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Horizontal and Vertical Distributions of Heartwood for Teak Plantation

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Abstract: *Tectona grandis* is a valuable timber species with heartwood that is used worldwide. Most of the previous studies on its heartwood and sapwood have focused on dominant or mean trees, while trees with different social status might show different vertical and horizontal distributions of heartwood and sapwood. Studies on their heartwood and sapwood properties could be conducive to increasing heartwood yield at stand level. In 31-year-old plantations of *T. grandis* in southwest Guangxi, China, the trees were divided into three groups including dominant, mean and suppressed trees. Stem analysis was conducted for sampled trees in each of these groups to explore the differences in the horizontal and vertical distribution of their heartwood and sapwood. The results indicated that the heartwood radius, heartwood and sapwood areas of *T. grandis* showed significant differences in horizontal and vertical directions among trees of different social status. Heartwood began to form when xylem radius was 2–3 cm, and the heartwood radius ratio tended to be stable when the xylem radius reached about 8 cm. Heartwood radius and area, sapwood area and section heartwood volume all decreased with increasing tree height. The ratios of heartwood radius and area were relatively stable for sections under 50% of tree height. The sapwood width did not vary largely in horizontal and vertical directions among the three social status tree groups, which mainly fluctuated in the range of 1–4 cm. The heartwood volume proportions for dominant, mean and suppressed trees were 60%, 55% and 51%, respectively. There was a significant exponential relationship between heartwood volume and diameter at breast height (DBH) regardless of social status. The model HV = $0.000011 \times DBH^{2.9787}$ ($R^2 = 0.8601$) could accurately estimate heartwood volume for all *T. grandis* with different social statuses at this age. These findings could provide evidence for stand management and high-quality and large-sized timber production of *T. grandis*.

Keywords: *Tectona grandis*; social status; heartwood; sapwood; vertical variation; horizontal variation

1. Introduction

Teak (*Tectona grandis*) is one of the most valuable timber species in the world. It is naturally distributed in India, Myanmar, Thailand and Laos, etc. [1]. Its heartwood is golden brown or dark brown, with a fine texture and strong decay resistance [2], and it can be used for manufacturing high-grade furniture and musical instruments as well as in house decoration and transportation [3]. Its wood has very high economic value [4] and is one of the most in demand in the international high-end market of tropical hardwood [5]. As log prices have been rising year by year in recent decades, Africa, Central America, South America and China have made great efforts to develop *T. grandis* plantations [6]. Currently, the plantation area has reached 4.35 million hectares worldwide [7].

T. grandis has been in China for nearly 200 years, and has now been extensively planted in more than 60 counties or cities in 10 provinces of southern China, with a planting area of 35,000 hectares [8].

Heartwood normally determines the value of wood [9], while sapwood is closely correlated with the physiological functions of trees [10]. There are a number of references on the heartwood of dominant or mean trees for *T. grandis*. For example, Pérez and Kanninen [11] studied the effects of thinning intensities on the heartwood volume of dominant *T. grandis* trees; Tewari and Mariswamy's [1] study showed that the proportion of heartwood increased while sapwood proportion was almost constant with increasing diameter at breast height (DBH) for *T. grandis*. In addition, Fernández-Sólis et al. [12] predicted the heartwood formation process of *T. grandis* based on randomly selected trees in each age class. However, mean and suppressed trees also account for a large proportion in stand [13] and their role in wood production cannot be ignored, especially for valuable timber species. Studies have also shown that tree differentiation could restrict the growth efficiency of trees' heartwood and sapwood [14], and thus lead to the sapwood and heartwood variations in horizontal and vertical directions [15,16]. Therefore, it is very important to know the differences in sapwood and heartwood attributes among dominant, mean and suppressed trees. Until now, only Kokutse [17] has illustrated the significant variations of heartwood radius at breast height among trees with different social status, but for the vertical variation, it is still unclear.

The rotation of *T. grandis* is traditionally 50–60 years [18], while Bhat [19] considers that a short rotation of 20–30 years may be more suitable for the current supply market of *T. grandis* timbers. In the current paper, differences in horizontal and vertical distribution of heartwood and sapwood were investigated among 31-year–old *T. grandis* trees with different social status in southern China, and relationships between heartwood volume and tree growth properties were analyzed. The findings could help the understanding of heartwood and sapwood formation, predict heartwood volume and further provide evidence for high quality timber production in this area.

2. Materials and Methods

2.1. Experimental Site

The *T. grandis* plantations are located in Guangxi Youyiguan Forest Ecosystem Research Station at the Experimental Center of Tropical Forestry (ECTF), Chinese Academy of Forestry, on the outskirts of Pingxiang City, Guangxi Zhuang Autonomous Region, southern China (21°57′–22°16′ N, 106°41′–106°59′ E), which belongs to a northern tropical monsoon climate. The annual mean temperature is 21.6 °C. The mean annual precipitation is 1200–1500 mm, and 75% of the rainfall is concentrated in May to September. The mean annual evaporation is 1261–1388 mm, and the relative moisture is 80%–84%. The altitudes of these plantations range from 130 m to 680 m. The soils are lateritic and red with a thickness pf above 60 cm. Their pH values range from 4.5 to 7.5.

The plantations were established in 1981 or 1982 with a planting density of 2500 stem·ha^{-1}. Conventional tendings of two times per year were conducted within the three years after planting. Thinning was carried out three times in 1988–1990, 1996–1998 and 2009–2011, respectively, with an intensity of 30%–40% each time. The stand densities were 333–400 stem·ha^{-1} when sampling (Table 1).

2.2. Sampling and Measurement

From December 2013 to February 2014, *T. grandis* plantations aged over 30 years in ECTF were investigated. Ten plots with a size of 600 m^2 (20 m × 30 m) were set up, and DBH, tree height, height to crown base (HCB) and crown width (four directions) for each tree were measured in each plot. After that, all the trees were divided into three social status classes including dominant, mean and suppressed trees according to the widely adopted system (Kraft class) described by Nicholas et al. [20], since the stands had been thinned three times and no dying trees existed. For each social status class, 1–2 trees in each plot (34 trees in total) were sampled for stem analysis (Table 2).

Table 1. Information of sampled *Tectona grandis* plots.

Plot	Altit-Ude (m)	Grad-Ient (°)	Slope Position	Slope Aspect	Planting Year	Stand Density (Stems·ha^{-1})	DBH [1] (cm)	Height (m)	HCB [2] (m)	CW [3] (m)
BY1	232	30	Down-slope	South-east	1981	367	27.05 (3.80)	19.9 (2.33) [4]	7.25 (2.57)	5.27 (1.37)
BY2	230	35	Down-slope	South-east	1981	333	25.91 (5.35)	16.93 (4.58)	6.61 (2.93)	5.46 (2.14)
BY3	350	40	Down-slope	North-west	1981	333	28.48 (2.51)	18.77 (2.23)	9.33 (4.21)	4.93 (2.31)
BY4	349	40	Down-slope	North-west	1981	383	27.57 (4.85)	18.42 (2.97)	8.24 (3.18)	5.13 (0.99)
QS1	199	0	Down-slope	North-west	1982	350	23.71 (4.10)	16.94 (2.36)	9.45 (2.84)	6.78 (1.09)
QS2	185	5	Down-slope	North	1982	350	26.07 (3.82)	19.4 (3.02)	10.79 (2.75)	7.80 (3.03)
QS3	153	16	Down-slope	North	1982	383	25.46 (4.33)	19.97 (2.95)	9.49 (1.90)	7.12 (2.69)
QS4	164	18	Down-slope	North	1982	400	25.17 (2.89)	22.23 (1.89)	12.75 (2.83)	5.19 (1.16)
QS5	146	25	Down-slope	North	1982	367	23.46 (3.65)	17.71 (2.48)	9.22 (2.16)	6.40 (1.58)
SPXS1	199	11	Down-slope	East	1982	400	22.13 (7.56)	15.78 (3.68)	8.13 (2.94)	5.01 (1.45)

[1] DBH: Diameter at breast height; [2] HCB: Height to crown base; [3] CW: Crown width; [4] The numbers in parentheses are standard deviation of mean.

Table 2. Description of sampled *Tectona grandis* trees with different social status.

Social Status	Sample No.	DBH [1] (cm)	Height (m)	HCB [2] (m)	CW [3] (m)
Dominant tree	13	27.55 (2.72) [4]	21.88 (1.14)	12.58 (2.47)	6.53 (1.04)
Mean tree	12	23.41 (1.78)	20.78 (1.32)	11.53 (2.63)	6.27 (2.50)
Suppressed tree	9	18.16 (3.21)	16.63 (1.91)	9.59 (2.88)	4.94 (1.61)

[1] DBH, diameter at breast height; [2] HCB, height to crown base; [3] CW, crown width; [4] The numbers in parentheses are standard deviation of mean value.

2.3. Stem Analysis

Before the sampled trees were cut down, their trunks were marked at east and north directions. After felling, stem discs with a thickness of approximately 5 cm were obtained at the heights of 0 m, 0.3 m, 1.3 m, 2 m, 4 m and then every 2 m until less than 1 m was left. Every disc was numbered and marked with the north direction. Each disc was polished and the borders of the annual ring, as well as heartwood and sapwood, were identified. Heartwood radius (HR) and sapwood width (SW) were measured (0.01 mm) in four directions (east, south, west and north) with an electronic caliper, and were calculated separately as the mean of the observed values in four directions (Figure 1).

2.4. Data Analysis

HR and SW of each disc were calculated as means of the observation in four directions. Individual stem volume and heartwood volume were estimated with a mean sectional area approximate quadrature method. The heartwood area (HA), sapwood area (SA), heartwood volume (HV) and individual volume (V) were calculated as follows:

$$\mathrm{HA} = \pi \times \left(\overline{\mathrm{HR}}\right)^2 \tag{1}$$

$$\mathrm{HA} = \pi \times \left(\overline{\mathrm{HR}}\right)^2 \tag{2}$$

$$\mathrm{HV} = \sum\left(\frac{1}{2} \times \left(\mathrm{g_n} + \mathrm{g_{n+1}}\right) \times \mathrm{L}_n\right), \quad (3)$$

where $\overline{\mathrm{HR}}$ and $\overline{\mathrm{HR} + \mathrm{SW}}$ were the mean radius for heartwood and xylem of each disc, respectively; $\mathrm{g_n}$ and $\mathrm{g_{n+1}}$ were the cross-sectional areas of the base and top heartwood for a stem section; and Ln is length of the section.

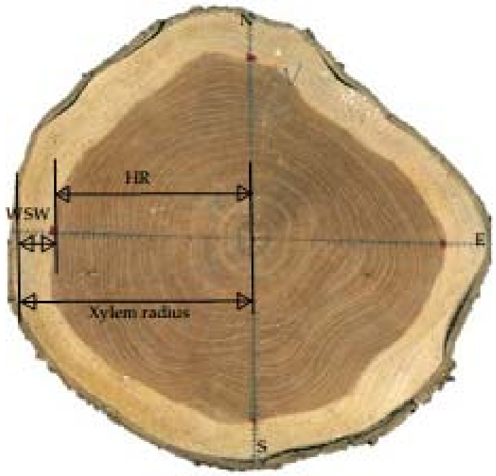

Figure 1. Measurement for heartwood radius and sapwood width of teak discs (HR: Heartwood radius; SW: Sapwood width; N: North; S: South; E: East; W: West.).

Analysis of variance (one-way ANOVA) was used for testing the difference in heartwood radius and sapwood width at breast heights. Relationship between tree growth traits and volumes of heartwood and sapwood was analyzed using a Pearson coefficient, and linear regression was further fitted for exploring the relationship between DBH and heartwood volume. The fitted models were further evaluated with four statistical indicators—deviation (B), absolute deviation (AB), mean square error (MSE) and determination coefficient (R^2) calculated from the following equations:

$$B = \sum_{i=1}^{n} \frac{\left(d_i - \hat{d}\right)}{n} \quad (4)$$

$$AB = \sum_{i=1}^{n} \frac{\left(d_i - \hat{d}\right)}{n} \quad (5)$$

$$\mathrm{MSE} = \frac{\sum_{\mathrm{i}=1}^{n}\left(d_{\mathrm{i}} - \hat{d}\right)^2}{n - m} \quad (6)$$

$$R^2 = \frac{\sum_{i=1}^{n}\left(d_i - \hat{d}\right)^2}{\sum_{i=1}^{n}\left(d_i - \overline{d}\right)^2}, \quad (7)$$

where d_i is the observed value, $\hat{d}$ is the predicted value, $\overline{d}$ is the mean observed value, n is the number of observed values in model fitting, and m is the number of model parameters. The paired t-test method was applied for testing the validity of the model; if there was no difference between the observed and predicted values ($p > 0.05$), the performance of the fitted model was better.

All analyses were performed with SPSS19.0 software (IBM-SPSS Inc., Chicago, IL, USA) and figures were drawn with Sigmaplot 10.0.

3. Results

3.1. Horizontal Variation

There were significant differences in heartwood radius (HR), heartwood area (HA) sapwood area (SA), and percentages of heartwood radius (HRP) and heartwood area (HAP) at breast height among *T. grandis* trees with different social status ($p < 0.05$). HR, HA and SA of dominant trees were remarkably larger than those of mean and suppressed trees, while no significant difference was observed in HRP and HAP between dominant and mean trees ($p > 0.05$). However, social status had no obvious effects on sapwood width (SW) at breast height (Table 3).

From the relationship between heartwood and xylem radius at any height along stem, it was found that heartwood of *T. grandis* could be observed when the xylem radius reached 20–30 mm, then it increased rapidly with increments of the xylem radius (Figure 2a). The percentage of heartwood radius also increased sharply with increments of the xylem radius from 20 mm to 80 mm. After that, it increased slowly and reached a relatively stable value of about 80% (Figure 2b).

The sapwood width showed no close relationship with xylem radius for all *T. grandis* trees regardless of their social status (Figure 2c). While the percentage of sapwood width decreased rapidly with increasing xylem radius up to about 100mm (Figure 2d), after that, it became more stable.

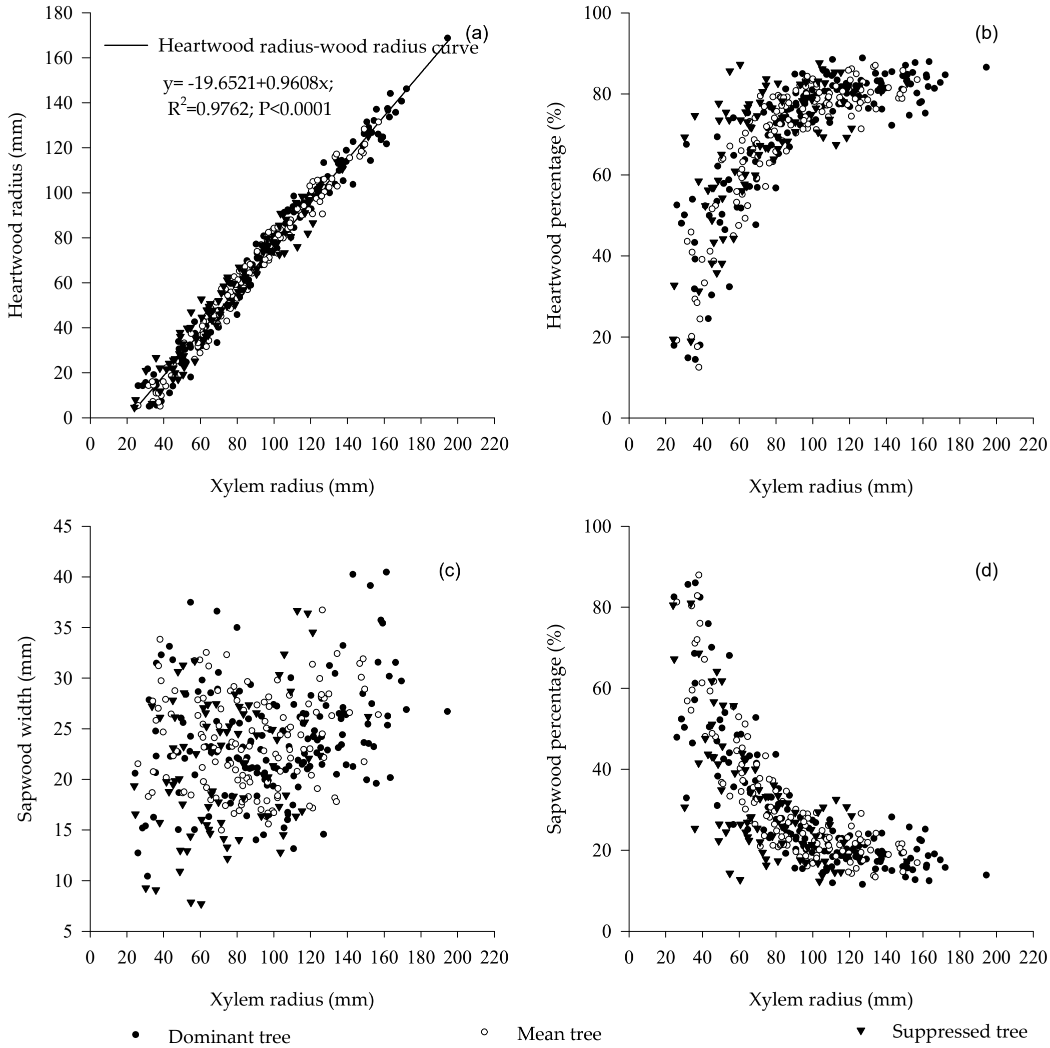

Figure 2. Relationship between xylem radius and (**a**) heartwood radius, (**b**) percentage of heartwood radius, (**c**) sapwood width and (**d**) percentage of sapwood width.

Table 3. Heartwood and sapwood attributes of sampled *Tectona grandis* trees with different social status.

Parameters	Dominant Tree	Mean Tree	Suppressed Tree
HR [3] (mm) [1]	107.97 (3.47) a [2]	89.23 (3.62) b	65.77 (4.17) c
SW [4] (mm)	22.77 (1.30) a	21.7 (1.36) a	20.39 (1.57) a
HA [5] (cm^2)	371.73 (20.69) a	252.95 (21.53) b	141.22 (24.87) c
SA [6] (cm^2)	171.08 (9.94) a	136.53 (10.35) b	99.56 (11.95) c
HRP [7]	0.83 (0.01) a	0.80 (0.01) a	0.76 (0.01) b
HAP [8]	0.68 (0.02) a	0.65 (0.02) a	0.58 (0.02) b
HV [9] (m^3)	0.32 (0.02) a	0.20 (0.02) b	0.11 (0.03) c
V [10] (m^3)	0.54 (0.03) a	0.37 (0.03) b	0.22 (0.04) c
HVP [11]	0.60 (0.02) a	0.55 (0.02) ab	0.51 (0.02) b

[1] Numbers in parentheses are standard error of mean value; [2] Different letters in the same row refer to significant differences between social status groups ($p < 0.05$); [3] HR: Heartwood radius at breast height; [4] SW: Sapwood width at breast height; [5] HA: Heartwood area at breast height; [6] SA: Sapwood area at breast height; [7] HRP: Heartwood radius percentage; [8] HAR: Heartwood area percentage; [9] HV: Heartwood volume; [10] V: individual volume; [11] HVP: Heartwood volume percentage.

The heartwood area was also significantly correlated with xylem radius at any given height along the stem (Figure 3a), its percentage increased rapidly to above 60% with increasing xylem radius from 20 mm to 100 mm, then became almost constant.

Different to the sapwood width, sapwood area showed a significantly positive correlation with xylem radius (Figure 3c). Like the percentage of sapwood width, percentage of sapwood area decreased significantly with increasing xylem radius from 20 mm to 80 mm and reached a relatively stable value of 30% afterwards (Figure 3d).

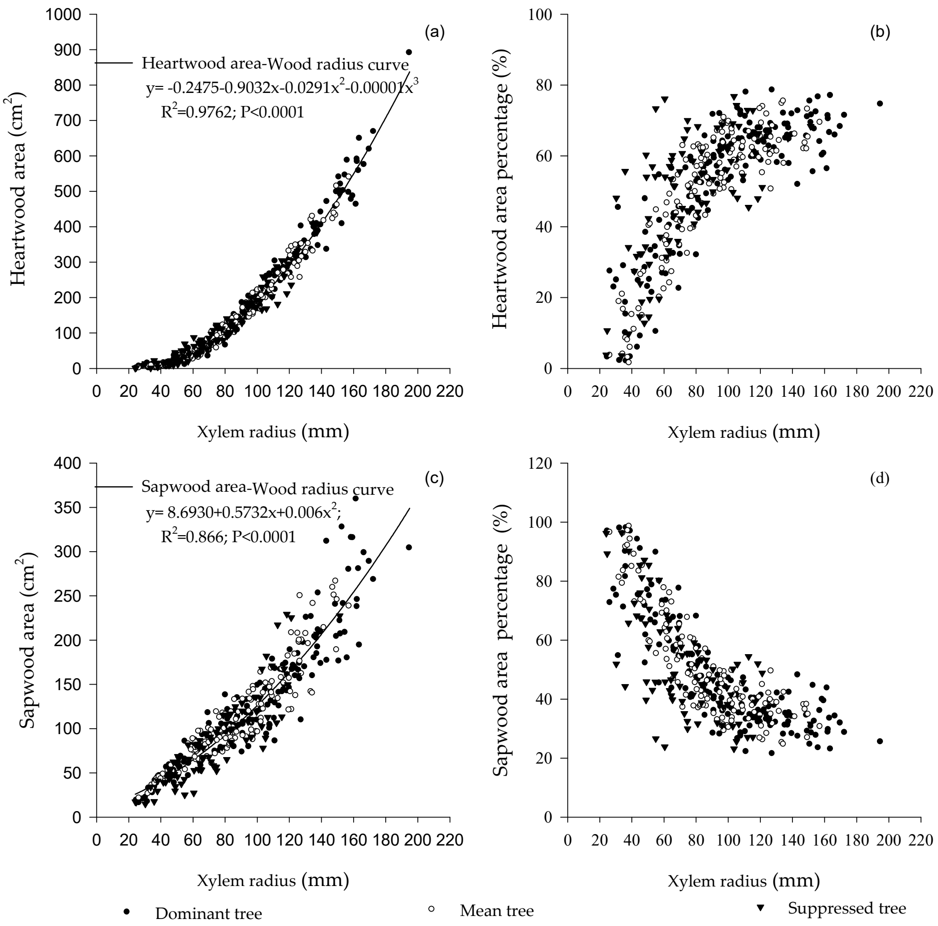

Figure 3. Relationship between xylem radius and (**a**) heartwood areas, (**b**) percentage of heartwood areas (**c**) sapwood areas and (**d**) percentage of sapwood areas.

3.2. Vertical Variation

3.2.1. Heartwood Radius and Sapwood Width

Heartwood radius and its ratio to xylem radius decreased with increasing tree height for *T. grandis* trees regardless of their social status (Figure 4a,c). The percentage of heartwood radius for dominant and mean trees is higher (>68%) at the lower half part of stem—it decreased with increasing tree height—and the decreasing rate was low with a raised position. At the upper half of the stem, the decreasing rate was much higher. For the heartwood radius percentage of suppressed trees, it decreased almost linearly with increasing height along the stem. The height of the heartwood could reach 84.19%–91.41% of the tree height (Figure 4c). The heartwood radius and its percentage were the highest for dominant trees at the same height or relative height, followed by mean trees and suppressed trees in turn.

As for the sapwood width, it was much larger at the base of the stem (0–1.0 m) and decreased sharply with tree height. It remained relatively stable at the middle part of the stem and then showed a slight increasing trend (Figure 4b). The section with stable sapwood width occupied 58.04%, 51.49% and 52.32% of total tree height for dominant, mean and suppressed trees, respectively.

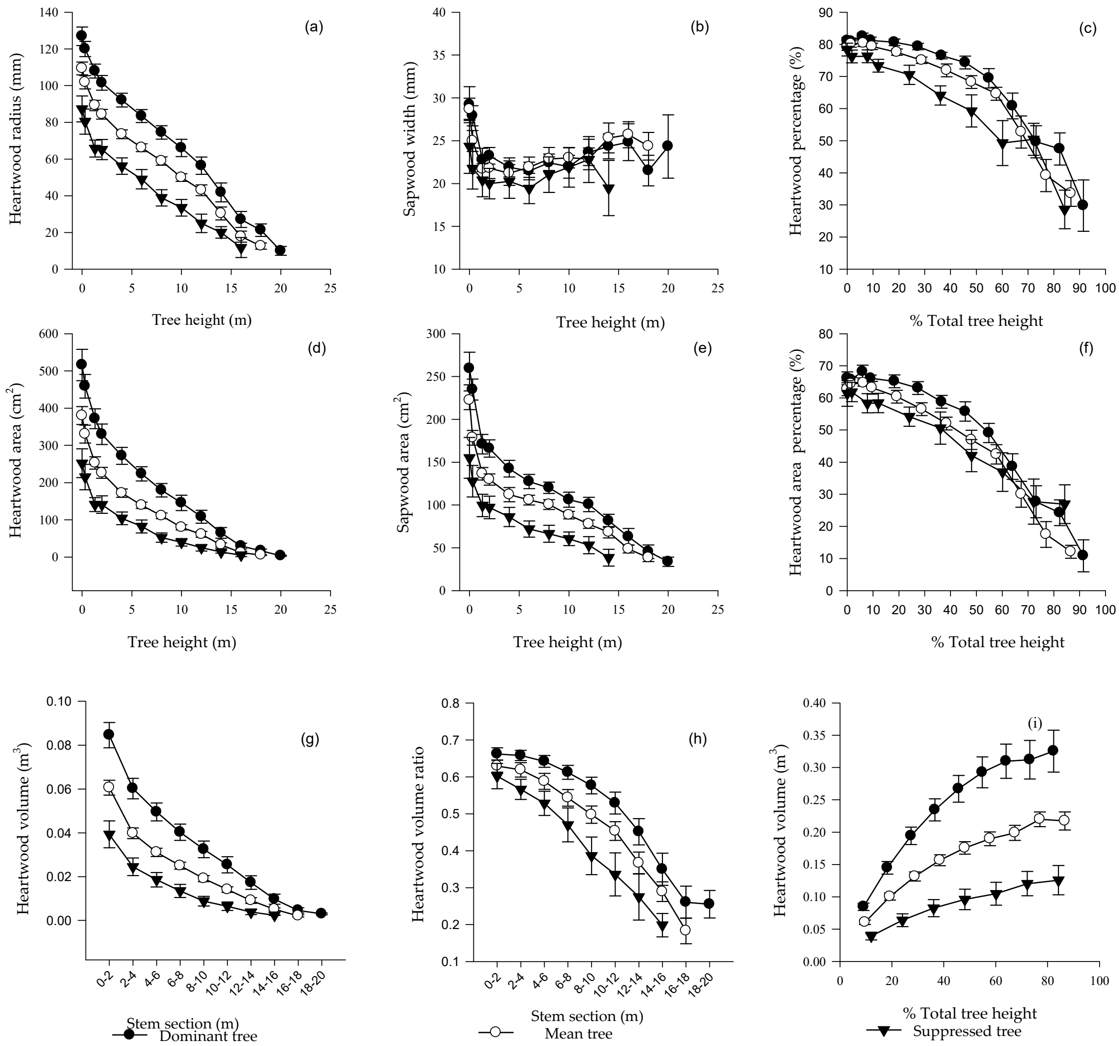

Figure 4. Vertical variations of (**a**) heartwood radius, (**b**) sapwood width, (**c**) percentage of heartwood radius, (**d**) heartwood area, (**e**) sapwood area, (**f**) percentage of heartwood area, (**g**) heartwood volume, (**h**) ratio of heartwood volume and (**i**) cumulative heartwood volume with increasing tree height or relative tree height.

3.2.2. Heartwood and Sapwood Areas

The heartwood and sapwood areas of *T. grandis* trees with different social status showed a continuous decrease with increasing tree height (Figure 4d,e). The vertical variation of heartwood area percentage was similar to that of heartwood radius (Figure 4f). The heartwood area percentage could reach more than 61% at the base of stem for all trees. For the upper part of stem (>70%), social status had smaller effects on percentage of heartwood area. At the same relative height from 70% to 80%, suppressed trees even showed a much higher percentage of heartwood area than dominant and mean trees.

3.2.3. Heartwood Volume

The heartwood volume and its ratio decreased significantly with increasing height of stem section (Figure 4g,h). It was obviously higher in the stem section of 0–2 m for all *T. grandis* trees regardless of social status, the ratio was up to 60.22%–66.20%. The heartwood volume percentage was above 50% at the age of about 31 years old, especially for dominant trees up to 60% (Figure 4i). In addition, the difference of heartwood volume and its ratio among three social status classes was much higher than those of heartwood radius and area. The individual heartwood volume and its percentage differed significantly among dominant, mean and suppressed trees ($p < 0.05$), while no significant difference was observed in the percentage of individual heartwood volume between dominant and mean trees as well as between mean and suppressed trees.

3.3. Relationship between Tree Growth and Heartwood and Sapwood Attributes

Tree growth characteristics were significantly correlated with heartwood radius and area at breast height, and individual heartwood volume. DBH had the highest correlation, followed by tree height, crown width and height to crown base. The sapwood area was significantly correlated with DBH and tree height, while sapwood width was only correlated with DBH (Table 4). Due to the fact that DBH had the closest relationship with heartwood and sapwood properties, and is the easiest and most accurate factor in individual measurement during forest inventory, the DBH of the 34 sampled trees was thus chosen to fit the individual heartwood volume (Figure 5). Based on model statistical evaluation (Table 5) and paired-T test (Figure 6, Table 6), it was shown that the heartwood volume of *T. grandis* could be accurately estimated by the model ($R^2 = 0.8601$).

Table 4. Correlations of tree growth characteristics with heartwood and sapwood attributes for *Tectona grandis.*

Growth Characteristics	Heartwood Radius	Sapwood Width	Heartwood Area	Sapwood Area	Individual Heartwood Volume
DBH [1]	0.920 ** [2]	0.345 * [3]	0.888 **	0.776 **	0.889 **
Tree height	0.531 **	0.306	0.486 **	0.514 **	0.539 **
Height to crown base	0.343 *	−0.010	0.370 *	0.192	0.438 **
Crown width	0.434 *	0.121	0.378 *	0.304	0.304

[1] DBH: diameter breast height; [2] **: $p < 0.01$; [3] *: $p < 0.05$. Heartwood radius, Sapwood width, Heartwood area and Sapwood area are attributes at breast height.

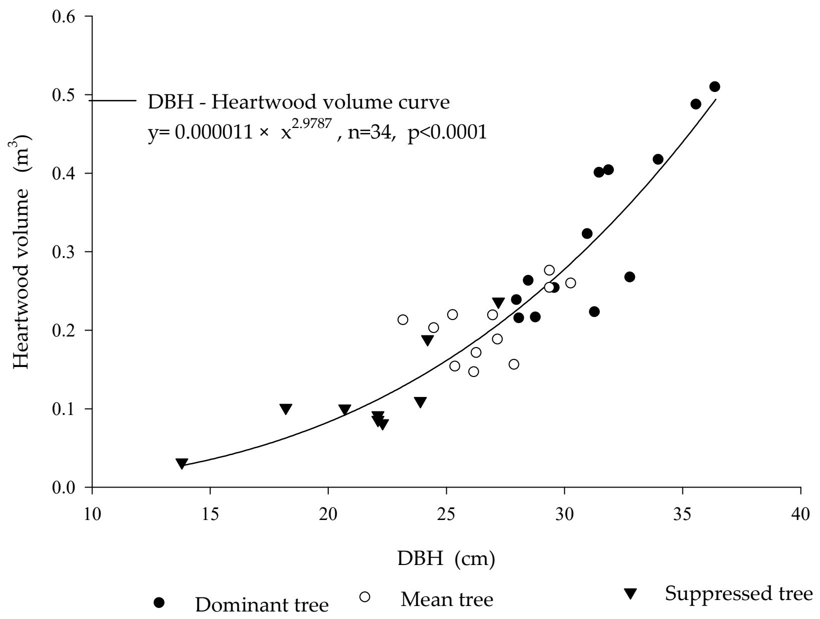

Figure 5. Relationship between diameter at breast and heartwood volume for *Tectona grandis.*

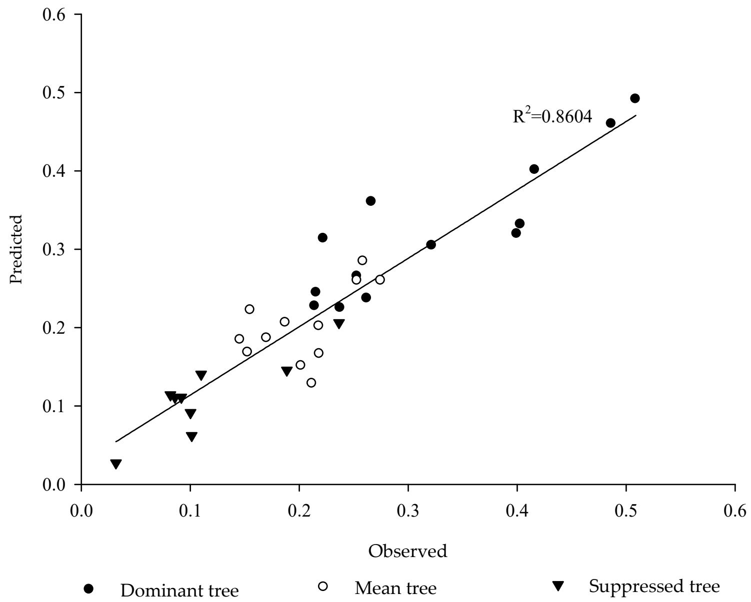

Figure 6. Relationship between observed and predicted values (based on fitted model) of heartwood volume.

Table 5. Statistical values of the fitting model.

	B [1]	AB [2]	MSE [3]	R^2 [4]	Model
Heartwood volume	0.0021	0.0337	0.0019	0.8601	HV [5] = 0.000011 * $DBH^{2.9787}$

[1] B: Bias; [2] AB: Absolute bias; [3] MSE: Mean standard error; [4] R^2: Determination coefficient; [5] HV: Heartwood volume, * DBH: Diameter at breast height.

Table 6. Student's paired *t* test for observed and predicted data.

Paired Samples	Mean	Standard Deviation	Standard Error	*t*	Significance Level (*p*)
Observed-Predicted	0.0021	0.0426	0.0073	0.287	0.776

4. Discussions

4.1. Horizontal Variation

In the present study of a 31-year-old *T. grandis* plantation, social status significantly influenced heartwood radius, heartwood area and sapwood area at breast height. This is similar to Kokutse's [17] study on 25-year-old *T. grandis* in west Africa; the only difference between studies is that the sapwood area of dominant trees did not differ remarkably to that of mean trees in their study ($p > 0.05$). This might be due to the fact that the leaning-stem trees were also sampled [17], where a higher percentage of sapwoods would convert to heartwood on the lower side of the leaning stem [21,22].

For all T. grandis trees, heartwood began to appear when the xylem radius was 20 mm to 30 mm, and then heartwood radius, heartwood area and sapwood area were in significantly linear correlation with xylem radius, while no significant correlation was found between sapwood width and xylem radius. Xylem radius was a good predictor of heartwood attributes [17,23,24] and large trees have a larger proportion of heartwood than small trees. In addition, the present study also showed that heartwood radius and area increased slowly after xylem radius reached 80 mm, and the percentage of heartwood radius was almost stable when the stem diameter reached 100 mm. This is of great significance for improving teak plantation management so as to harvest the most heartwood in short rotation. For example, proper thinning or fertilization can promote stem growth and thus accelerate heartwood formation. Pérez and Kanninen [11] confirmed that the highest percentage of heartwood volume could be obtained through moderate and heavy thinning.4.2. Vertical Variation

The heartwood height of 31-year-old *T. grandis* trees could reach 84.19%–91.41% of tree height. At the same height or relative height, heartwood radius and area as well as their percentage was much higher in dominant trees, followed by mean and suppressed trees. The heartwood volume was mainly distributed under the lower middle stem section (<60% of tree height), and the cumulative heartwood volume and ratios were much higher for dominant trees since the diameter growth of mean and suppressed trees suffered from inhibitions in stands with high canopy density—this is in accordance with Knapic's [24] study on *Acacia melanoxylon*. This could be explained by the trees producing more ethylene when they were swaying, which could promote heartwood formation [25], especially for dominant and mean trees [26,27]. The results indicated that the lower part of the trunk is the target section for heartwood production. Combined with the horizontal distribution of heartwood, harvesting the lower stem section with a small end diameter larger than 16 cm could maximize the heartwood production of *T. grandis*.

The vertical variation of sapwood width in *T. grandis* of different social statuses was relatively stable, mainly ranging from 10 mm to 40 mm. This was consistent with Knapic et al.'s [24] study on *Acacia melanoxylon*, where the range of sapwood width was 20–50 mm. This may be due to the fact that sapwood is the tissue that transports water in the stem, and the xylem area is closely correlated with water use, leaf area and leaf biomass [10,28,29]. The differences in sapwood widths among different species indicated the similarities and differences in interspecific water utilization, photosynthetic and respiration consumption strategies [30]. The sapwood width remained relatively stable in the middle section of the trunk; this indicated that the radial growth of the heartwood and trunk was approximately equal [31]. Although sapwood width did not vary greatly along the trunk, the sapwood area still decreased significantly with increasing tree height, and the sapwood area of dominant and mean trees was much higher than that of suppressed trees. This could be explained that dominant and mean trees had higher leaf biomass and area, and need more water and so forth, so as to ensure their growth demand [28,32].

4.2. Relationship between Tree Growth and Heartwood and Sapwood Attributes

For most valuable tree species, heartwood determines the value of wood [9], while in practice, heartwood cannot be measured directly for living trees. Accurate heartwood volume estimation based on easily measured tree variables was thus needed before logging. In the present study, diameter at breast height (DBH) had the highest correlation with heartwood radius, area and volume among the four tree growth factors tested (DBH, tree height, height to crown base, and crown width), and the fitted heartwood volume model based on DBH could predict accurately for *T. grandis* trees of different social status. The findings were in accordance with Fernandez-Solis's [12] study on *T. grandis* and Wang's [33] study on several temperate tree species, where DBH was also demonstrated as the most commonly used and the most effective variable for estimating heartwood volume.

5. Conclusions

Dominant *T. grandis* trees produced heartwood more efficiently since their heartwood radius, area and volume were much larger or higher than those of mean and suppressed trees. Heartwood began to appear when the xylem radius was 20–30 mm, and the percentages of heartwood radius and area tended to be stable when the xylem radius was larger than 100 mm. The heartwood mainly distributed the lower middle part of the stem (<60%). The present study confirms the advantages of crop trees (normally dominant trees) and targeted stem section management for efficient high quality heartwood production, and provides evidence for optimizing heartwood production of *T. grandis* in short rotation. However, the temporal dynamics for heartwood formation of *T. grandis* are still unclear, and we need to investigate trees of different ages in the future.

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