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ORIGINAL PAPER

Development of heartwood, sapwood, bark, pith and specific gravity of teak (*Tectona grandis*) in fast-growing plantations in Costa Rica

Alexander Berrocal[1] · Johana Gaitan-Alvarez[1] · Róger Moya[1] · David Fernández-Sólis[1] · Edgar Ortiz-Malavassi[1]

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Abstract To elucidate the development of heartwood, bark, sapwood, pith and specific gravity of wood in fast-growing teak (*Tectona grandis*) plantations in Costa Rica, we sampled three trees in each of 55 plantations and modelled each variable with age, site and different tree heights. Age and stand density of plantations were significant correlated with stem diameter at breast height and total height of the tree. Formation of heartwood was initiated at the age of 4-year-old and increased in direct proportion with age. The age of plantation had a significant relationship with stem diameter at breast height, heartwood percentage, sapwood thickness, sapwood percentage, percentage of bark, pith diameter and percentage, and specify gravity. The model for these tree parameters was model with these parameters as dependent variable and in relation to age as independent variable.

Keywords Teak · Growth · Tree morphology parameters · Morphology · Tree development

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✉ Róger Moya
rmoya@itcr.ac.cr

[1] Instituto Tecnológico de Costa Rica, Escuela de Ingeniería Forestal, Cartago Apartado 159-7050, Costa Rica

Introduction

Teak (*Tectona grandis* Linn.f.) is native to India, Laos, Myanmar and Thailand (Gyi and Tint 1998). Teak wood is very durable and has good aesthetic qualities (Thulasidas et al. 2006), which makes it a valuable resource in the international market, that is why plantations of this species have expanded in tropical zones of Latin America, Asia, Africa and Oceania (FAO 2006). According to various estimates, approximately 4.35 million hectares of teak plantations have been established in 69 countries.

Rotation cycles of teak plantations vary from 15 to 30 years (Moya et al. 2014), contrary to the concept applied in the previous century in Asian countries, where rotations of 70 years or more were used (Moya et al. 2014). Trees in short-rotation plantations have a higher proportion of juvenile wood and low proportion of heartwood, has a lighter colour in trees in plantation than in natural forests. These characteristics in wood from plantation trees are considered less desirable than wood from natural forest trees (Moya and Marín 2011; Moya et al. 2014).

Heartwood formation in teak trees is controlled by diverse physiological processes, environmental conditions, soil fertility and genetic composition (Kampe and Magel 2013; Moya and Alvarado-Calvo, 2012; Moya and Berrocal, 2010; Moya et al. 2014). In general, a high proportion of heartwood and low proportion of sapwood make trees in general excellent for the sawlog industry and market development (Hegde et al. 2014). Because of these unique aspects of heartwood, much research has focused on the study of heartwood formation and variation during different growth stages, particularly in teak trees (Miranda et al. 2011; Moya et al. 2014; Anish et al. 2015; Kumar and Dhillo 2015).

Various models have been developed to describe the relationship between the heartwood of teak trees and variables such as diameter at breast height (DBH) and tree height (Ht) (García et al. 2011a, b). There are also models that relate the diameter and percentage of heartwood with tree age using DBH as a reference (Pérez and Kanninen 2003; Kokutse et al. 2004). Models for the formation of heartwood (diameter and percentage) at different tree heights have also been developed (Trockenbrodt and Josue 1999; Bhat et al. 2001; Pérez and Kanninen 2003). Despite these important studies, research has yet been be directed on the formation of the heartwood and other properties such as the thickness of bark, pith and sapwood in trees from fast-growing plantations at different ages, heights and stand densities (Moya et al. 2014).

Moya et al. (2014), in a recent review of the formation of heartwood formation in fast-growing teak plantations, suggested that heartwood formation starts when the tree is between 4 and 6 years old. This suggestion is supported by several studies, including one on 4-year-old teak trees by Solórzano et al. (2012b), who found heartwood made up 12% proportion of the stem at the base of the trees. Likewise, Moya et al. (2014) indicated that the thickness of the sapwood is not related to age, DBH or site conditions, and ranges between 2 and 5 cm. In addition, studies by Trockenbrodt and Josue (1999), Thulasidas and Bhat (2012) confirm that sapwood thickness is not related to DBH or height.

Another wood property worth evaluating due to its influence on other properties is specific gravity (SG) (Sinha et al. 2017), the ratio of the oven-dry mass of a piece of wood to the mass of water displaced by the wood at a given moisture content (Ross 2010). The SG of fast-growing trees shows no clear tendency, sometimes increasing, decreasing or remaining stable with various factors such as age, tree height, and site and is considered an intrinsic genetic characteristic of each species (Zobel and Van Buijtenen 1989; Moya et al. 2015; Tenorio et al. 2016). The relationship of SG with other silvicultural variables such as management, genetics, region and altitude are in some cases confusing and contradictory (Zobel and Van Buijtenen 1989; Tondjo et al. 2015).

Wood properties such as SG are also affected by climate and soil type (Cutter et al. 2007), which in turn affect heartwood formation, physical and mechanical properties, and the chemical composition of the trees in fast-growing teak plantations (Bhat et al. 2001; Pérez and Kanninen 2003; Kokutse et al. 2004; Bhat et al. 2005; Thulasidas and Bhat 2007).

A number of studies have shown that the variation of the SG of trees of fast-grown teak plantations in Costa Rica depends on the fertility of the soil (Alvarado and Fallas 2004; Moya et al. 2009), tree age (Moya and Marín 2011), different clonal origin (Moya and Marín 2011; Moya et al. 2013). Conversely, other studies by Moya and Pérez (2008) found that the properties of the soil do not influence the physical and chemical properties of teak. Pérez and Kanninen (2005), on the other hand, concluded that the SG does not relate to the site conditions where the trees are grown. The studies showed that they are specific to these conditions, not for a behaviour by age or H_t of the tree, so as to show the variation of the trees under these two conditions in Costa Rica.

Despite being a small country, Costa Rica has a significant area reforested with teak. The soils in Costa Rica are variable with regard to fertility (Bermejo et al. 2004) and climate conditions; precipitation, in particular, is changeable from one site to another, even in close vicinity (Clark et al. 2010). Another aspect of teak plantations in Costa Rica is that it is possible to commercialize the wood at a very early age (4–5 years) up to the end of its rotation (18–25 years) (ONF 2015). Other important uses for teak from thinning interventions is the production of panels or blockboards, which is used locally for the construction of low-cost furniture, floors and other important uses (Moya and Pérez 2007).

In addition to the large area occupied by teak plantations in Costa Rica, approximately 4000 ha (ONF 2016), plantations also have been established in areas with variable climatic and fertility conditions. Another characteristic is that the plantation are harvested at early age. Yet, there is a lack of information on the development of the heartwood and other morphological variables for trees in these fast-growing plantations. Therefore, the objective of the present work is to study the effect of diameter, height, thickness and percentage of heartwood and sapwood, bark and pith, and SG in trees at different ages in the teak plantations in Costa Rica.

Methods and materials

Study area

Fifty-five fast-growth plantations of *Tectona grandis* (teak) were sampled in different parts of Costa Rica: (1) North Pacific, (2) Central Pacific, (3) South Pacific, (4) Atlantic Zone, (5) Northern Zone. Although these parts of Costa Rica present five climatic conditions (IMN 2017), teak plantations are not planted uniformly across those regions; the North Pacific and Northern zones are more important for commercial plantation area (ONF 2016). In addition, teak plantations are not planted in the Central Valley because its altitude is over 800 m a.s.l., where it is not convenient to plant teak trees (Fernández-Sólis et al., 2018). Thus, it was not possible to sample the any plantation in all regions. The plantations sampled represented different ages, from 2 to 22 years, and plantation density.

Plantation, tree characteristics and sampling

Total height (H_t) and the diameter at breast height (DBH) were measured in each sampled plots. Each temporary sample plot had a 13-m radius (531 m^2), in which all trees were measured for its DBH and Ht. The stand density of the plantations was determined using data from the sample plot, where the number of trees in the temporary plot was divided by plot area (531 m^2) to obtain the density (trees/m^2). This value was multiplied per one hectare (10,000 m^2) to extrapolate trees per hectare.

From each plantation, three straight, defect-free (a tree healthy without any disease or deformation) trees were randomly selected and felled. In total, 155 trees were sampled and DBH and H_t measured for each trees. A disc approximately of 4 cm thick was cut at the base of the tree, and additional discs were taken every 2.3 m interval from the base to the tree top.

Determination of physical and mechanical properties

Heartwood diameter ($H_{W\varnothing}$), sapwood thickness (S_{Wth}), bark thickness (B_{arkth}), pith diameter ($P_{ith\varnothing}$), were measured, and the percentage of heartwood (H_W%), sapwood (S_W%), bark (B_{ark}%) and pith (P_{ith}%), estimated for each disc (Fig. 1). To estimate the H_W%, the area and disc area were calculated by measuring four radii at right angles to one another, and the four measurements were averaged for each disc. The B_{ark}% was calculated as the difference between disc area with bark and disc area without bark. The S_W% was calculated as the difference between disc area and sum of H_W% and B_{ark}%. If no heartwood was present, that was noted, and S_{Wth} was estimated as the difference between the disc diameters without bark and $H_{W\varnothing}$ (Fig. 1) divided by two, according to the method of Wilson and Witkowski (2003).

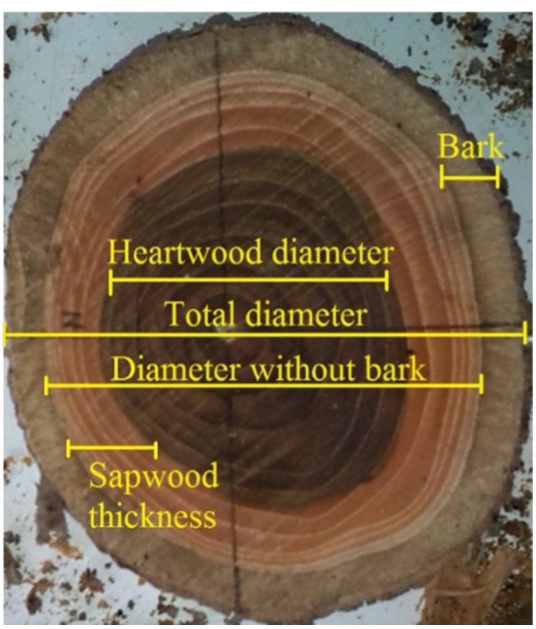


Fig. 1 Variables measured in cross section of trees of *Tectona grandis*

Specify gravity (S_G) and B_{ark}% were measured for the same wood discs. For measuring wood S_G, diametrical segments were cut along the center of each disk and divided into two subsamples (Moya and Muñoz 2010). The pith tissue is excluded from samples, because it is small core of primary parenchyma tissue formed by the apical meristem at the growing tip (Akachuku and Abolarin 1989) and the author believe that this tissue can affect the wood material of sample. The pith is observed easily in the cross-section stem by a hole, approximately from 1.0 to 3.0 cm (Moya and Pérez 2008) *SG* of wood was calculated as the ratio between oven-dry weight and green volume each subsample (ASTM 2003). The green volume was measured by water displacement method (Olesen 1971).

Statistical analyses

All the measured variables for checked for the normality and homoscedasticity and studied the variability with respect to age and plantation density. Different linear regression models were carried out using DBH and H_t (Table 1). Linear regression model was again applied to other variables (S_W%, B_{arkth}, B_{ark}%, P_{ith}%, S_G) of the trees using the measurements obtained at a height of 2.50 m, and only tree age as the independent variable (Table 2). Other variables were not considered because only variation with tree age was of interest.

Statistics such as coefficient of determination, standard error, *F*-value and coefficient of variation were used to evaluate the model. A *p* value of 0.05 was used as the significance level. In addition, residuals errors were plotted with the independent variable to see the tendency and behavior of these errors. The models were obtained using Excel and Statistica software.

Results and discussion

Teak morphology in Costa Rica

DBH and H_t variation with respect to age adjusted better with the linear regression models (Table 2). In addition, the

Table 1 Regression statistics for diameter at breast height and total height in *Tectona grandis* trees from plantations in Costa Rica

Variable	Model	R^2	R^2 adjusted	S_{xy}	F-value	C_V (%)
DBH	$y = 16.59 + 0.\ A_{ge} - 0.006$ (stand density)	0.64	0.63	3.64	45.29	16.93
Height	$y = 18.22 + 0.\ A_{ge} - 0.006$ * (stand density)	0.57	0.56	3.24	34.13	17.29

S_{xy} standard error, C_V coefficient of variation, A_{ge} is Age

Table 2 Regression models and statistics for heartwood, sapwood, bark, pith, and specific gravity for *Tectona grandis* trees

Variable	Model	R^2	R^2 adjusted	S_{xy}	F-value	C_V (%)
Heartwood diameter	$y = 0.31 + 0.95\ A_{ge}$	0.60	0.60	4.07	192.41	38.01
Percentage of heartwood	$y = 1.21 + 2.85\ A_{ge}$	0.65	0.65	10.93	239.58	33.79
Sapwood thickness	$y = 3.49 - 0.07\ A_{ge}$	0.26	0.25	0.65	44.35	24.34
Percentage of sapwood	$y = 68.32 - 2.22\ A_{ge}$	0.59	0.59	9.74	183.25	22.11
Bark thickness	$y = 0.82 + 0.02\ A_{ge}$	0.18	0.17	0.28	27.48	25.57
Percentage of bark	$y = 30.48 - 0.63\ A_{ge}$	0.34	0.34	4.61	65.59	19.54
Pith thickness	$y = 0.99 - 0.004\ A_{ge}$	0.01	0.01	0.25	1.02	26.46
Percentage of pith	$y = 0.92 - 0.05\ A_{ge}$	0.39	0.39	0.30	83.05	73.30
Specific gravity	$y = 0.43 + 0.01\ A_{ge}$	0.23	0.23	0.06	39.64	11.76

S_{xy} standard error, C_V coefficient of variation, A_{ge} Age

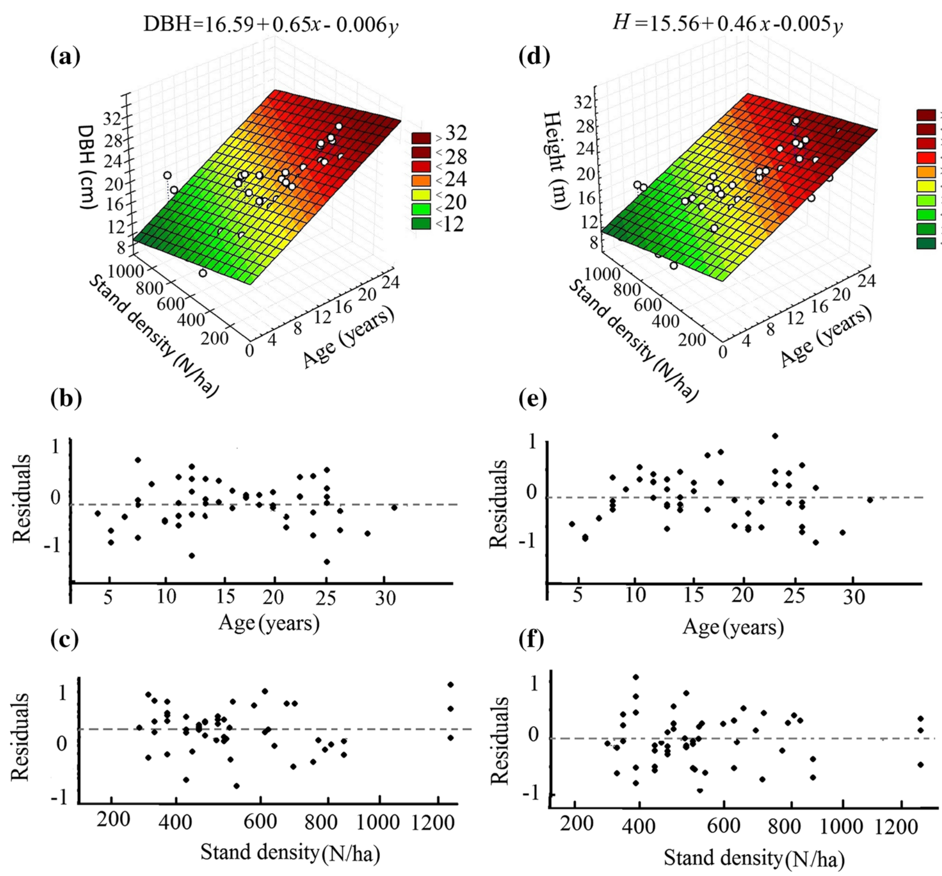


Fig. 2 Relationship of diameter at breast height with stand density and age (**a**), relationship of total height with stand density and age (**b**), error distribution of the diameter at breast height model (**c**) and residual distribution of the total height model (**d**)

DBH and H_t were significantly correlated to the age and stand density (Table 1). The model statistics indicate that age and stand density explain 64% of the DBH and 57% of the H_t (Table 1). Figure 2 shows the response of DBH and H_t in relation to the two correlated variables. The remainders of both models, for age and for stand density were acceptable, since the residual errors do not present any pattern and their distributions are completely randomized for relationships DBH versus stand density, DBH versus age, H_t versus stand density and H_t versus age (Fig. 2c, d).

In other studies however, strong correlations have been observed between DBH and H_t and stand density (Huang and Titus 2000), which is supported by the fact that H_t depends on one of two fundamental trade-offs, involving shifts with tree H_t in dry-mass allocational allometry or photosynthetic hydraulic limitations (Givnish et al. 2014).

In plantations for timber production, H_t, DBH and stand density commonly influence volume production (Sumida 2015), as was found in the case of teak trees in the plantations in Costa Rica (Fig. 3a, b). The influence of stand density on H_t is due to higher competition for nutrients and minerals necessary for tree growth (Monserud and Sterba 1996; Pérez and Kanninen 2005). Kanninen et al. (2004), simulating different scenarios of density in teak plantations in Costa Rica, found that the DBH changes in plantations depending on the stand densities, thus agreeing with the present study (Table 1).

Heartwood variation in trees in fast-growth teak plantations

Age explained 60% of $H_{W\varnothing}$ and 65% of H_W% at 2.50 m (Table 2). Both variables tended to increase as the age of the tree increased (Fig. 3a, b). The remainders of both models are acceptable, since they show no tendency and are completely randomized.

Figure 4 shows the variation in $H_{W\varnothing}$ and H_W% with age and at different heights. The highest values were found in the oldest trees and in the lower parts of the trees, while young trees had the lowest $H_{W\varnothing}$ and H_W%. At the age of 4 years, a small proportion of heartwood was observed in the lower part of the tree. The lack of heartwood at higher tree heights was also observed at different ages, i.e., at the age of 8 the heartwood is absent at approximately 8 m, in 20 years, it is absent at 16–18 m (Fig. 4).

$H_{W\varnothing}$ and H_W% showed that the heartwood started to develop approximately at 4 years, coinciding with the results of Solórzano et al. (2012a, b) and Trockenbrodt and Josue (1999) in teak produced in Costa Rica and Malaysia, respectively. With regard to the increment of $H_{W\varnothing}$ and H_W% with increasing age (Fig. 3a, b) and decreasing height of the tree (Fig. 4a, b), it also coincides with other studies (Pérez and Kanninen 2005; Miranda et al. 2011; García et al. 2011a, b). Heartwood formation results from the death of the parenchyma and accumulation of substances (extractives) in the inner part of the tree and is regulated by the physiological behavior of the enzymes in the sapwood, which in turn is regulated by growth conditions (Taylor et al. 2002). Knowledge about heartwood formation is scarce in tropical species (Taylor et al. 2002) and very limited for trees growing in fast growth conditions

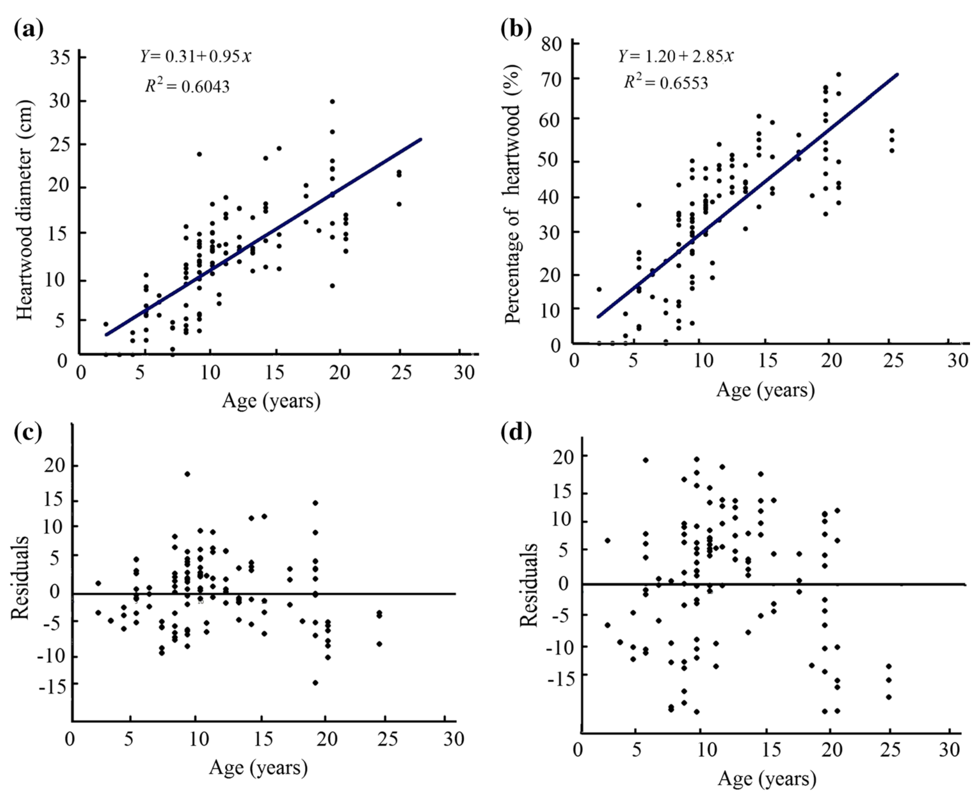


Fig. 3 Relationship of heartwood diameter with age (**a**), relationship of percentage of heartwood with age (**b**), error distribution of the heartwood diameter model (**c**), and residuals distribution of percentage of heartwood model (**d**) at 2.50 m height

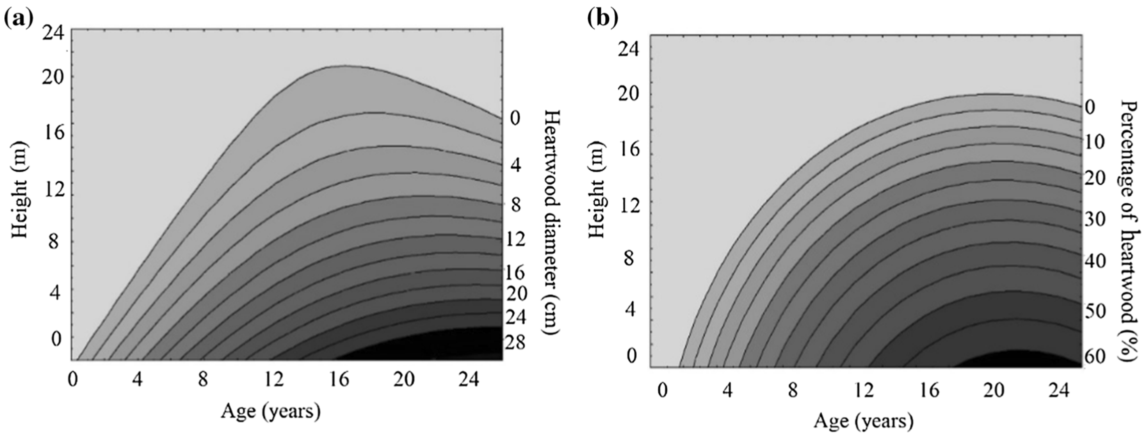


Fig. 4 Relationship of heartwood diameter with age at different heights (**a**) and percentage of diameter with age at different heights (**b**)

(Moya et al. 2014). However, different studies about heartwood formation suggest that with tree aging, many chemical modifications occur in the components and in the sapwood substances, which are stored in the sapwood–heartwood boundary, which subsequently form the heartwood (Taylor et al. 2002; Moya et al. 2014). This process occurs throughout the entire tree, and this limit is more distant each year from the pith; when the heartwood is formed, $H_{W\varnothing}$ and $H_W\%$ increase in the different tree heights (Figs. 3a, b, 4a, b).

Sapwood variation

The models developed for sapwood variables, S_{Wth} and $S_W\%$, showed a moderate correlation with age (Table 2, Fig. 5). The remainders for this model showed an adequate distribution (Fig. 5b). $S_W\%$ decreased with age (Fig. 5) with 59% of the correlation; the rest of the correlation may be related to other variables not studied in the present paper.

The relation of $S_W\%$ with tree age (Table 2; Fig. 5a) agreed with the results of Thulasidas and Bhat (2009) and Bhat (2000) in teak planted in India, and in older trees from plantations in Costa Rica (Pérez and Kanninen 2003).

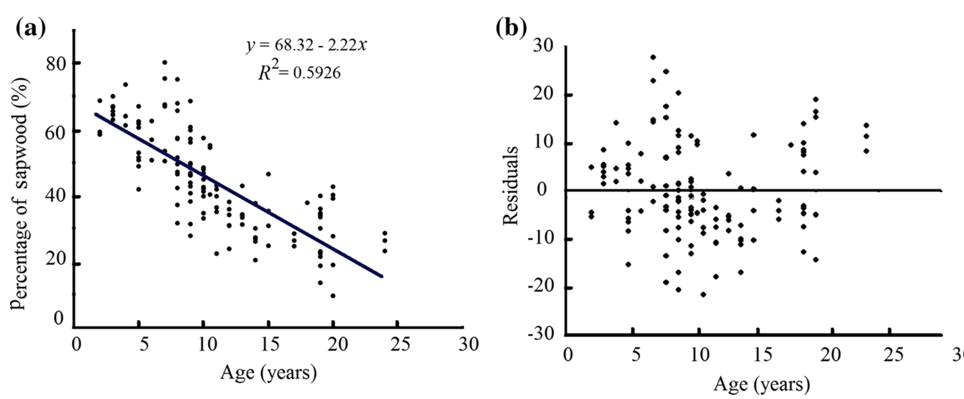
Sapwood contains living cells that carry the transpiration water, and it contains energy reserves (starch) (Taylor et al. 2002; Gartner 1995). And sapwood was found to be more abundant in juvenile wood than in older trees (Fig. 5a).

Bark variation

The models developed for the variation in bark variables, B_{arkth} and $B_{ark}\%$, showed that age did not influence B_{arkth} at 2.50 m height (Table 2). With increasing age, $B_{ark}\%$ decreased (Fig. 6a), and the remainders in this model showed adequate distribution (Fig. 6b).

The correlation of B_{arkth} with tree age at 2.50 m was low (Table 2). However, $B_{ark}\%$ had a negative correlation with age (Table 2, Fig. 6a) as found in teak trees in Costa Rica between 5 and 47 years of age (Pérez and Kanninen (2003) and in teak trees in plantations in Karnataksa (India) between 11 and 36 years of age (Prasad and Mariswamy 2013). However, Pérez and Kanninen (2003) reported that in trees over 30 years old, the $B_{ark}\%$ stabilizes at 20%, although we could not confirm this finding because the maximum age we studied was 22 years.

Fig. 5 Relationship of the percentage of sapwood with age (**a**) and residual distribution of the percentage of sapwood thickness model (**b**) at 2.50 m height



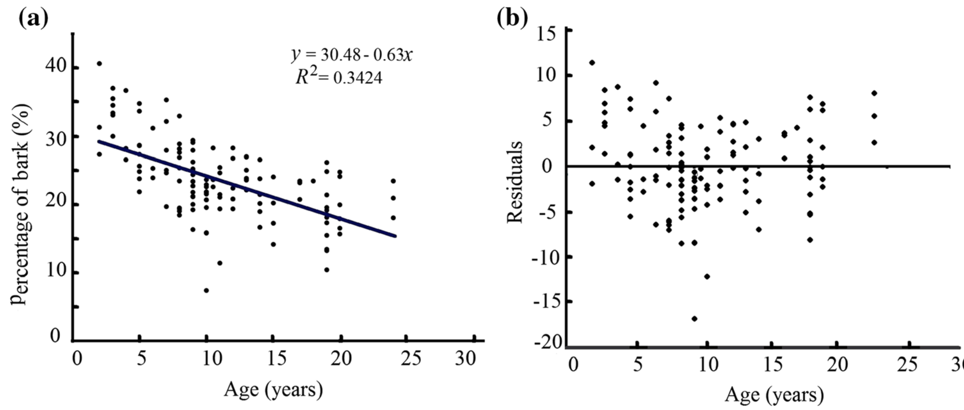


Fig. 6 Relationship of percentage of bark with age (**a**) and residual distribution of percentage of bark model (**b**) at 2.50 height

Wilson and Witkowski (2003) explained that in mature trees, greater B_{arkth} is needed to protect the trees from fire, insect attack and other factors. But bark thickness in relation to cross-sectional area, Bark% decreased (Fig. 6a); however, decreasing $B_{ark}\%$ does not mean lack of protection because B_{arkth} increasing.

Pith variation

The models developed for variation in pith variables, Pith diameter$_{\varnothing}$ and $P_{ith}\%$, also showed a negative relationship with age (Table 2, Fig. 7).

Archer (1986) suggested that the stress of growth in the tree is reflected in tree age and increases as the diameter increases, producing greater compression on the pith. This strength can reduce the diameter of the pith as the tree ages, as found for the trees in teak in the present study (Table 2, Fig. 8a), particularly in the lower section of the tree (Moya et al. 2008).

The change in $P_{ith\varnothing}$ and $P_{ith}\%$, at different heights and ages increased under 12 m and decreased above 12 m height, $P_{ith\varnothing}$ in particular. This situation occurred in trees of all ages. The same tendency was observed by Moya et al. (2008) in *Gmelina arborea* trees aged between 8 and 14 years planted in different sites in Costa Rica. Research has shown that a high percentage of pith diminishes the quantity and quality of wood from teak sawlogs (Moya et al. 2014).

Specific gravity

SG was positively correlated with tree age (Table 2, Fig. 8a) and tended to increase close to the pith and decrease near the bark (Jayawardana and Amarasekera 2009; Sinha et al. 2014, 2017), as shown in Fig. 1 and in other studies on teak trees in Costa Rica (Moya and Pérez 2008; Solórzano et al. 2012a, b). In general, for many species, specify gravity increases with tree age or from the bark inward to the pith (Zobel and Van Buijtenen 1989; Woodcock and Shier 2002; Wiemann and Williamson 2007). On the other hand, the diminution of *SG* with height is not clearly established, since there is significant variation among different species (Zobel and Van Buijtenen 1989).

Management aspects

The objective of a teak plantation is to obtain the maximum proportion of heartwood and less sapwood, because heartwood is the most important part of the wood to export and is the part of the tree with the highest market value (Moya et al., 2014). Teak plantations are subject to different management practices in Costa Rica, but all are

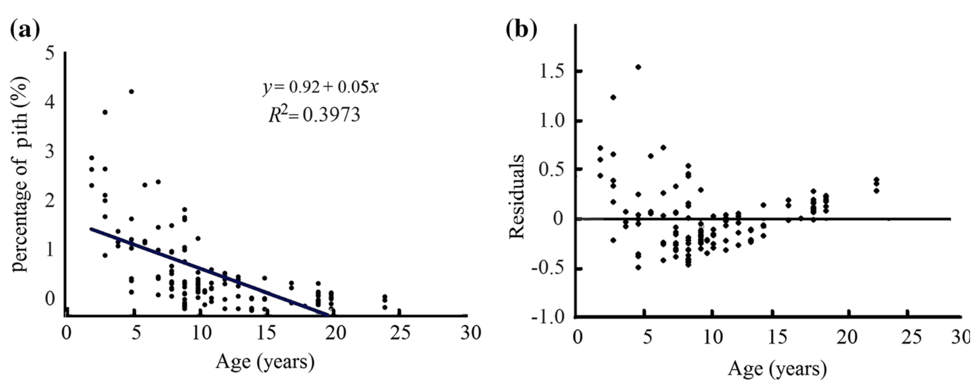


Fig. 7 Relationship of percentage of pith with age (**a**) and residual distribution model of percentage of pith (**b**) at 2.50 height

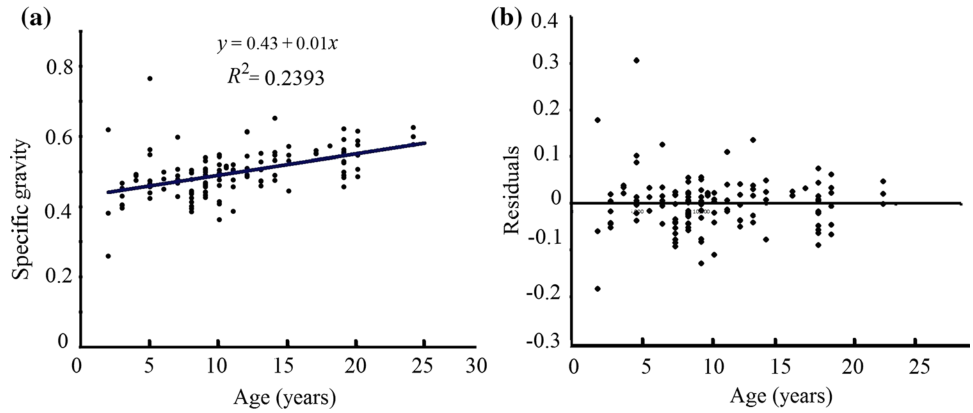


Fig. 8 Relationship of specific gravity with age (**a**) and residual distribution of the specific gravity model (**b**) at 2.50 m height in *Tectona grandis*

designed for maximum development in diameter and thus high heartwood proportions to increase wood quality and economic return of the plantation. Toward this goal, the present study described the general state of teak plantations in Costa Rica to visualize the production of this heartwood in the country.

Conclusions

Tree age and density of the plantation showed a significant statistical relationship with DBH and total height. The measurements of the heartwood ($H_{W\varnothing}$ and $H_W\%$) showed that heartwood formation in teak started at the age of 4, continuing with age, concentrated especially in the lowest sections of the tree. S_{Wth} remained constant along the tree, while in the juvenile period, the $S_W\%$ will be greater than in adult stages. $B_{ark}\%$ is high at the base of the trees. $P_{ith\varnothing}$ showed no relationship with the age of the trees, but $P_{ith}\%$ decreased with growth of the tree. The *SG* had a positive correlation with age, given by tree aging.

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