Heartwood formation and prediction of heartwood parameters in *Tectona grandis* L.f. trees growing in forest plantations in Costa Rica

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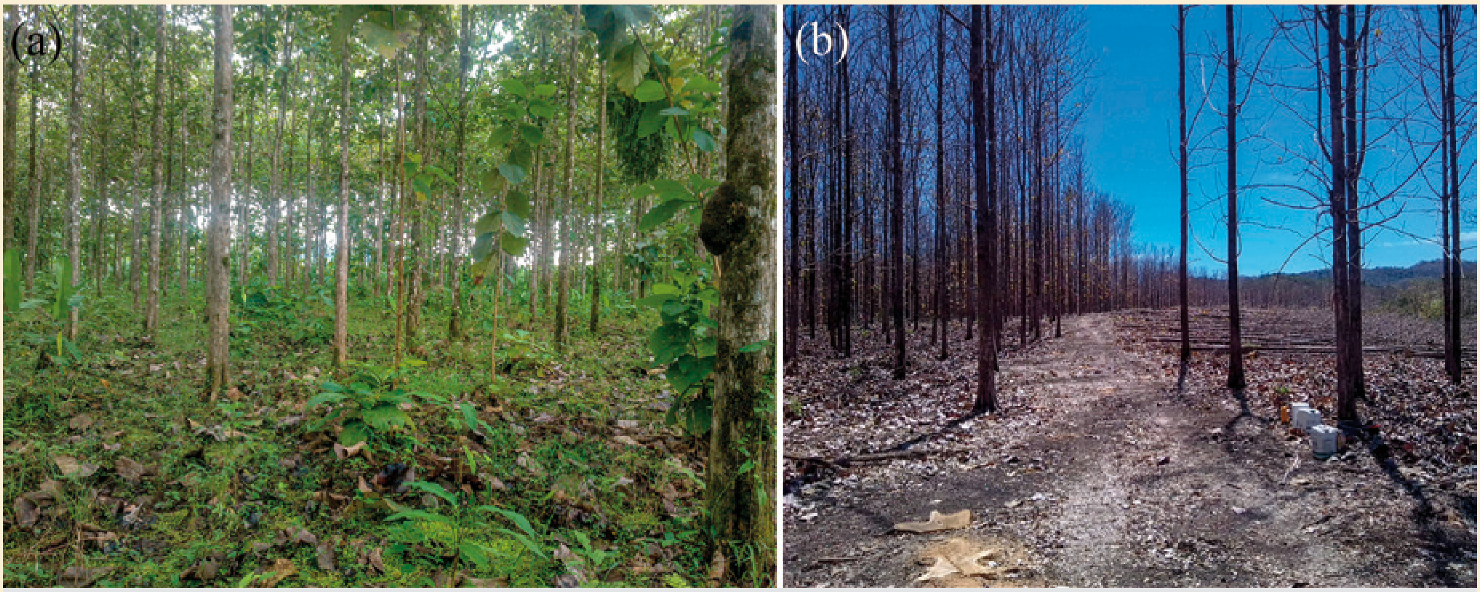

Photo 1.
Tectona grandis plantation of 9 years growing in wet tropical (a) and dry tropical climatic (b) in Costa Rica.

Doi : 10.19182/bft2018.335.a31499 – Droit d'auteur © 2018, Bois et Forêts des Tropiques – Date de publication : 12 mars 2018

Citer l'article / Cite the article
Fernández-Sólis D., Berrocal A., Moya R., 2018. Heartwood formation and prediction of heartwood parameters in *Tectona grandis* L.f. trees growing in forest plantations in Costa Rica. Bois et Forêts des Tropiques, 335 : 25-37.
Doi : https://doi.org/10.19182/bft2018.335.a31499

RÉSUMÉ

Formation de duramen et prédictivité des paramètres associés pour des plantations de *Tectona grandis* L.f. au Costa Rica

La présente étude vise à établir les variations du duramen (pourcentage, diamètre, rayon, volume) rapportées à la hauteur des arbres et à l'épaisseur de l'aubier, ainsi que l'âge de début de formation du duramen et sa hauteur maximale pour les arbres de l'essence *Tectona grandis*. Les résultats de l'échantillonnage de seize plantations réparties dans différentes zones du Costa Rica, âgées de 2 à 22 ans, montrent que l'aubier est plus épais entre 2 et 10 ans d'âge qu'entre 10 et 22 ans. La formation du duramen commence à la base des arbres âgés de 2 à 3 ans, mais il n'apparaît à hauteur de poitrine qu'à partir de 3 à 4 ans. Le duramen disparaît à une hauteur allant de 0 à 90 % de la hauteur totale selon l'âge de l'arbre. Enfin, des modèles statistiques prédictifs ont été développés pour l'épaisseur de l'aubier et pour le rayon, la hauteur maximale et le pourcentage du duramen, en se basant sur le modèle $Y = K_0 + K_{1*}$(épaisseur de l'aubier) + K_{2*}(hauteur relative de l'échantillonnage) + K_{3*}(diamètre à hauteur de poitrine) + K_{4*}(âge de l'arbre). Ces modèles indiquent des coefficients de détermination de 70 %, 90 %, 95 %, 73 % et 31 %, respectivement.

Mots-clés : duramen, aubier, *Tectona grandis*, variation verticale, modèles prédictifs.

ABSTRACT

Heartwood formation and prediction of heartwood parameters in *Tectona grandis* L.f. trees growing in forest plantations in Costa Rica

The aim of this study was to establish variations in heartwood (percentage, diameter, radius, volume) in relation to tree height and sapwood thickness. The age at which heartwood formation begins and the maximum heartwood height in *Tectona grandis* trees were also investigated. Samples were taken from sixteen plantations in different zones of Costa Rica, ranging in age from 2 to 22 years. Our results showed that the sapwood is thicker at 2-10 years than at 10-22 years of age. Heartwood begins to form at the basal part of the trees at 2 and 3 years of age but does not appear at breast height until 3 to 4 years of age. The heartwood disappears at a height ranging from 0 to 90% of the total height, depending on the age of the tree. Finally, statistical predictive models were developed for sapwood thickness, heartwood radius, maximum heartwood height, heartwood percentage and heartwood volume, using the model $Y = K_0 + K_{1*}$(sapwood thickness) + K_{2*}(relative sampling height) + K_{3*}(diameter at breast height) + K_{4*}(tree age). These models showed determination coefficients of 70%, 90%, 95%, 73% and 31%, respectively.

Keywords: heartwood, sapwood, *Tectona grandis*, vertical variation, predictive models.

RESUMEN

Formación del duramen y predicción de los parámetros asociados en plantaciones de *Tectona grandis* L.f. de Costa Rica

El objetivo de este estudio consistió en determinar las variaciones en el duramen (porcentaje, diámetro, radio y volumen) y su relación con la altura de los árboles y el espesor de la albura. También se investigó la edad en la que empieza a formarse el duramen y su altura máxima en árboles de *Tectona grandis*. Se tomaron muestras en dieciséis plantaciones de diferentes zonas de Costa Rica, con edades comprendidas entre 2 y 22 años. Los resultados mostraron que la albura es más gruesa entre 2 y 10 años que entre 10 y 22 años. La formación del duramen comienza en la base de los árboles a la edad de 2 o 3 años, pero no aparece a la altura del pecho hasta los 3 o 4 años. El duramen desaparece a una altura que va del 0 al 90% de la altura total, según la edad del árbol. Por último, se desarrollaron modelos estadísticos predictivos para el espesor de la albura y para el radio, altura máxima, porcentaje y volumen de duramen, basándose en el modelo $Y = K_0 + K_{1*}$(espesor de la albura) + K_{2*}(altura relativa de muestreo) + K_{3*}(diámetro a altura del pecho) + K_{4*}(edad del árbol). Estos modelos mostraron unos coeficientes de determinación del 70%, 90%, 95%, 73% y 31%, respectivamente.

Palabras clave: duramen, albura, *Tectona grandis*, variación vertical, modelos predictivos.

Introduction

Tectona grandis L.f. grows naturally in India, Myanmar, Laos and Thailand, and its wood is highly valuable in the international market (Minn *et al.*, 2014). In other regions of the tropical zones in countries of Africa, Central America and South America (Koskela *et al.*, 2014), it was introduced as part of fast-growth forest plantations for small-diameter log production. *T. grandis* timber coming from plantations has been widely studied, mainly regarding silvicultural development and genetic improvement programs and their effects on wood properties (Moya *et al.*, 2014).

T. grandis heartwood represents the most commercially valuable wood of the trunk due to its color, durability and resistance (Lourenço *et al.*, 2015), which give it great salability in the timber market. Hegde *et al.* (2014) stress that its high proportion of heartwood and proportionally low sapwood at different tree heights make *T. grandis* an excellent species for the timber sawing industry. For this reason, many studies have investigated heartwood formation during the growth of the tree (Moya *et al.*, 2014). For example, Miranda *et al.* (2011), Kumar and Dhillon (2015), Anish *et al.* (2015), and Galeano *et al.* (2015) observed a decrease in the diameter and proportion of heartwood as the total tree height increases. García *et al.* (2011a and 2011b) developed a prediction model that relates the variation of heartwood diameter to total tree height and to the diameter at breast height (DBH) for 2- to 14-year-old plantations of *T. grandis*.

Other investigations have determined the variation of the percentage of heartwood ($HW_{percentage}$) with management conditions and DBH, among other morphological parameters of the tree. For example, Serrano *et al.* (2015) and Arce and Moya (2015) show that different site and climatic conditions, soil fertility and management of the plantation affect sapwood thickness (SWT) and $HW_{percentage}$ at DBH. Thulasidas and Bhat (2009) found great differences in $HW_{percentage}$ and heartwood diameter ($HW_{diameter}$) between wet and dry sites in India, with the wet sites presenting larger heartwood diameters. In contrast, Pérez and Kanninen (2003) and Crespo *et al.* (2008) reported, for studies conducted in Costa Rica and Ecuador, respectively, significantly greater $HW_{diameter}$ in plantations growing at dry sites.

Moya *et al.* (2014) mentioned that heartwood formation is affected by variables such as DBH, age of the tree and total tree height. On the other hand, studies by Pâques and Charpentier (2015), Nocetti *et al.* (2015) and Kennedy *et al.* (2014) found that SWT varies slightly, and this variable is little affected by tree morphology (height or diameter), growing conditions or types of wood. Based on this theory, the authors expect that through statistical methods, it is possible to estimate the heartwood parameters at a specific height, considering SWT, diameter at a specific height and age of the tree.

As mentioned, $HW_{diameter}$ is a feature correlated to tree age and total height of the tree (Knapic *et al.*, 2014). Zhang and Jiang (2015) established a model of the variation of $HW_{diameter}$, considering the tree age and height accurately and precisely. Miranda *et al.* (2015) carried out some estimations for predicting $HW_{diameter}$ and maximum heartwood height in *Eucalyptus globulus* trees and developed a model involving DBH and total height of tree.

In the specific case of *T. grandis* heartwood, there are various models to estimate $HW_{diameter}$ based on DBH (Pérez and Kanninen, 2003; Okuyama *et al.*, 2005; García *et al.*, 2011a and 2011b); however, these models are restricted to tree age, and only DBH is used. Therefore, there are no models to predict these features in standing trees while considering multiple factors such as tree age, DBH, total tree height, and SWT, among other types of variables affecting heartwood development.

Thus, this work focuses on the characterization and prediction of variables related to heartwood in *T. grandis* L.f. trees growing in fast-growth plantations at different ages in Costa Rica. Specifically, the aim of the study is to establish the variability of SWT, $HW_{diameter}$, $HW_{percentage}$ and maximum heartwood height. In addition, statistical models were developed for predicting SWT, heartwood radius (HW_{radius}), maximum heartwood height, $HW_{percentage}$, and heartwood volume (HW_{volume}) at various tree heights.

Photo 2.
Heartwood formation in *Tectona grandis* trees in basal area of 2 years old (a) and 21 years old (b) growing in Costa Rica.

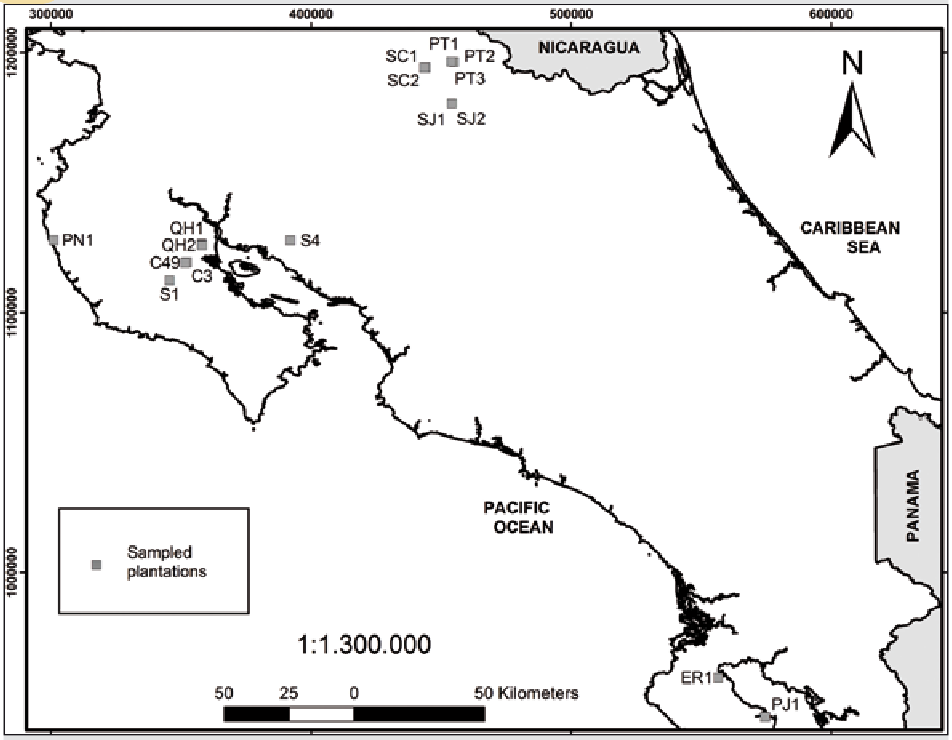

Figure 1.
Localization of *Tectona grandis* sampled places of different ages in fast growth plantations in Costa Rica.

Methodology

Sampled plantations

Sixteen fast-growth plantations of *T. grandis* (teak) were sampled in different regions of Costa Rica: the North Pacific, South Pacific and northern regions (figure 1). The dasometric parameters of the trees are presented in table I. The plantations presented different ages, altitudes and silvicultural management. Age categories varied from 2 to 22 years (table I). These ages represent the age range of the tree before it is cut for sawlog production in Costa Rica; the age rotation for cutting is 20-25 years. A 13-m-radius (531 m^2) temporary plot was established in each plantation, in which all trees were measured by their DBH, total tree height and height up to the beginning of the crown, marked by the first living branch, or height of the crown. The plantation density was determined using the number of trees in the plot, as detailed in table I.

Table I.
Dasometric parameters and age of the *Tectona grandis* L.f. fast growth plantations sampled in different places in Costa Rica.

Region	Identification	Age (years)	DBH (cm)	Total tree height (m)	Height to crown start (m)	HWrh (m)
South-Pacific	ER1	13	20.5	22.4	11.3	16.5
South-Pacific	PJ1	3	8.7	9.2	3.4	0.2
North-Pacific	S1	5	18.3	17.3	5.6	7.1
North-Pacific	S4	20	22.5	20.3	9.0	16.2
North-Pacific	PN1	22	26.7	23.3	13.7	19.6
North-Pacific	C3	9	23.0	19.95	9.2	12.6
North-Pacific	C49	9	25.0	20.6	8.4	12.4
North-Pacific	QH2	14	21.4	19.3	9.6	12.6
North-Pacific	QH1	19	29.5	23.4	13.1	19.4
North	PT1	2	9.3	8.7	3.6	1.8
North	PT2	9	18.3	15.5	4.0	7.3
North	PT3	10	24.6	20.3	6.4	14.4
North	SC1	7	10.5	11.7	4.3	1.7
North	SC2	8	12.1	14.1	4.3	4.14
North	SJ2	7	9.4	10.3	3.9	3.6
North	SJ1	9	12.1	9.9	4.2	5.8

DBH: diameter breast height; HWrh: relative maximum heartwood height.

Sampling within the plantation and tree variables measured

From each plantation, three trees with diameters within the category of variation present in the plantation were selected randomly. A total of 48 trees was sampled, corresponding to a total of 3 samples x 16 sites. DBH was measured in each sampled tree. After the tree was cut, the height of the crown and total tree height were recorded. Then, a disc approximately 4 cm thick was cut at the base of the tree and additional discs every 2.3 m from the base of the tree to the highest part. During this process, the height in meters at which each disk was cut—which corresponds to the distance from the base of the tree to the height of this sampling—was recorded. Next, the maximum heartwood height of the tree was located based on the disks at the different heights. Once located, the distance from the tree base to maximum heartwood height was measured.

Measurements in cross-sections

In each disc, two perpendicular radial directions were marked, passing through the pith. In each direction, diameter without bark, heartwood diameter and pith diameter were measured. The sapwood-heartwood boundary was determined by the difference in color.

Data analysis

The following parameters were determined from the measurements with the discs: relative sampling height, sapwood thickness (SWT), heartwood radius (HW_{radius}), percentage of heartwood ($HW_{percentage}$), heartwood volume (HW_{volume}), maximum heartwood height and relative height where the heartwood disappears (HWrh). The relative sampling height of each disc obtained from the tree was estimated as the height in meters of the disc, taken at different heights, divided into the total height of that tree and expressed as a percentage.

For SWT determination, the difference between the disc diameter without bark and heartwood diameter was calculated and divided in two. Where there was no presence of heartwood, SWT was estimated as the difference between the disc diameter without bark and the mean of the pith diameter, divided in half. HW_{radius} was determined based on the heartwood diameter measured in the discs and divided in two. Another parameter determined for each disc was $HW_{percentage}$, calculated as the area of heartwood with respect to the disc cross-section area and expressed as a percentage. HWrh was calculated by the ratio of maximum heartwood height and total tree height, expressed as a percentage. Lastly, HW_{volume} was estimated by the conical volume method (Equation 1), which estimates the heartwood volume from the base of the tree to where the maximum heartwood height is reached.

$$HWvolume\ (m^3) = \frac{a_b\ (m^2) * H_{HWD}\ (m)}{3} \quad \text{(Equation 1)}$$

$$a_b\ (m^2) = \frac{\pi * d^2\ (m)}{4} \quad \text{(Equation 2)}$$

where HW_{volume} is the heartwood volume, estimated from the base of the tree to the highest heartwood height in the trunk; a_b is the cross-section area of the heartwood at the tree base, estimated through Equation 2; maximum heartwood height is the maximum height of the heartwood in meters; and diameter is the heartwood diameter at the measured height.

It should be mentioned that some authors (Berthier *et al*., 2001; Climent *et al*., 2003; Sousa *et al*., 2012) did not take into account the measurements at the tree base while studying the variation of properties because of the irregularity in the shape of the tree at that height. This work considered those measurements in the analysis except in the plantations of Pueblo Viejo and Hojancha, where discs at the base of the trunk could not be obtained due to trunk base rotting. The parameters of the cross-sections were measured using the small and large diameters of the cross-sections.

Statistical methods

First, SWT behavior with respect to the sampled height was studied through the variation of SWT along the tree-trunk height. SWT normality was confirmed; and then a one-factor analysis of variance (ANOVA) was applied for each age of the plantation, using the sampling height (in meters) as the independent variable and SWT as the dependent variable. The Tukey test was used for the comparison of this analysis of variance at a statistical level (P) of 0.05. Another analysis performed was the linear correlation between the variables in the study, compared through Pearson's correlation coefficient analysis (95% significance). This test established the most significant variables for the multiple linear regression models.

Prediction models

The multiple linear regression method was used to obtain the prediction models for the tree variables SWT, HW_{radius}, maximum heartwood height, $HW_{percentage}$, HWrh and HW_{volume}. The Ryan-Joiner normality test was used to test the normal distribution of the data of each variable. A suitable transformation was applied to the variables to be modeled that did not present a normal distribution. The models were tested with the best-fitting independent variables according to correlation with the variables to be modeled. Residual plots were analyzed to evaluate the validity of the models.

Results

Sapwood thickness variation along the trunk

SWT of *T. grandis* trees in fast-growth plantation conditions tended to decrease with increasing tree height in both total tree height and relative sampling height (figure 2a-b). The coefficients of determination for linear regression between SWT and the relative sampling height or the height of sampling indicate a statistically non-significant relationship (correlation coefficients 0.026 and 0.028, respectively), showing that SWT is uniform along the trunk of the trees. However, it is also possible to observe a wide variability in SWT along the tree trunk. SWT decreases with tree height at ages 2, 3 and 7 years, with significant differences in total tree height, whereas other tree ages do not present significant differences in SWT in the entire trunk.

SWT separation by tree age showed two distribution patterns (figure 3a-b). The first pattern occurred in trees from plantations aged 2 to 10 years, with SWT showing a tendency to decrease with increasing total tree height. The second pattern is associated with trees from plantations aged 11 to 22 years, with SWT showing no increasing or decreasing pattern relative to total tree height. The t-student test of the two age ranges (trees less than and equal to 10 years and trees over 10 years) showed that there are significant differences between the two groups in sapwood thickness (α = 0.05; T = 9.83; P value = 0.00); therefore, trees aged 11 to 22 years have a statistically lower SWT than trees 2 to 10 years old. In the former age category, SWT is 0.5 to 3.2 cm, and for trees aged from 2 to 10 years, SWT is 1.4 to 6.5 cm.

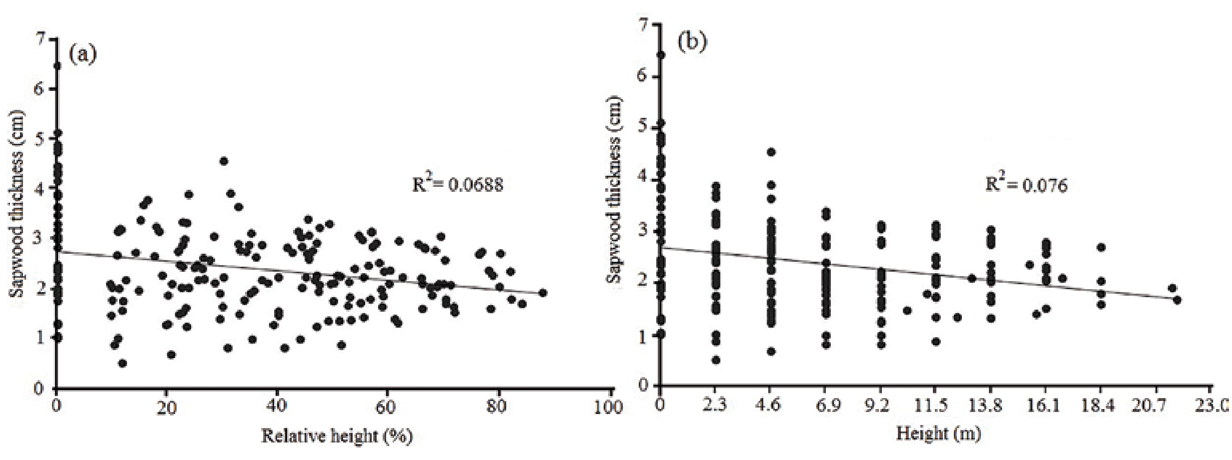

Figure 2.
Sapwood variation in relation to relative height (a) and total height (b) in *Tectona grandis* trees from fast growth plantations of different ages in Costa Rica.

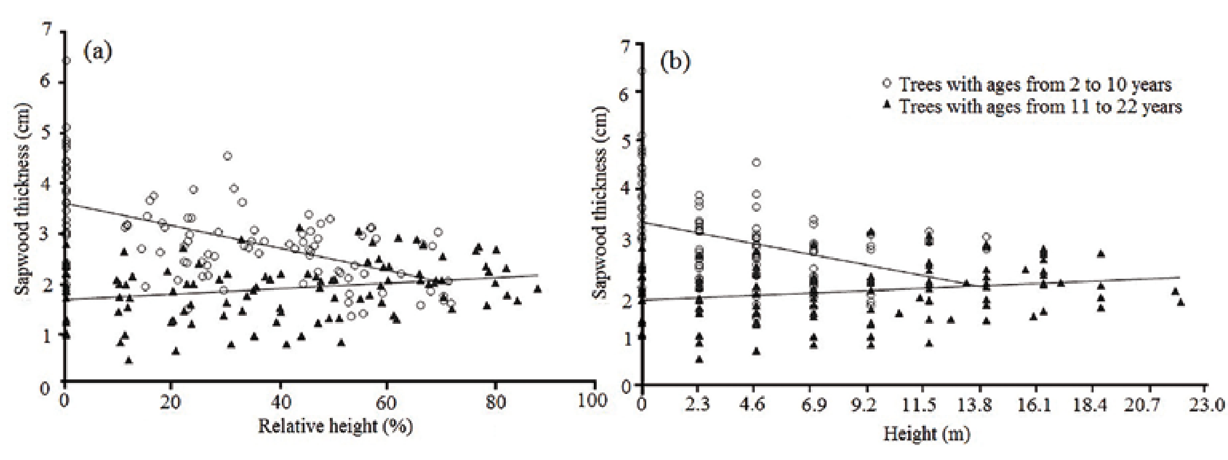

Figure 3.
Relation of sapwood thickness with relative height (a) and total height (b) of *Tectona grandis* trees from fast growth plantations of different ages in Costa Rica.

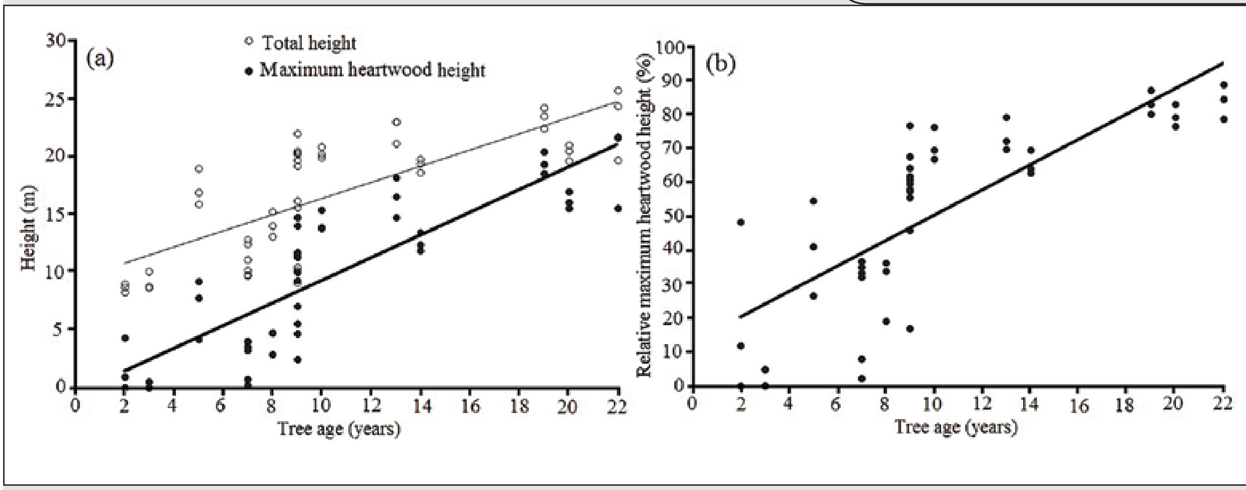

Figure 4.
Relationship between the heartwood disappearing height and tree age (a) and relative heartwood disappearing height (b) and age of *Tectona grandis* trees from fast growth plantations of different ages in Costa Rica.

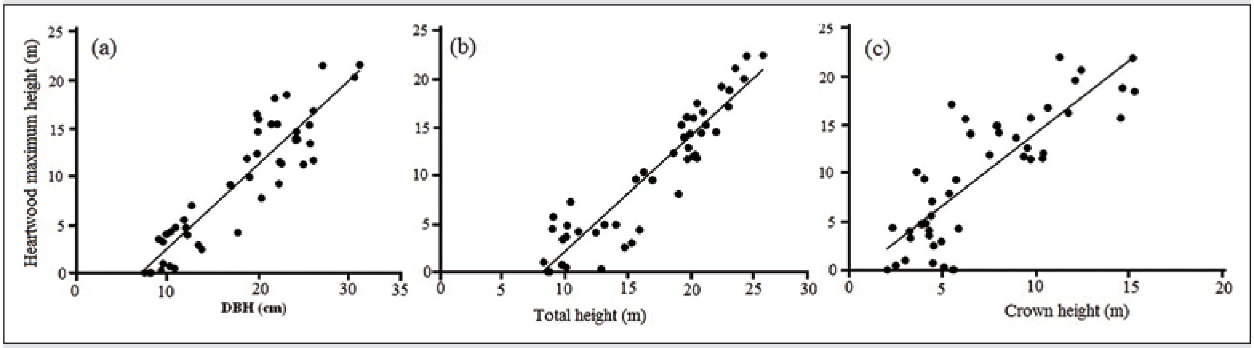

Figure 5.
Relationship between relative height where the heartwood disappears (HWrh) and diameter at breast height (DBH) (a), total tree height (b) and height of crown (c) of *Tectona grandis* trees from fast growth plantations of different ages in Costa Rica.

Age of formation and maximum height of heartwood

Heartwood formation at the base of sampled trees 2-3 years of age was found in only two trees of each age (figure 4a) and not in the rest of the heights analyzed at these ages. Meanwhile, maximum heartwood height was proportional to the age of the plantation; i.e., as the tree ages (figure 4a), heartwood disappears at greater heights (R^2 = 72.29%). Additionally, maximum heartwood height tended to approach the total height of trees (figure 4a). In younger trees, the distance between maximum heartwood height and the apex of the tree tends to diminish as the tree ages. HWrh presented a significant proportionality with tree age (R^2 = 63.00%) (figure 4b): the older the plantation, the greater the height at which heartwood disappears.

Relationship between maximum heartwood height and dasometric variables of the tree

In addition to the relationship between tree age (figure 4) and maximum heartwood height, it was found that this height was positively correlated with other variables of the trees (table II, figure 5a-b-c). DBH, total tree height and height of crown are proportional to maximum heartwood height. Moreover, HW_{radius}, $HW_{percentage}$ and HW_{volume} presented a positive correlation with maximum heartwood height.

Additional correlations were established with the parameters of the trees (table II): (*i*) DBH showed a significant and positive correlation with maximum heartwood height (figure 5a), HW_{radius}, HW_{volume} and $HW_{percentage}$; (*ii*) the total height of the trees also presented a positive significant correlation with maximum heartwood height (figure 5b), HW_{radius}, HW_{volume} and $HW_{percentage}$; (*iii*) to a lesser extent, the relative sampling height showed a positive and significant correlation with the variable maximum heartwood height, in contrast with HW_{radius}, HW_{volume} and $HW_{percentage}$, for which the correlation was significantly negative; (*iv*) the height of sampling in the tree was negatively correlated with HW_{radius}, HW_{volume} and $HW_{percentage}$ and significantly positively correlated with maximum heartwood height; and (*v*) both height of crown and age of the plantation showed a positive and significant correlation with maximum heartwood height (figure 5c), HW_{radius}, HW_{volume} and $HW_{percentage}$. The variable SWT at different heights of the tree showed a significant negative correlation with total tree height, DBH,

Table II.
Correlation coefficients of tree parameters sampled in *Tectona grandis* from fast growth plantations in Costa Rica. Coefficient significance $p < 0.05$.

Tree variables	DBH	Total tree height	HWrh	Sampling height	Height of crown	Age
Heartwood maximum height	0.912**	0.955**	0.193*	0.478*	0.817**	0.867**
Sapwood thickness	-0.402*	-0.444*	-0.262*	-0.276*	-0.571*	-0.580*
Heartwood radius	0.659**	0.587*	-0.518**	-0.318*	0.475*	0.550*
Heartwood volume	0.566*	0.482*	-0.437*	-0.311*	0.422*	0.479*
Heartwood percentage	0.679**	0.659**	-0.384*	-0.162*	0.619**	0.666**

DBH: diameter breast height; HWrh: relative maximum heartwood height.

Table III.
Adjusted regression for sapwood thickness and maximum heartwood height prediction models for *Tectona grandis* trees from fast growth plantations in Costa Rica.

	Standard error	R^2 adjusted (%)	FI	Models
SWT	0.50	69.54	-	$SWT = 3.049 + 0.6965\ SWT_{2.3} + 0.2891\ Hs - 0.114\ Ht - 0.05872\ Hr$ (1)
HW_{radius}	0.37	-	89.18	$\sqrt{HWradius} = -1.523 + 0.201\sqrt{DBH} + 0.6518\sqrt{HWrh} - 1.058\sqrt{Hs} + 0.487\sqrt{Ht} + 0.2518\sqrt{Hr}$ (2)
H_{HW}	1.48	94.79	-	$H_{HW} = -3.688 - 1.545\ SWT_{2.3} + 0.2802\ DBH + 0.7543\ Ht$ (3)
$HW_{percentage}$	1.17	-	73.49	$\sqrt{HWpercentage} = -1.16 - 1.036\sqrt{SWT_{2.3}} + 1.933\sqrt{HWrh} - 2.083\sqrt{Hs} + 1.196\sqrt{Ht} + 0.497\sqrt{Hr}$ (4)
HW_{volume}	0.12	-	30.91	$\sqrt{HWvolume} = -0.4337 + 0.1172\sqrt{DBH} + 0.0307\sqrt{Hc}$ (5)

Legend: H_{HW}: Maximum heartwood height; HWrh: relative height where the heartwood disappears; Ht: total tree height; Hr: relative sampling height; Hs: height of this sampling; Hc: height of crown or first living branch; DBH: diameter at breast height; $HW_{percentage}$: percentage of heartwood; SWT: sapwood thickness; $SWT_{2.3}$: sapwood thickness at 2.3 m height; $HW_{diameter}$: heartwood diameter; HW_{radius}: heartwood radius; HW_{volume}: heartwood volume;
FI: R^2 in real units for transformed models.

relative sampling height, height of sampling, height of crown and age of the plantation. Finally, maximum heartwood height was the variable that presented the strongest significant correlations in proportion to the rest of the variables. In addition to this variable, in trees presenting heartwood, its maximum height was within the category of 0.27 to 21.7 m.

Prediction models

For the variables to be modeled (SWT, HW_{radius} at different heights, maximum heartwood height, $HW_{percentage}$ and HW_{volume}), the normality of data distribution was tested by means of the Ryan-Joiner test. SWT and maximum heartwood height presented data normality (p-value < 0.01; RJ value of 0.98 and 0.96, respectively), and transformation was unnecessary. In contrast, HW_{radius}, $HW_{percentage}$ and HW_{volume} did not show a normal distribution; therefore, transformation by means of the square root was required to achieve normality (P value < 0.01; RJ value of 0.98. 0.97 and 0.94, respectively).

After transformation in the case of SWT, the best fit for the determination of this parameter was obtained with the variables SWT at 2.3 m height, height of sampling, relative sampling height and total tree height. This fit explained 70% of the variation of SWT at different heights of the tree in addition to presenting adequate error distribution (model 1 in table III, figure 6a).

In the estimation of HW_{radius} with the best fit, based on the coefficient of determination and standard error, the multiple square root should be considered with DBH, HW_{radius} at 2.3 m height, the height of sampling and relative height. This model explains 89% of the variation of HW_{radius} at different heights (model 2 in table III), and the error distribution was appropriate, as shown in figure 6b.

The maximum heartwood height is a difficult feature to measure. A prediction model was adjusted in this case (explaining 95% of the variation), including the fitting variables of SWT at 2.3 m height ($SWT_{2.3}$), DBH and total height of the tree (model 3 in table III). The error distribution was significantly appropriate for the model (figure 6c).

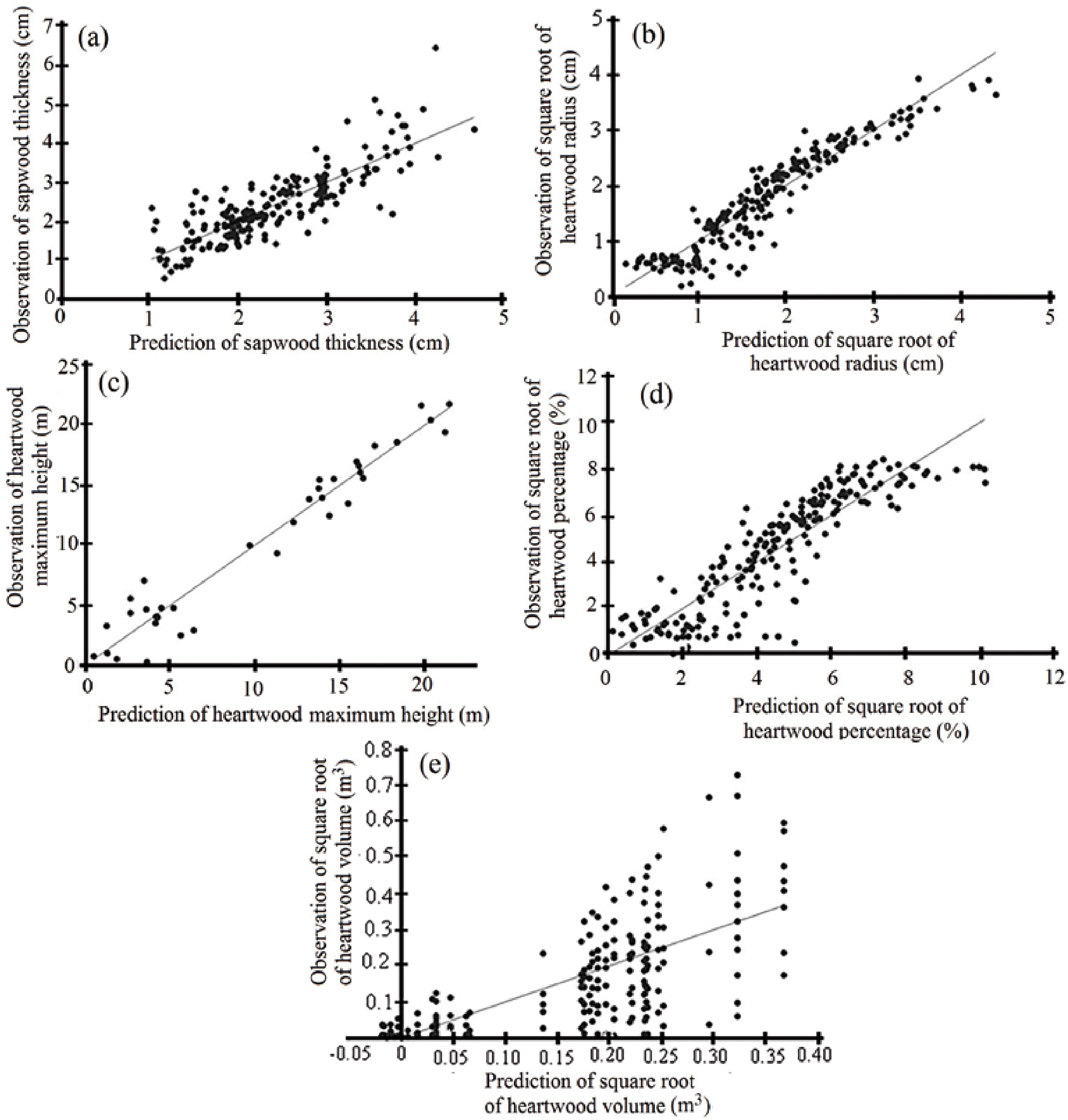

Figure 6.
Error distribution for prediction models: sapwood thickness (SWT) (a), heartwood diameter (HW_{radius}) (b), maximum heartwood height (c), percentage of heartwood ($HW_{percentage}$) (d) and heartwood volume (HW_{volume}) (e) for *Tectona grandis* trees from fast growth plantations in Costa Rica.

The $HW_{percentage}$ present in a cross-section was modeled based on the transformed variables of the multiple square root of SWT at 2.3 m, the HW_{radius} at 2.3 m, relative sampling height, total tree height and the height of sampling in the individuals, for a precision of 73% (model 4 in table III), being the least adjusted model. The distribution of the errors of the model, as shown in figure 6d, is not significantly adequate.

Finally, for HW_{volume}, the best fit was achieved with the inclusion of the transformed variables of the multiple square root of DBH and tree crown height (model 5 in table III). This prediction model accounts for 31% of the dependent variable, with a uniform distribution of the data error (figure 6e).

Bois et Forêts des Tropiques – ISSN: L-0006-579X
Volume 335 – 1st quarter - January 2018 - p. 25-37

Discussion

Sapwood variation along the trunk

The correlation between SWT and relative sampling height or height of sampling was not significant (figure 2a-b), which means that SWT is uniform in the tree trunk. These results agree with those affirmed in Moya *et al.* (2014), who hypothesized that SWT for different ages of trees of *T. grandis* is stable with height, varying from 2 to 5 cm in SWT. However, this study of SWT is lower than 0.5 to 6.5 cm.

Furthermore, from the results, it is important to note that two patterns of SWT variation are present according to the age of the trees: in trees from 2 to 10 years of age, more SWT is present than in trees between 11 and 22 years of age (figure 3a-b). The formation of heartwood occurs due to the death of parenchyma and the accumulation of substances (extractives) in the inner part of the tree, while the degree of formation is regulated by the physiological behavior of the enzymes in the region of the sapwood, a situation that is regulated by growth conditions (Taylor *et al.*, 2002). Thus, heartwood formation is a biochemical transformation occurring in an already existing tissue (sapwood). The wood cells are still the same in terms of position, dimensions and composition of the cell walls. Thus, the cell is still xylem that has lost its sap transportation and stocking functions (Taylor *et al.*, 2002). Although knowledge of the formation of heartwood is extensive in the case of conifers (Yang *et al.*, 1994), it is less so for tropical species (Taylor *et al.*, 2002) and very limited for teak trees from young plantations (Moya *et al.*, 2014). However, after applying the concepts developed by Taylor *et al.* (2002) in the present study, it is possible to affirm that the tree regulates its physiological processes to maintain sapwood, preventing the formation of heartwood during the first years of growth, since the tree invests its physiological processes in reaching a greater height quickly. Therefore, higher SWT is expected during the juvenile period (trees under 10 years of age) than in older trees, as found in the present study.

This same behavior was found by Pérez and Kanninen (2003), who in their study on *T. grandis* plantations 5 to 47 years old observed a greater proportion of sapwood in juvenile plantations, while as heartwood develops with age, SWT decreases until it reaches constant variation. Furthermore, Kokutse *et al.* (2004), in a study on the presence of heartwood in trees from different life zones in Togo, found that heartwood is already present in trees with diameters from 10 to 20 cm, while its transformation occurs between 11 and 13 years of age. On the other hand, the variation in SWT can be expected to decrease with the utilization of clone trees or of plantations with similar silvicultural management because the properties are uniform in clones (Moya *et al.*, 2013) or plantations with uniform management properties (Moya and Berrocal, 2010).

Age of formation and maximum height where heartwood is present

Early formation of heartwood was found in only two trees from plantations aged 2 to 3 years, unlike the rest of the trees of the same age (figure 4a). These two trees presented an average DBH of 9.9 and 9.4 cm, and the presence of heartwood was evidenced at the base of the tree instead of at DBH. Although a number of studies have addressed heartwood formation in *T. grandis*, few have studied in detail the age at which such formation starts. For example, Solórzano *et al.* (2012a and 2012b) found 12% heartwood on average at DBH in a four-year-old plantation of *T. grandis*, although the age at which heartwood formation started was not mentioned. This result contradicts the assumptions

Photo 3.
Variation of heartwood across the trunk in *Tectona grandis* trees of 18 years old (a) and the height at which the heartwood disappears (b) in *Tectona grandis* trees.

made by Moya *et al*. (2014), who suggested that the differentiation between sapwood and heartwood occurs between the ages of 4 and 6 years in fast-growth plantations, with diameters at breast height between 6 and 10 cm. Therefore, the results of this study suggest, along with other references, that heartwood formation begins at the age of 2 years at the base of the tree and that if there is more accelerated development of the diameter, such as 10 cm DBH, heartwood can begin its earliest formation at the base of the tree at the age of 2 years.

If comparing the age of appearance of heartwood in teak trees with that of other species, Hillis (1999), for example, describes the heartwood formation of some species of *Eucalyptus* at the age of 5 years. On the other hand, Gominho *et al*. (2001) found that in the variety *Eucalyptus grandis* x *E. urophylla* at 5-6 years of age in Portugal, heartwood is present in 65% of the total height of the tree. In natural *Pinus* spp. (Hillis, 1999), the formation of heartwood can start at 12 years old. This indicates that the fast-growth conditions of *T. grandis* trees produce an early appearance of heartwood by accelerating the physiological processes that transform sapwood into heartwood (Taylor *et al*., 2002).

Relationship between maximum heartwood height and some dasometric variables of the tree

The maximum heartwood height and HWrh relative to total tree height show a positive relationship to tree age (figure 5a-b). This result was to be expected, for as the tree ages, the height at which heartwood can be found increases (Yang *et al*., 1994). Anish *et al*. (2015) agree with the results of this study, indicating that heartwood growth increases with increasing age until reaching a maximum point in the tree height in fast-growth *T. grandis* plantations.

This study found that *T. grandis* heartwood reaches a maximum height from 0 to 90% (0.27 to 21.7 m) of total tree height (figure 4b). Gominho *et al*. (2001) observed for the hybrid *Eucalyptus urograndis* that the heartwood reaches up to 65% of total tree height in 5-year-old trees, slightly lower than in the present study. On the other hand, Gominho and Pereira (2000) found maximum heartwood height varying from 65 to 70% of total tree height in 9-year-old *E. globulus* trees, again a lower value than the maximum value found in *T. grandis* trees. Meanwhile, mature *Pinus radiata* (Wilkes, 1991) tree sampling found heartwood at 17.6 m in height, while in *Pinus pinaster* (Pinto *et al*., 2004) trees with mature ages between 42 and 83 years, heartwood was found even at a height of 20 m and in some branches. These references show an increase in the height at which heartwood disappears with tree age, suggesting that in the case of *T. grandis* trees, the maximum heartwood height is expected to increase with age, and heartwood could be present even in the branches.

Prediction models

The variation of the different parameters of heartwood observed within and between trees in this study demonstrates that HW_{radius}, maximum heartwood height, $HW_{percentage}$ and HW_{volume} are statistically predictable with the following variables: DBH, height of sampling, Hr, and total tree height (table III). On the other hand, SWT showed no variation regarding tree height when this parameter was evaluated in two age ranges (1-10 and 10-25 years) (figure 2a). However, the model can explain 70% of the variation in total tree height and relative sampling height (table III). Moya *et al.* (2014) did not define prediction models for SWT, as it remained invariable along the trunk, and they observed a category between 2 and 5 cm thickness for the different ages and heights. For that reason, their results are not consistent with those presented in this work. However, the predictions of the model can increase if the information comes from clone trees, where the variation decreases (Moya *et al*., 2013), or from plantations with similar silvicultural management because the properties are more uniform in managed than in un-managed plantations (Moya and Berrocal, 2010).

The variation of HW_{radius} can be explained at 89% by means of DBH, HW_{radius} at 2.3 m tree height, height of sampling, relative sampling height and total tree height (table III). García *et al*. (2011a and 2011b), as well as Moya and Marín (2011), showed a relationship between the heartwood diameter with respect to tree total tree height and tree age; however, they did not present prediction models, although their results are consistent with the tendency found in this study with respect to heartwood decreasing with height. The best adjusted modeling is maximum heartwood height, explained at 95%, which can be predicted using SWT at a tree height of 2.3 m, DBH and total tree height (table III). The maximum heartwood height is a hardly studied variable, and there is no explanatory model for *T. grandis* for different tree ages, heights and diameters (Moya *et al*., 2014). Climent *et al*. (2003) obtained a strong correlation of maximum heartwood height with the variables HW_{radius} at DBH and total tree height in *Pinus canariensis* growing in natural forests. This coincides with the relationships found for maximum heartwood height in this study on *T. grandis* with the variables DBH and total tree height (table III).

Of the variation in $HW_{percentage}$, 74% is explained by the SWT and HW_{radius} variables at the height of 2.3 m, height of sampling, relative sampling height and total tree height (table III). This trend coincides with the results of Miranda *et al*. (2011), who obtained the relationship between the decrease of $HW_{percentage}$ and the increase of the height of the tree. Finally, HW_{volume} at different heights is explained at 31% by means of DBH and height of crown (table III). According to Víquez and Pérez (2005), HW_{volume} correlates with DBH and total height of the trees, which can be affected by silvicultural management in *T. grandis* plantations, meaning that plantation management can help increase the HW_{volume}.

It is important to clarify that in this study on *T. grandis* trees, SWT and HW_{radius} were incorporated in some models at a tree height of 2.3 m because the sampled trees were obtained during a commercial cutting, and arrangements had not been made to extract discs at DBH. For a future variable prediction with the developed models, HW_{radius} and SWT at the height of 2.3 m can be obtained by means of a drill as a non-destructive technique to characterize standing wood.

Conclusions

SWT with respect to tree height in the plantation of *T. grandis* presented variations from 0.5 to 6.5 cm. Regarding the age of the plantation, it was observed that for juvenile trees between 2 and 10 years old, SWT (1.4 to 6.5 cm) is greater than for 11- to 22-year-old trees (0.5 to 3.2 cm).

The present study found that heartwood formation occurred between 2 and 3 years of age in *T. grandis* fast-growth plantations among trees of 10 cm DBH. However, heartwood formation starts at this age at the base of the tree but not at DBH height. Heartwood formation at DBH starts later, at 3-4 years of age. The maximum heartwood height in trees that presented heartwood growth is in the category of 0.27 to 21.7 m.

Prediction models were developed for sapwood thickness, heartwood radius, maximum heartwood height, proportion of the area of the heartwood and heartwood volume at different heights. Those models showed goodness of fit of 70%, 90%, 95%, 73% and 31%, respectively. These models can be incorporated by commercial plantations for more accurate data in heartwood production and thus for greater security in sawlog commercialization.

Acknowledgements
The authors wish to thank the Vicerrectoría de Investigación y Extensión at the Instituto Tecnológico de Costa Rica and all companies for the providing raw material and other assistance in carrying out this study.

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