & PALMA HAL. 2009. Avaliação do módulo de elasticidade de madeiras de reflorestamento com uso não destrutivo de vibração transversal. Madeira 10(25): 5-14.

BAO FC, JIANG ZH, JIANG XM, LU XX, LUO XQ & ZHANG SY. 2001. Differences in wood properties between juvenile and mature wood in 10 species grown in China. Wood Sci Technol 35: 363-375. https://doi.org/10.1007/s002260100099.

BARNETT JR & BONHAM VA. 2004. Cellulose microfibril angle in the cell wall of wood fibres. Biol Rev Camb Philos Soc 79: 461-472. Doi: 10.1017/s1464793103006377.

CLARK A III, JORDAN L, SCHIMLECK L & DANIELS RF. 2008. Effect of initial planting spacing on wood properties of untinned loblolly pine at age 21. For Prod J 58: 78-83.

CUNHA AB & MATOS JLM. 2010. Determinação do módulo de elasticidade em madeira laminada colada por meio de ensaio não destrutivo ("*stress wave time*"). Árvore 34(2): 345-354.

EN 338. 2016. Structural timber: strength classes. European Committee for Standardization, Brussels.

ERASMUS J, KUNNEKE A, DREW DM & WESSELS B. 2018. The effect of planting spacing on *Pinus patula* steam straightness microfibril angle and wood density. Forestry 91: 247-258. doi: https://10.1093/forestry/cpy005.

FIORELLI J, DIAS AA & COIADO B. 2009. Propriedades mecânicas de peças com dimensões estruturais de *Pinus* spp: correlação entre resistência à tração e classificação visual. Árvore 33(4): 741-750. https://doi.org/10.1590/S0100-67622009000400017.

FRONEMAN GM & WESSELS CB. 2017. Increased planting density as a means for improving *Pinus elliotti* lumber stiffness. South For 1-6. https://doi.org/10.2989/20702620.2017.1354282.

HOSSEIN MA, SHAHVERDI M & ROOHNIA M. 2011. The effect of wood knot as a defect on Modulus of Elasticity (MOE) and dampling correlation. Not Sci Biol 3(3): 145-149. https://doi.org/10.15835/nsb336119.

IBÁ – INDUSTRIA BRASILEIRA DE ÁRVORES. 2019. Relatório 2019. Ibá.

KOPONEN T, KARPPINEN T, HÆGGSTROM E, SARANPAA P & SERIMAA R. 2005. The stiffness modulus in Norway spruce as a function of year ring. Holzforschung 59(4): 451-455. https://doi.org/10.1515/HF.2005.074.

KRETSCHMANN DE. 2010. Mechanical Properties of wood. In: FPL, Wood Handbook – Wood as an engineering material, Madison (WI): U.S Department of Agriculture, Forest Service, Forest Products Laboratory, p. 5-1-5-46.

LASSERRE JP, MASON EG, WATT MS & MOORE JR. 2009. Influence of initial planting spacing and genotype on microfibril angle, wood density, fibre properties and modulus of elasticity in *Pinus radiata* D. Don corewood. For Ecol Manag 258: 1924-1931. https://doi.org/10.1016/j.foreco.2009.07.028.

LUCENA R, TEREZO RF, VALLE A, RIGHEZ J & MOTTA G. 2019. Confecção e análise de rigidez de painéis de madeira lamelada colada cruzada de Pinus taeda. Braz J Technol 2(1): 439-452.

MOORE JR & COWN DJ. 2017. Corewood (Juvenile wood) and its impact on wood utilization. Curr Forestry Rep 3: 107-118. DOI: 10.1007/s40725-017-0055-2.

MOORE JR, COWN DJ, MCKINLEY RB & SABATIA CO. 2015. Effects of stand density and seedlot on three wood properties of young radiata pine grown at a dry-land site in New Zealand. N Z J For Sci 45: 15. https://doi.org/10.1186/s40490-015-0035-x.

MOORE JR, LYON AJ & LEHNEKE S. 2012. Effects of rotation length on the grade recovery and wood properties of Sitka spruce structural timber grown in Great Britain. Ann For Sci 69: 353-362. https://doi.org/10.1007/s13595-011-0168-x.

MOORE JR, LYON AJ, SEARLES GJ, LEHNEKE SA & RIDLEY-ELLIS DJ. 2013. Within and between stand variation in selected properties of Sitka spruce sawn timber in the UK: implications for segregation and grade recovery. Ann For Sci 70: 403-415. DOI 10.1007/s13595-013-0275-y.

NIKLAS KJ & SPATZ HC. 2012. Worldwide properties of wood disproportionately increase with increasing density. Am J Bot 99 (1): 169-170.

PANSHIN AJ & ZEEUW C. 1980. Textbook of wood technology, 4ed., New York: McGraw-Hill College, 722 p.

RAIS A, POSCHENRIEDER W, PRETZSCH H & VAN DE KUILEN JWG. 2014. Influence of initial plant density on sawn timber properties for Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco). Ann For Sci 71: 617-626. https://doi.org/10.1007/s13595-014-0362-8.

ROSA TO, TEREZO RF, RIOS PD, SAMPIETRO JA & ROSA GO. 2019. *Schizolobium parahyba* var. *amazonicum* glulam classified by non-destructive tests. Floresta Ambiente 26 (2). https://doi.org/10.1590/2179-8087.120217.

SCHIMLECK L, ANTONY F, DAHLEN J & MOORE J. 2018. Wood and fiber quality of plantation-grown conifers: a summary of research with an emphasis on Loblolly pine and Radiata pine. Forests 9(298). doi:10.3390/f9060298.

STANGERLIN DM, CALEGARI L, SANTINI EJ, DOMINGUES JMX, GATTO DA & MELO RR. 2008. Determinação do módulo de elasticidade em madeiras por meio de métodos destrutivos e não destrutivo. Rev Bras Cienc 3(2): 145-150.

WATT MS, CLINTON PC, PARFITT RL, ROSS C & COKER G. 2009. Modelling the influence of site and weed competition on juvenile modulus of elasticity in Pinus radiata across broad environmental gradients. For Ecol Manag 258: 1479-1488. https://doi.org/10.1016/j.foreco.2009.07.003.

WESSELS CB, DOWSE GP & SMIT HC. 2011. The flexural properties of young *Pinus elliottii* × *Pinus caribaea* var. *hondurensis* timber from the Southern Cape and their prediction from acoustic measurements. South For J For Sci 73: 137-147. https://doi.org/10.2989/20702620.2011.640427.

ZOBEL BJ & SPRAGUE JR. 1998. Juvenile wood in forest trees, 1st ed., Heidelberg: Springer Berlin, 304 p.

How to cite

ROSA TO, IWAKIRI S, TRIANOSKI R, TEREZO RF & RIGHEZ JLB. 2023. Influence of juvenile wood proportion on density and modulus of elasticity in softwood boards for structural use: a preliminary study. An Acad Bras Cienc 95: e20200809. DOI 10.1590/0001-3765202320200809.

Manuscript received on May 28, 2020;
accepted for publication on December 29, 2020

TALITHA O. ROSA[1]
https://orcid.org/0000-0002-3639-2240

SETSUO IWAKIRI[1]
https://orcid.org/0000-0003-0390-3830

ROSILANI TRIANOSKI[1]
https://orcid.org/0000-0002-3761-6728

RODRIGO F. TEREZO[2]
https://orcid.org/0000-0002-7562-1931

JOÃO L.B. RIGHEZ[2]
https://orcid.org/0000-0002-6919-0338

[1]Universidade Federal do Paraná, Departamento de Engenharia Florestal, Av. Lothário Meissner, 632, Jardim Botânico, 80210-170 Curitiba, PR, Brazil

[2]Universidade do Estado de Santa Catarina, Departamento de Engenharia Florestal, Av. Luiz de Camões, 2090, 88520-000 Lages, SC, Brazil

Correspondence to: **Talitha Oliveira Rosa**
E-mail: rosa.talitha@gmail.com

Author contributions

Conceptualization: Talitha O. Rosa; Setsuo Iwakiri; Rodrigo F. Terezo. Methodology: Talitha O. Rosa; Setsuo Iwakiri; Rodrigo F. Terezo; João L. B. Righez. Software analysis, Data curation, and Writing – original draft: Talitha O. Rosa. Formal Analysis: Talitha O. Rosa; Setsuo Iwakiri. Investigation: Talitha O. Rosa; João L. B. Righez. Resources: Rodrigo F. Terezo; João L. B. Righez. Writing – review and editing: Talitha O. Rosa; Setsuo Iwakiri; Rosilani Trianoski. Supervision: Setsuo Iwakiri; Rodrigo F. Terezo; Rosilani Trianoski. Project Administration: Talitha O. Rosa; Setsuo Iwakiri; Rodrigo F. Terezo. Funding acquisition: João L. B. Righez.