Heartwood, Sapwood and Bark Content, and Wood Dry Density of Young and Mature Teak (*Tectona grandis*) Trees Grown in Costa Rica

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The aim of this study was to evaluate the heartwood, sapwood and bark content, and wood dry density in young and mature teak (*Tectona grandis*) trees. For this, 17 plantations were selected from 11 sites representing different climatic conditions and plantation densities (156 to 1600 trees ha^{-1}, and line planting). From these plantations, a total of 87 trees with ages between 5 and 47 years were felled for stem analysis.

The highest heartwood proportion of stem volume (over bark) was 61% and the lowest 0.4%. The sapwood proportion ranged between 24 and 72%, while bark represented from 14 to 37% of the total volume. Heartwood proportion was significantly different ($P<0.05$) among climatic zones: 'wet' sites producing less heartwood than 'dry' sites. Stem diameter (under bark) and heartwood diameter at different stem heights differed among sample trees, even when plotted in relative values to avoid dependency with stem size.

Dry density was statistically different between 8-year-old trees or younger and 47-year-old trees, and between line planting trees and 13-year-old trees or younger, but did not differ statistically between line planting trees and mature trees. No significant differences were found between climatic zones or between different stand densities. Dry density values for *T. grandis* plantations in Costa Rica are similar to those reported elsewhere.

Keywords cross-sectional area, relative stem curves, stand density, stem analysis
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1 Introduction

Fast growing and high yielding forest plantations are becoming an important source of wood in the tropics. In these areas, where the economy is based on agricultural and forest activities, the need to increase wood productivity is of primary importance. When selecting tree species for large plantation programs, reforestation projects should consider not only the survival and growth of trees, but the quality and utilization potential of the promising tree species (Laurila 1995). For fast growing species in particular, these criteria are of great importance, since commercial dimensions are reached in a relative short period and the wood quality may be lower than expected. The estimation of heartwood content helps to define differences in durability and other wood characteristics, while dry density is considered as an indicator of timber strength (Wiemann and Williamson 1989, Bhat 1995).

Tectona grandis has gained a worldwide reputation on account of the attractiveness and durability of its wood. Market demands have prompted the establishment of plantations within and beyond its native countries (Hoare and Patanapongsa 1988, Monteuuis and Goh 1999, Bhat 2000). Approximately 223 000 ha of *T. grandis* plantations have been established in Central America (Pandey and Brown 2000). In Costa Rica, reports indicate that teak plantations cover 40 000 ha (Arias and Zamora 1999).

During the last two decades, the Costa Rican government has promoted the establishment of high-yielding and high-quality-timber of teak plantations. However, the scenario for this species has turned out to be uncertain, since wood quality and yield are found lower than anticipated. Therefore more knowledge about wood properties of young and mature plantations is necessary. High proportions of heartwood and high dry density are the two most desired wood characteristics for plantation grown teak (Tewari 1999, Baillères and Durand 2000).

Several studies report on heartwood content and variations in wood dry density, from pith to bark, with stem height, with age, with stand density, and with climatic conditions for teak in different countries (Nair and Chavan 1985, Bhat 1995, Brennan and Radomiljac 1998, Trockenbrodt and Josue 1998, Priya and Bhat 1999, Bhat et al. 2001). A few similar studies have been carried out for younger teak (< 10 years) in Costa Rica and documented by Moya (2000), Arce (2001), Moya (2001b), as well as for mature teak (26 years), documented by González et al. (1979). Nevertheless, more research is needed to evaluate differences in wood properties of young and mature *T. grandis* plantations growing on different climatic zones of the country.

The aim of this study is to evaluate the heartwood, sapwood and bark content, as well as wood dry density of young and mature teak trees. The hypothesis was that heartwood content and wood dry density increase with increasing age, and that both are higher in the 'dry' zone (sites with more than 5 months with a precipitation less than 100 mm) than in the 'wet' zone. This hypothesis was based on the common believe in Costa Rica that teakwood from 'dry' sites is of higher quality (e.g. higher content of heartwood, higher density, darker color) than that of 'wet' sites.

2 Materials and Methods

The material was collected from plantations in private farms of different zones of Costa Rica (Fig. 1). For this study 17 plantations were selected from 11 sites covering different climatic conditions (Table 1) and plantation densities (156 to 1600 trees ha^{-1}). Line planting trees, i.e. trees planted in lines to serve as living fences or wind breakers, were also harvested with the aim of evaluating the characteristics of such teak trees that grow up under totally different competition levels. A total of 87 trees with ages between 5 and 47 years were felled for stem analysis. A larger sample was intended, however advance-aged teak plantations are scarce in Costa Rica and private owners allowed the harvesting of only few trees. From each plot, one to three individuals with average DBH were selected for harvesting. The dry density was determined from all the 11 sites (32 trees); heartwood, sapwood and bark content were measured in 70 trees of sites 1 to 9.

Stem cross-sectional samples (disks) were taken from each felled tree at 0.3 m and at 1.3 m from the base. Starting the height of 2.0 m, sec-

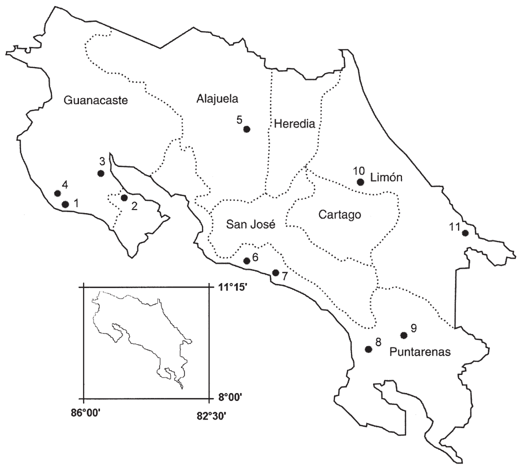

Fig. 1. Location of the sites where teak plantations were evaluated in Costa Rica. For site codes see Table 1.

tions were taken along the stem at 2.0 m intervals. Firstly, heartwood mean diameter was calculated as the average of two cross-sectional measurements (direction North-South and East-West) for each stem section. Secondly, total mean diameter (with and without bark) was calculated following the same procedure. Next, heartwood, sapwood and bark cross-sectional area (cm^2) were calculated as geometric circle. Finally, the total volume (cm^3) of sapwood, heartwood and stem (with and without bark) was calculated using the Smalian formulae (Clutter et al. 1983). The last stem section from the last-taken disk to the tip of the tree was calculated as a geometric cone.

Wood dry density was determined using wood samples of stem sections ($4 \times 2 \times 12$ cm) taken at the base of the tree and at the base of the living crown. The volume of each sample was determined from the volume of water it displaced when submerged, according to ASTM standard norms (ASTM 1986). Dry density was calculated as oven-dry weight divided by oven-dry volume (105 °C, 48 hours).

Linear and non-linear regression analyses were used to determine the relationship of heartwood, sapwood and bark content, and wood dry density with tree age, DBH, stand density, and geographic location (plantation sites). The best-fit models were selected based on the criteria of the model's biological logic, the adjusted coefficient of determination (r^2), and root mean square error (RMSE) of the fitted equation (Parresol 1999). The equations developed to explain the variation of the heartwood proportion and dry density with age were used to eliminate the effect of tree age in further analyses. Analysis of variance (ANOVA) was carried out in Systat 6.0 to evaluate the variations in heartwood content and wood dry density with age, stand density, and sites.

Table 1. General data of the research sites in Costa Rica where teak trees were harvested.

Site code	Location	Precipitation (mm year^{-1})	Dry months[a)]	Elevation (m)	Mean annual temperature (°C)	Sampled trees (n)	Stand density (trees ha^{-1})	Age[b)] (years)
1	Carrillo	1659	6	100	26.1	4	667–736	8–10
2	Jicaral	1659	6	85	26.8	2	333–750	11–18
3	Tempisque	1901	6	30	27.1	6	389	14–20
4	Garza	2205	6	90	25.9	33	816	6
5	San Carlos	3393	1	90	26.1	24	640–1600	7
6	Parrita	3117	3	25	26.0	4	156–541	13–47
7	Quepos	3900	3	70	25.9	2	775	19
8	Palmar Norte	3644	3	80	27.0	1	893	23
9	Buenos Aires	3627	4	300	27.0	1	357	27
10	Guapiles	4107	0	250	26.0	8	494–896	5–12
11	Cahuita	3000	0	50	26.0	2	Lines[c)]	9

a) Months with rainfall less than 100 mm.
b) Single age entry means that sampled trees were of same age (does not mean average age).
c) Trees planted in lines at a distance of 3 meters one from the other.

3 Results

The highest heartwood proportion of total tree volume was 61% with the lowest values of 0.4%. The proportion of sapwood ranged between 24 and 72%, while bark represented from 14 to 37% of the total volume. Heartwood proportion increased with increasing age, while the proportion of sapwood and bark decreased (Fig. 2). Similar tendencies were observed between heartwood, sapwood and bark proportion and DBH; however they showed a sharper tendency with DBH than with age (Fig. 3).

Tree total volume and heartwood increased exponentially with increasing DBH, while sapwood and bark content increased more linearly (Fig. 4). However, heartwood proportion (%) decreased with increasing stand density (Fig. 5a), even after eliminating the effect of age by using the equation on Fig. 2 (Fig. 5b), as the younger plantations had higher stand densities than the older ones. Significant differences in heartwood proportions were found between stand densities lower than 800 trees ha^{-1} and the stand density of 1600 trees ha^{-1}.

Cross-sectional area of heartwood, sapwood, and bark at various stem heights varied considerably among sampled trees of different size.

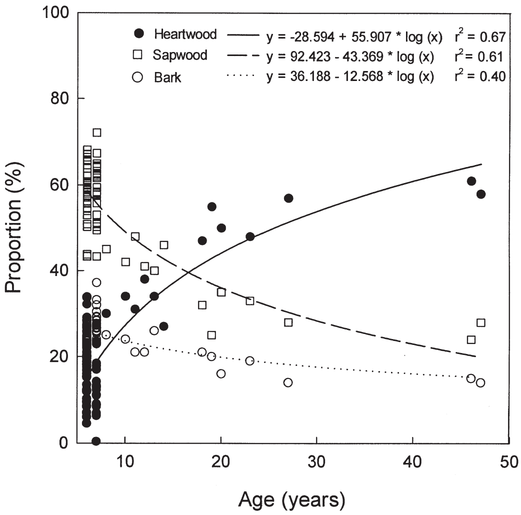

Fig. 2. Proportion of bark, sapwood, and heartwood of total tree volume at different ages for teak in Costa Rica.

Without a sharp tendency, heartwood proportion decreased with increasing stem height, varying between 0 and 60%, while sapwood proportion increased, varying between 15 and 85%. Bark proportion remained constant, ranging between 10 and 35%.

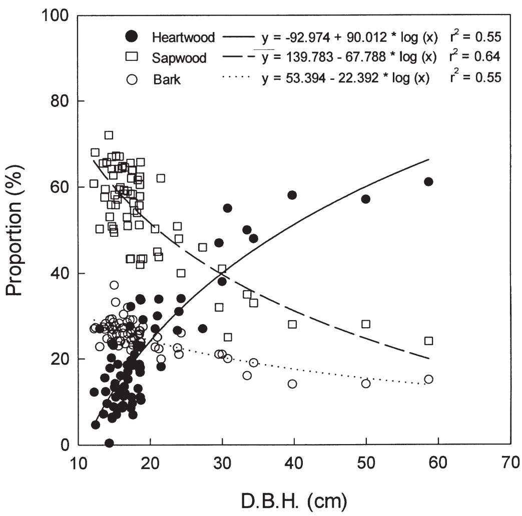

Fig. 3. Variation of bark, sapwood, and heartwood proportion of total tree volume with DBH for teak in Costa Rica.

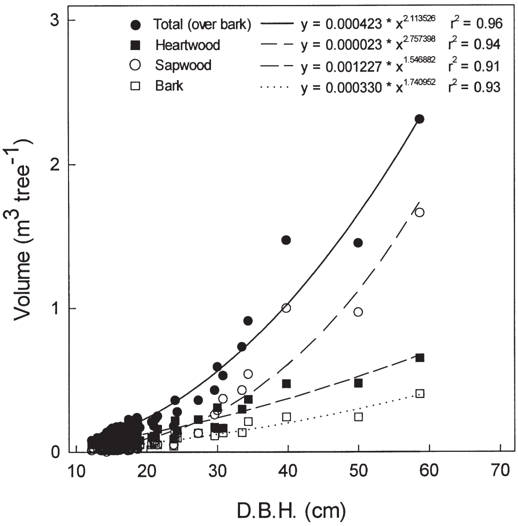

Fig. 4. Relationships between total, sapwood, heartwood, and bark volume with DBH of teak in Costa Rica.

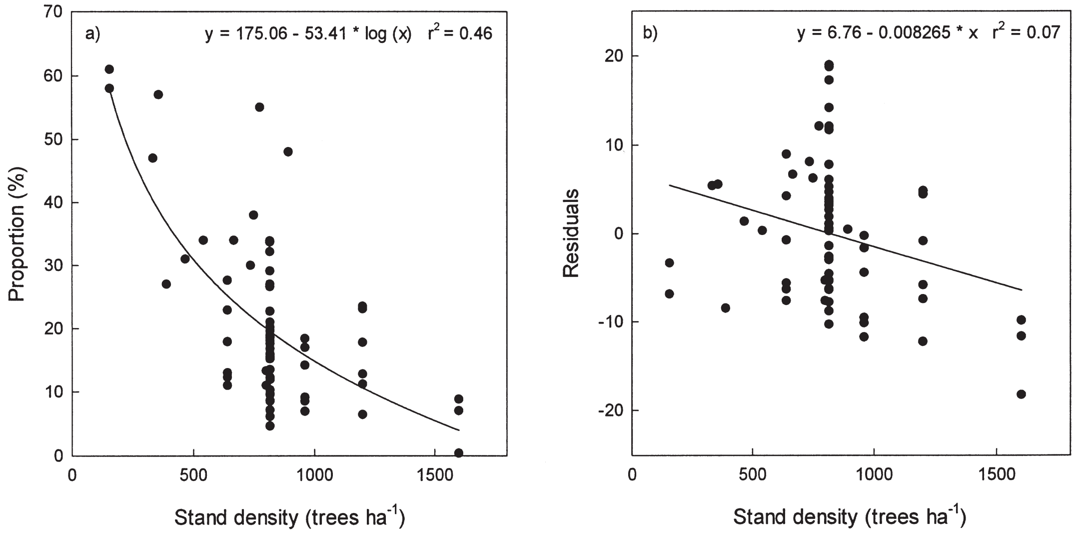

Fig. 5. Relationships between a) heartwood proportion of total tree volume, and b) residuals from the regression between heartwood proportion and age (from Fig. 2), and stand density for teak in Costa Rica.

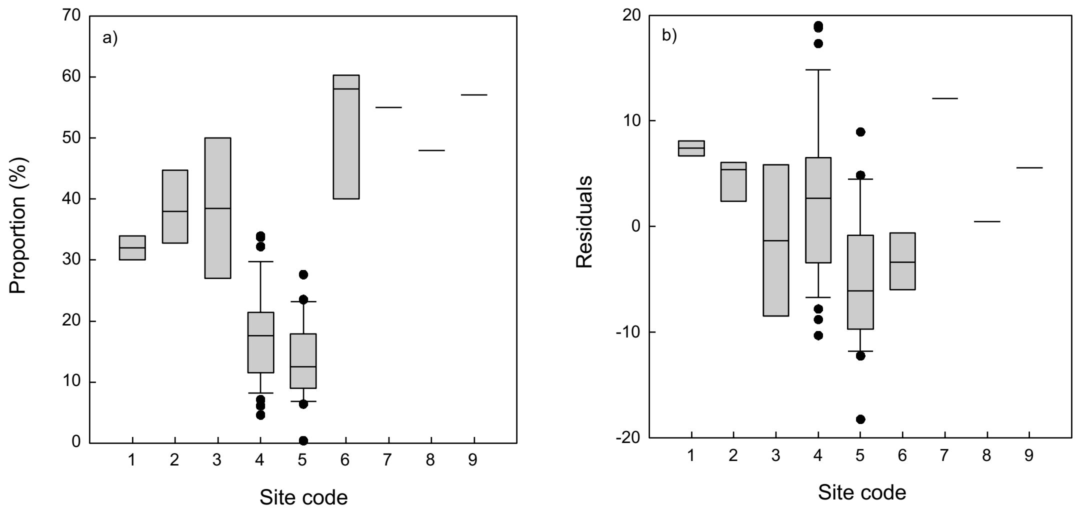

Fig. 6. Variation of a) heartwood proportion of total tree volume, and b) residuals from the regression between heartwood volume and age (from Fig. 1), in different sample sites for teak in Costa Rica. For site codes, see Table 1.

The heartwood proportion of total tree volume varied among sample sites (Fig. 6a). First, the 'dry' sites (sites from 1 to 4) presented non-significant differences in relation to the 'wet' sites (sites from 5 to 9). Then it was suspected that this result was influenced by age, since older plantations were on 'wet' sites; therefore the influence of age was eliminated by using the equation in Fig. 1 and the residuals compared between sample sites (Fig. 6b). Contrary to the previous results,

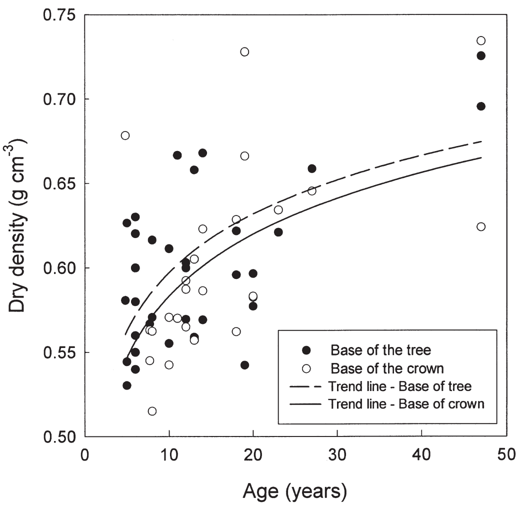

Fig. 7. Relationship between dry density (at the base of the tree and at the base of the crown) and age for teak in Costa Rica.

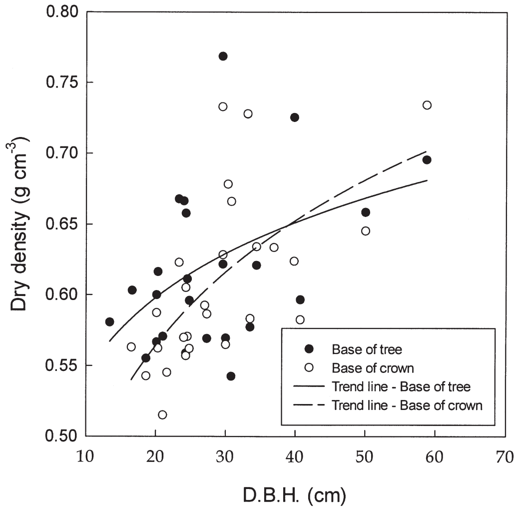

Fig. 8. Relationship between dry density (at the base of the tree and at the base of the crown) and DBH for teak in Costa Rica.

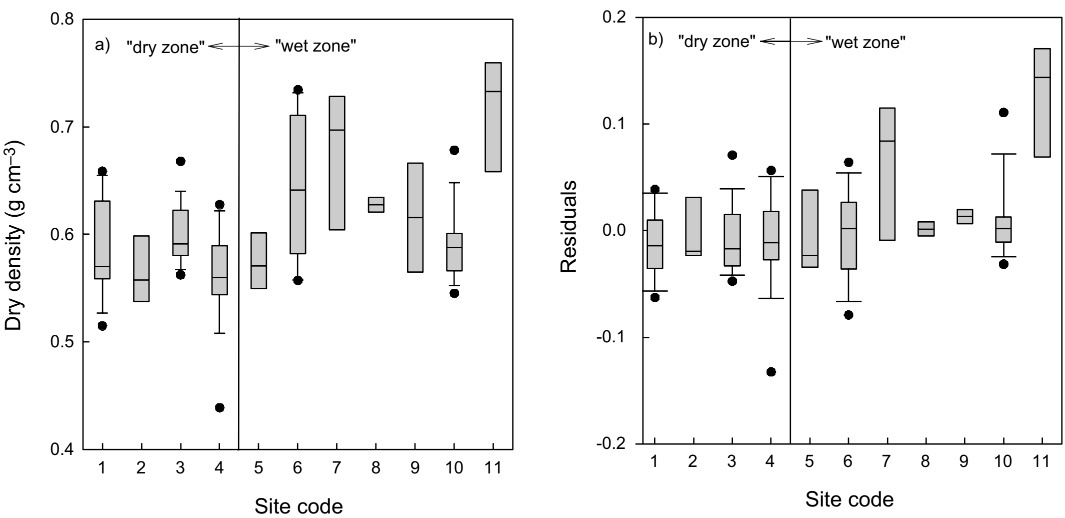

Fig. 9. Variation of a) dry density, and b) residuals from the regression between dry density and age (from Fig. 2), in different sites for teak in Costa Rica. For site codes, see Table 1.

the heartwood proportion was statistically different ($P<0.05$) between climatic zones: 'wet' sites had lower values than 'dry' sites.

Wood dry density increased slightly with age (Fig. 7), presenting a higher correlation at the base of the tree ($r=0.61$) than at the base of the crown ($r=0.51$). Wood samples taken at the base of the stem from line planting trees of 10 years old presented higher values than those from plantation trees of 47 years old (0.77 vs. 0.73 g cm^{-3}, respectively). Dry density values (both at the base of the tree and at the base of the crown) were statistically different ($P<0.05$) between 8-year-old trees or younger and 47-year-old trees, and between line planting trees and 13-year-old trees or younger, but did not differ statistically between line planting trees and mature trees.

Dry density tended to increase with increasing DBH, and was not statistically different between stem sections (base of the tree vs. base of the living crown). Moreover, the dry density at the base of the tree was higher than that at the base of the living crown in trees of DBH less than 38 cm but after this diameter the former became lower than the latter (Fig. 8).

Significant differences in wood dry density were found among sites. In general, the sites corresponding to the 'dry' region (sites 1 to 4) presented lower values than those of the 'wet' region (sites 1 to 4, Fig. 9a). Nevertheless, when eliminating the effect of age since older trees were located in the 'wet' sites, no significant differences were found between climatic zones (Fig. 9b). The trees in the site 11 are from line planting, which showed significantly higher values than trees in the other sites, except those of the site 6, as they corresponded to the oldest trees in the sample. No significant differences were found in wood dry density between different stand densities (from 156 to 1600 trees ha^{-1}).

4 Discussion

Teak is a relatively fast-grown species, therefore recommended rotations for stands under high input management are close to 30 years. The present study indicates that, in Costa Rica, this species presents a heartwood proportion of 55% of the total volume at 30 years, increasing logarithmically with increasing age and consequently with DBH. Arce (2001) found heartwood proportions of 33–37% in 10-year-old teak grown in a dry region of Costa Rica.

Heartwood volume in a tree increases exponentially with increasing DBH. A physiological explanation was suggested by Bamber (1976), who considered that as sapwood must be continually laid down concurrently with growth of the crown, its amount can only be maintained at an optimum by the formation of heartwood, acting as a regulatory mechanism to control the amount of sapwood.

Trees in high-density plantations would be expected to produce higher heartwood proportions than trees in plantations with low densities, since smaller crowns and consequently less conducting sapwood area would influence a greater heartwood formation. However, in the present study, trees in wide spacing plantations (150–800 trees ha^{-1}) presented a higher heartwood proportion than more dense plantations (1600 trees ha^{-1}). In concordance with this, Arce (2001) reports greater heartwood proportions for densities of 830 trees ha^{-1} than for densities of 1111 trees ha^{-1} in 10-year-old *T. grandis* plantations.

Sapwood area remained constant up to 65–70% of the stem height. Moya (2001b) found also constant values of sapwood diameter with increasing height in 5 to 9-year-old *T. grandis* trees in Costa Rica, concluding that the annual increment in heartwood diameter coincides with the yearly diameter growth and as consequence the sapwood diameter remains constant (usually the last 4 growth rings).

Cross-sectional area of heartwood increased with increasing age, but decreased with increasing tree height. Other studies on plantation-grown teak, such as those of Moya (2001b) for 5 to 9-year-old trees, Arce (2001) for 10-year-old trees, and Bhat (1995) for 51–52-year-old trees, reported similar results.

'Wet' sites were found to produce less heartwood volume than 'dry' sites, although both presented similar tree sizes at same ages. A possible reason for this may be the fact that tree growth occurs almost continuously in the 'wet' sites throughout the 8 to 12 months of growing period; while in 'dry' sites the shorter growing season causes a more intense tree growth, leading to a greater deposit of inert material (i.e. heartwood formation). Since 'wet' sites normally present an almost continuous diameter growth, heartwood forms at a lower rate than that on 'dry' sites, where tree growth ceases during the dry months and may induced the yearly formation of heartwood during this period. Araya (2001) also found higher proportions of heartwood in 'dry' sites than in 'wet' sites for *Gmelina arborea* plantations in Costa Rica.

In general, the average values of wood dry density found in this study are at similar level to those reported elsewhere for plantation grown teak (Kandya 1974, González et al. 1979, Sanwo 1987, Bhat 1995, Vallil 1997, Brennan and Radomiljac 1998, Baillères and Durand 2000, Betancur et al. 2000, Bhat 2000, Moya 2001b).

Moya (2001a) found that basic density for teak grown in Costa Rica presented a positive correlation with age of vascular cambium ($r = 0.66$), suggesting that wood density increases with increasing age and with decreasing tree growth rate. Baillères and Durand (2000) also found a positive correlation of wood density ($H = 12\%$) with distance from the pith ($r = 0.77$) for 30-year-old plantation grown teak trees coming from northern Côte d'Ivorie. On the other hand, other studies report no significant differences in wood density between young and mature *T. grandis*, hence rotation period of fast-growing tree species can be reduced without affecting timber strength (Bhat 1995, Bhat 1998, Bhat et al. 2001).

Moya (2000) reported that wood dry density in *T. grandis* decreases from base of the tree to a certain height (50% of total height), and increases thereafter with increasing height (up to 75% of total height). Sekhar and Negi (1966) reported an unstable behavior of dry density with increasing tree height for plantation grown teak in India. It was found that the dry density and strength properties decreased from bottom up to the height of about 6.3 m and thereafter increased up to 12.3 m with a tendency to become greater than at the base of the tree. These findings support the results of the present study, where the trend line for the dry density at the base of the crown (located at stem heights corresponding to more than 50% of the tree total height) crosses that of the dry density at base of the tree.

No significant differences in dry density were found between the 'dry' and the 'wet' zones. Moya (2001a) found similar results for teak grown in Costa Rica. On the contrary, Bhat (2000) found in a study undertaken in Nilambur (India) a lower dry density for irrigated *T. grandis* in relation to control, i.e. mean standard Indian teak. In 'dry' sites, teak can produce high percentages of vessels in order to absorb water when it becomes a limiting factor. For this reason, more free space is produced and the wood density may be lower than that in the 'wet' sites without water absorption limits (Moya 2001, personal communication). Nair (1997) reported variations in wood quality of teak growing under different climatic conditions in Kerala, India. Teak occurring in dry deciduous forests was found to be heavier and stronger than ordinary teak. Other plantation grown species, e.g. *Cupressus lusitanica* in Tanzania, have also shown non-significant differences in basic density under different plantations densities (Malende and Ringo 1987).

Strong relationships between wood density and some mechanical properties (e.g. static bending, module of elasticity, module of rupture, stress proportional limit) were found by Betancur et al. (2000) for 13-year-old teak grown in Colombia. Further research on this topic could facilitate the estimation of mechanical properties from more easy determining variables, such as dry density. In addition, dry density would gain even more interest and possibly become the most desire characteristic in the teak market.

5 Conclusions

Heartwood volume increases with increasing age and with increasing DBH on planted *T. grandis* trees in Costa Rica. Wide spacing plantations (150–800 trees ha^{-1}) present a significant higher proportion of heartwood than those with narrow spacings (1600 trees ha^{-1}). Total diameter and stem diameter of heartwood vary considerably among trees, even when investigated in relative values. Cross-sectional area of heartwood increases with increasing age but decreases with increasing tree height. 'Wet' sites produce less heartwood volume in *T. grandis* trees than 'dry' sites, even when comparing trees of similar age and size.

Dry density was found to increase with increasing age. Average values for *T. grandis* plantations in Costa Rica are at a similar level to those reported elsewhere. Dry density at the base of the tree is higher than at the base of the crown on small-to-medium size teak trees (< 39 cm DBH). 'Wet' sites present a slight higher dry density than 'dry' sites, but no significant relationship could be established.

Acknowledgments

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