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Characteristics of growth and heartwood formation in planted teak in South China

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Abstract

Dominant trees in 31 and 32 years old teak plantation were selected for trunk analysis to study the growth process and heartwood formation characteristics by scanning the disk with scanner and measuring the data with software. The results showed that tree height at the early growth stage (1 to 8 years) was more than that of the DBH (1 to 4 years) for 4 years. The middle growth stage of DBH (5 to 18 years) (stable growth stage) was longer than that of tree height (9 to 13 years) for 9 years. The average growth curve of the volume was not intersected with annual growth curve, which indicated that 31 years old teak plantation had not reached maturity age. The total number of annual rings and the number of heartwood rings were decreased with the increase of tree height, while the number of sapwood rings at different heights changed little. The number of sapwood rings below 16 m of trunk varied about 8 rings, and began to decrease gradually over 16 m. The diameters of xylem, heartwood and sapwood at different heights showed the same trend as the ring, the sapwood width below 22 m was stable, and decreased gradually above 22 m. Affected by taperingness, the heartwood area was larger than sapwood below 10 m, but smaller above 10m. There was a significant positive correlation between the number of heartwood rings with xylem age, diameter of heartwood and xylem diameter ($p < 0.01$). The growth of dominant tree DBH and tree height in teak plantation began to decline at 18 and 13 years respectively, the current growth and predicted maximum growth were still far lower than cultivation target (DBH ≥ 60cm). The heartwood formation of teak was positively correlated with the diameter growth. It is necessary to breed and utilize teak varieties with small taper and thinning should be done from 13 years for reserved dominant trees.

Keywords: Tectona grandis L. f.; dominant tree; stem analysis; growth process; heartwood; sapwood

Introduction, scope and main objectives

Teak (*Tectona grandis* L.f.) is one of the most valuable tropical hardwoods in the world due to its high wood quality, aesthetic appearance and extensive use. Natural teak forests are rapidly dwindling and the supply of teak wood is now mainly from plantations in 70 countries throughout tropical Asia, Africa, Latin America and Oceania [1, 2]. However, teak log produced from plantations are not as large as the harvested from natural forests. High-quality (logs having high percentage of heartwood) and large-diameter timber (DBH ≥ 60cm) of teak is in short supply [3] in many countries. Hence, the focus now is on the cultivation of high-quality and large-diameter timber. Selection of the dominant or target trees in the plantation and devising appropriate silvicultural management are the strategies for cultivating large-sized timbers, we call this the target tree management technique, which is effective technical strategies for cultivating large-diameter timbers [4].
The trees growth process is a direct manifestation of their growth process at different ages. Thus, studying the growth process of forest trees, especially the pattern of growth and formation of the heartwood and sapwood of precious timbers, has important theoretical and practical significance for devising rational silviculture management of forest stand to obtain high-quality and large-sized

timber [5]. It could be used by district foresters as well as private land owners to make sound decision for better management of teak plantation. Stem analysis is an intuitive technique of studying the growth process of forest trees [6, 7, 8]. Novaes *et al.* [9] used total and partial analysis data of the trunk of teak trees and of permanent plots, for the construction of site index curves and growth and production modeling, at the level of individual trees and of the population. Perez [6] constructed the growth equations of diameter at breast height (DBH), tree height and volume, and growth database of teak through stem analysis. Koirala *et al.* [10] created a suitable height-diameter equation as well as localized and generic volume equations for teak in central lowland, Nepal.

Precious timber trees are mainly appreciated for their heartwood, the growth of which is positively correlated with the tree age [11], and also significantly affected by stand density and management measures [12]. Fernández-Sólis *et al.* [13] conducted prediction on the tree height, DBH, and volume growth of teak of different ages, statistical predictive models were developed for sapwood thickness, heartwood radius, maximum heartwood height, heartwood percentage and heartwood volume. Dominant trees became the focus of study, because such trees have a significant contribution to stand productivity [14].The dominant trees in the stand have the advantages of high increment rates and prolonged stage of fast growth and therefore are the targets for obtaining large-diameter timber [15]. Thus, the study on the growth patterns of dominant trees in the stand can lead to guidelines for the effective management of plantation, especially for target trees. In the present study, teak plantations of 31 and 32 years old at Experimental Center of Tropical Forestry, Pingxiang, Guangxi, south China were selected. Stem analysis on dominant trees was performed to study the growth process and heartwood formation, the relationship between tree growth and heartwood formation, predict the maximum growth, explore the rate of heartwood formation for dominant trees, the initial tree age of heartwood formation, the transforming width from the sapwood to the heartwood every year, and thereby provide basic data and a theoretical basis for the efficient cultivation of high-quality and large-sized log from teak plantations.

Methodology

1. Overview of the study area

The study sites were located at Qingshan (QS) and Baiyun (BY) Experimental Fields of Experimental Center of Tropical Forestry, Chinese Academy of Forestry, Pingxiang, Guangxi (Figure 1.). It is located in the southwest of the south subtropical monsoon climate region and adjacent to the northern margin of the north tropical zone, which had a humid and subhumid climate. This area had abundant sunshine and rainfall, as well as clear dry and wet seasons. It was rich in the light, water, and warmth. The mean annual temperature was 20.5–21.7°C, with the extreme high temperature being 40.3°C and the extreme low one being -1.5°C; the active accumulated temperature of ≥10°C was 6000°C –7600°C. The mean annual precipitation was 1200–1500 mm, and the relative humidity was 80%–84% (1981-2013). The main landform types were low mountains and hills. The zonal soil was latosol, with soil thickness thicker than 1 m.

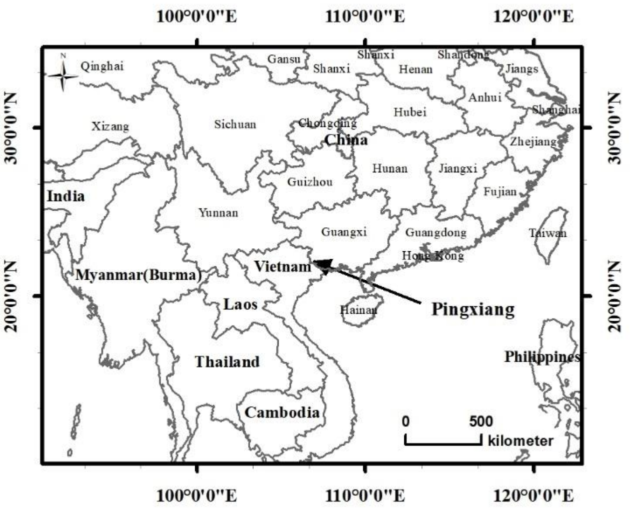

Figure 1. Location of study sites teak in Pingxiang, China.

Our selected teak plantations were planted in the end of 1981 and the beginning of 1982. The planting density was 2500 trees·ha^{-1}. After three intermediate thinning (in 1988–1990, 1996–1998 and 2009–2011), the planting density of all existing sample plots was approximately 410 trees·ha^{-1}. At the end of 2013, eight plots of 20 × 30 m were set in the aforementioned teak stands, including five at the QS Experimental Field and three at the BY Experimental Field.

2. Sample-plot survey

Table 1. Growth performance of teak in eight plots.

Plot	Number of trees in each plot	Stand Density (trees·ha^{-1})	Growth of trees in each plot		Growth of dominant trees in each plot		Sample number in each plot	Growth of sampled trees	
			DBH[1] (cm)	Height (m)	DBH (cm)	Height (m)		DBH (cm)	Height (m)
BY1	24	400	27.05 (0.81) [2]	18.90 (0.50)	32.05 (0.61)	21.56 (0.31)	2	32.35, 32.35	22.32, 23.43
BY2	25	417	25.91 (1.26)	16.93 (0.84)	31.91 (0.96)	20.70 (0.86)	2	31.89, 32.88	22.21, 21.88
BY3	25	417	28.48 (1.01)	18.77 (0.53)	31.48 (0.81)	22.26 (0.27)	3	32.28, 31.65, 32.28	22.63, 22.41, 22.54
QS1	24	400	23.71 (0.91)	16.94 (0.58)	29.91 (1.21)	21.90 (0.25)	2	31.51, 32.15	22.29, 21.86
QS2	26	433	26.07 (0.86)	19.40 (0.68)	30.07 (0.96)	22.98 (0.61)	2	30.89, 31.14	23.58, 23.22
QS3	25	417	25.46 (0.90)	19.97 (0.62)	29.43 (1.81)	22.76 (0.30)	2	31.93, 31.35	22.86, 22.91
QS4	25	417	25.17 (0.59)	22.23 (0.39)	32.17 (0.91)	25.00 (0.53)	2	33.12, 32.88	25.36, 24.89
QS6	24	400	27.57 (0.51)	18.42 (0.30)	31.87 (0.81)	22.69 (0.27)	2	31.68, 32.45	22.79, 22.85

[1] DBH, diameter at breast height; [2] The numbers in parentheses are standard deviation of mean value.

The diameter at breast height, tree height, height to crown base, and crown diameters in four directions for all trees in each sample plot were measured. The statistical data of the growth are shown in Table 1. According to the results, 2-3 dominant trees were sampled for stem analysis in each plot (17 trees in total).

3. Stem analysis and measurement of growth rings

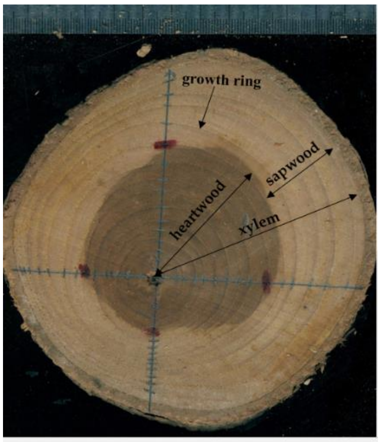

Figure 2. Sapwood, Heartwood, Xylem and Growth Ring of teak.

Before the sampled trees were cut down, their trunks were marked at east and north directions. After felling, stem disks with thickness of 5 cm were cut at a height of 0.3, 1.3, and 2 m and then every 2 m until the tree top. The height, position, and north orientation were marked for each disk. The disks were taken back to the laboratory to dry, and then the working face of each disk was polished. The images were scanned with a high-definition scanner (UNIS M2900, Beijing, China). The scanned images were opened with Adobe Acrobat Professional 7.0 software, and the measuring tool in the software menu was used to measure the over-bark radius of four directions of each disk and the distance from the four directions of each growth ring to the pith [16].

4. Data analysis

The ForStat 2.2 software [17] was used to analyze the data of trees, and the sequence clustering analysis of the growth process of DBH and tree height was performed [18]. Four representative mathematical models were used, including Weibull, Richards, Logistic, and Gompertz. DPS 16.05 (Data processing system) was used to fit the growth regression equations of DBH, tree height, and volume of teak dominant trees. The evaluating indexes of the fitted equation included the coefficient of determination (R^2), root mean square error (*RMSE*), and model parameter test P value.

According to the regression curve of the growth ring number of the heartwood and xylem age, when the heartwood ring number was 0, the xylem age was the initial age of heartwood formation, and the slope indicated the rate of the heartwood formation [19, 20, 21]. Also, based on the regression curve of heartwood diameter and xylem diameter, when the heartwood diameter was 0, the xylem diameter was the initial stem diameter of the heartwood, and the slope indicated the transforming width from the sapwood to the heartwood every year [22].

Results

1. Growth process of teak dominant trees

The growth curve of DBH and age of dominant teak trees (Figure 3a) showed the DBH of 31 years old teak dominant trees was 27.30 cm. The average increment (AI) of DBH maintained a growth trend before 9 years, increasing from 0.67 cm· years^{-1} in the second year to 1.00 cm· years^{-1} in the ninth year, and then tending to be slow at 27 years, maintaining a range of 0.90–1.00 cm· years^{-1}; after 27 years, it showed a downward trend. The growth process of DBH included three phases: early growing phase (1–4 years); middle growing phase (5–18 years); and late growing phase (19–31 years); the phases basically conformed to the changing trend of the CAI curve of DBH in Figure 2. The CAI of DBH in the early growing phase (1–4 years) was in the rapid growth stage, which was maintained above 1.08 cm· years $^{-1}$, and the highest CAI of DBH appeared in the third year (1.44 cm· years $^{-1}$). The CAI of DBH in the middle growing phase (5–18 years) was in a stable growth stage, which was maintained at approximately 1.00 cm· years $^{-1}$, and the highest CAI could reach 1.09 cm· years $^{-1}$. The CAI of DBH in the late phase (19-31 years) showed a downward trend, in which the CAI was only 0.69 cm· years $^{-1}$ and basically less than 0.6 cm· years $^{-1}$ after 27 years.

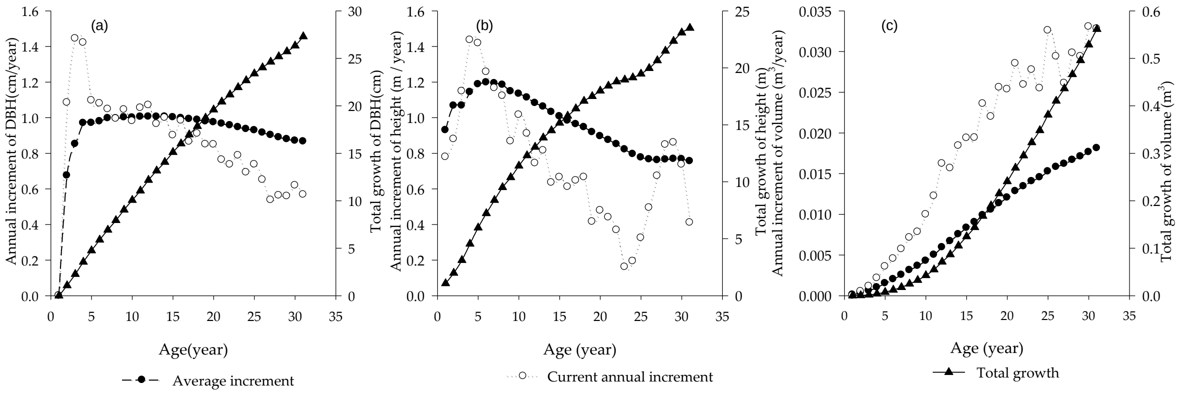

Figure 3. Growth process of DBH (a), height (b), and volume (c) of teak dominant trees in teak plantations.

The height of the 31 years old teak dominant trees was 23.49 m. According Figure 3b, the average increment (AI) of the tree height increased first and then decreased with age, increasing from the AI of 0.93 m· years $^{-1}$ in the first year to 1.20 m· years $^{-1}$ in the sixth year, and then gradually decreasing to 0.76 m· years $^{-1}$ in the 31th year. The ordered clustering analysis of current annual increment (CAI) of tree height for the 31 years old teak dominant trees was carried out. The growth process of tree height included three phases: early growing phase (1–8 years), middle growing phase (9–13 years), and late growing phase (14–31 years); the division into phases basically conformed to the changing trend of the CAI of tree height in Figure 2. The CAI of tree height in the early growing phase (1–8 years) was in the rapid growth stage, and the peak value was present in the third year, reaching 1.48 m· years $^{-1}$. The CAI of tree height in the middle growing phase (9–13 years) was in a stable growth stage, and the average value was 0.87 m· years $^{-1}$. In the late phase (14–31 years), the CAI of tree height showed a downtrend, and the average value was only 0.53 m· years $^{-1}$. Moreover, the CAI of tree height in this phase showed slight fluctuation, with the maximum value of 0.86 m· years $^{-1}$ and the minimum value of only 0.16 m· years $^{-1}$.

The growth curves of volume and age of teak dominant trees (Figure 3c) showed the total volume increment for the 31 years teak dominant trees reached 0.56 m^3. The average increment (AI) curve of the volume showed a steady growth trend and did not intersect with the current annual increment (CAI) curve. The CAI of the volume continued to grow steadily before 12 years and then showed a multiple kurtosis upcurve: the two highest peak values (0.0326 and 0.0330 m^3 · years $^{-1}$) appeared in the 25th and 30th years, respectively.

2. Fitting of the growth process of teak dominant trees

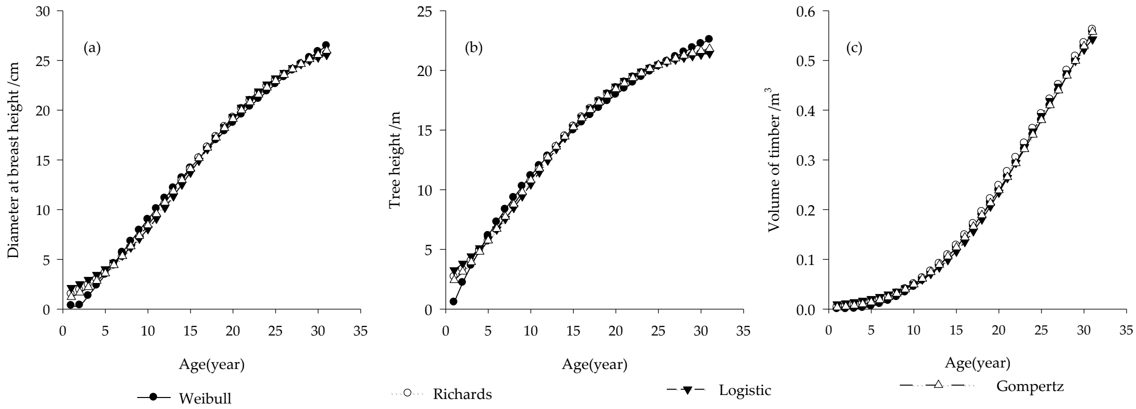

Figure 4. Diameter at breast height (a), tree height (b), and volume (c) fitted curves of the dominant teak trees using Weibull, Richards, Logistic, and Gompertz model

The tree age was used as the independent variable, and DBH, tree height, and volume of the dominant trees at different ages for the teak plantation were used as the dependent variables. The selected four models were used for fitting Weibull, Richards, Logistic, and Gompertz, the results are shown in Table 2, and the fitted curves were shown in Figure 4. By comparing the coefficient of determination (R^2), root mean square error (RMSE), and model parameter test *P* value of these four equations, the optimal-growth-fitting equation for the DBH was Weibull equation, which had the highest fitting degree ($R^2 = 0.9074$) compared with the other three, and all parameters passed the test ($P < 0.01$) and *RMSE* was the smallest (*RMSE* = 2.6983). The optimal-growth-fitting equation for tree height was the Gompertz equation ($R^2 = 0.9090$, *RMSE* = 2.6983). Although the Weibull had the highest fitting degree ($R^2 = 0.9170$) and *RMSE* was the smallest (*RMSE* = 1.9057), the parameter *b* failed to pass the test ($P > 0.01$). The optimal-growth-fitting equation for the volume was also the Gompertz equation, with the fitting degree of $R^2 = 0.8019$ and *RMSE* = 0.0815, and all parameters passed the test ($P < 0.01$). Although the Weibull had the highest fitting degree ($R^2 = 0.8022$), the parameter *b* failed to pass the test ($P > 0.01$). Therefore, the optimal-fitting models of DBH, tree height, and volume were Weibull, Gompertz, and Gompertz, respectively. The parameter estimation value *a* indicated that under the existing site conditions and management levels, the extreme growth values of DBH, tree height, and volume of teak dominant trees were 39.29 cm, 23.17 m, and 1.1831 m^3, respectively.

Table 2. Parameters and related statistics for the growth models.

Factor	Model	Sample number	Parameter estimation				R^2	*RMSE*
			a	*b*	*c*	*d*		
Diameter at breast height	Weibull	17	39.2900 (0.0000)	1.4726 (0.0019)	26.8203 (0.0000)	1.1741 (0.0000)	0.9074	2.6983
	Richards	17	28.1228 (0.0000)	0.1330 (0.0000)	1.9766 (0.0000)	0.3428 (0.0000)	0.9013	2.7857
	Logistic	17	27.0153 (0.0000)	2.6296 (0.0000)	-0.1775 (0.0000)		0.8968	2.8193
	Gompertz	17	30.0016 (0.0000)	3.5701 (0.0000)	0.1034 (0.0000)		0.9037	2.7018
Tree height	Weibull	17	30.8549 (0.0000)	0.7254 (0.0113)	22.3843 (0.0000)	0.9072 (0.0000)	0.9170	1.9057
	Richards	17	22.3450 (0.0000)	0.1487 (0.0000)	1.4444 (0.0000)	0.3824 (0.0000)	0.9051	2.0403
	Logistic	17	21.9296 (0.0000)	1.9231 (0.0000)	-0.1831 (0.0000)		0.7969	2.9843
	Gompertz	17	23.1719 (0.0074)	2.5505 (0.0000)	0.1204 (0.0000)		0.9090	2.0323

Volume of timber	Weibull	17	1.0777 (0.0000)	1.6517 (0.6121)	33.7547 (0.0000)	2.2623 (0.0000)	0.8022	0.0876
	Richards	17	0.9714 (0.0000)	0.0880 (0.0000)	1.1188 (0.0000)	0.1291 (0.0000)	0.8005	0.0878
	Logistic	17	0.6687 (0.0000)	4.3933 (0.0000)	-0.1888 (0.0000)		0.8001	0.0892
	Gompertz	17	1.1831 (0.0000)	6.3126 (0.0000)	0.0686 (0.0000)		0.8019	0.0815

Note: The values in parentheses are *P* values of the parameter significance testing.

3. Distribution characteristics of the heartwood of teak dominant trees

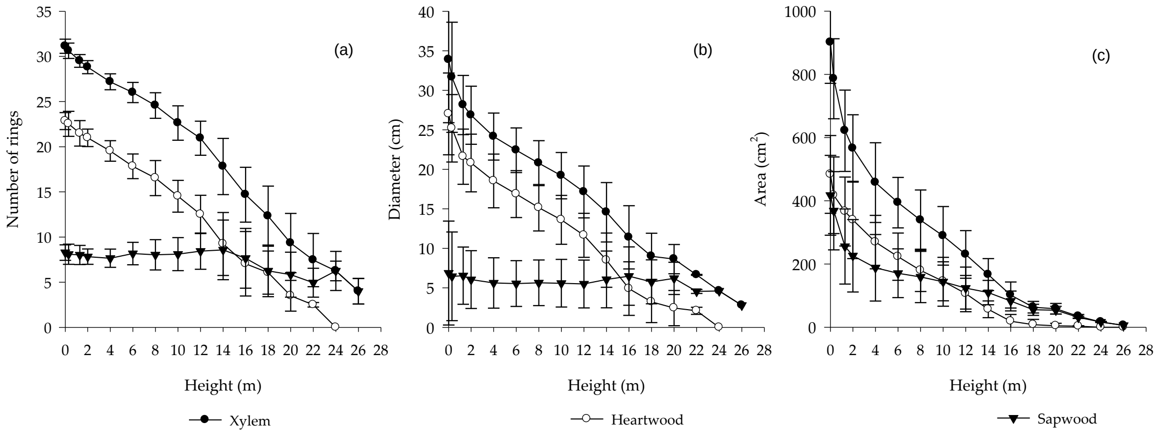

Figure 5. Vertical structure of number of rings (a), diameter (b), and area (c) of xylem, heartwood, and sapwood of dominant trees.

Figure 4 shows that the total number of growth rings and the number of heartwood growth rings in the xylem of teak dominant trees followed the increasing tree height. The number of sapwood growth rings had a smaller change with the increase in height compared with that of the heartwood: fluctuating around 8.00 below 16.00 m and gradually decreasing above 16.00 m (Figure 5a). The xylem diameter and heartwood diameter of the teak dominant trees had the same changing trend with the growth rings as the change in stem height (Figure 5b). The diameter of the sapwood also showed a smaller changing trend, fluctuating around 6.00 cm below 22.00 cm. The range of fluctuation was less than 0.5 cm except for the base (0.87 cm), and it showed gradual decrease above 22.00 m. Based on analysis of the vertical change in xylem, heartwood, and sapwood areas (Figure 5c), the heartwood area of stem xylem below 10.00 m was larger than the sapwood area, and that above 10.00 m was smaller than the sapwood area.

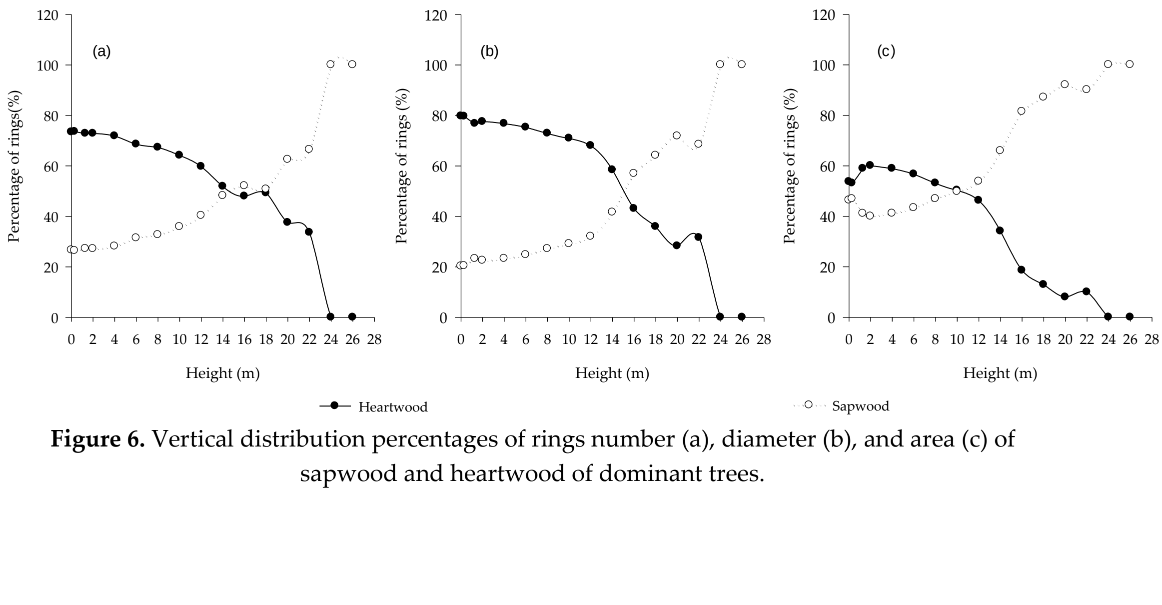

Figure 6. Vertical distribution percentages of rings number (a), diameter (b), and area (c) of sapwood and heartwood of dominant trees.

Figure 5 shows the changing trend in the ratio of the number of growth rings, diameter, and area of the heartwood and sapwood with the change in stem height. The percentages of the number of growth rings for heartwoods and sapwoods of the xylem between 0 m and 15 m showed slow decreasing and increasing trends, respectively, the percentages had a similar trend between 15 m and 18 m. The percentages of growth ring number of the heartwood and sapwood between 18 m and 24 m significantly decreased to 0% and increased to 100%, respectively (Figure 6a). The diameter of the heartwood and sapwood of the xylem showed decreasing and increasing trends (Figure 6b), respectively, with the increase in stem height, which intersected at about 15 m. Affected by the growth of the stem base, the heartwood and sapwood areas between 0 m and 2 m showed increasing and decreasing trends (Figure 6c), respectively, and generally decreasing and increasing trends, respectively, between 2 m and 24 m, intersecting at about 9 m.

4. Growth characteristics of the heartwood of teak dominant trees

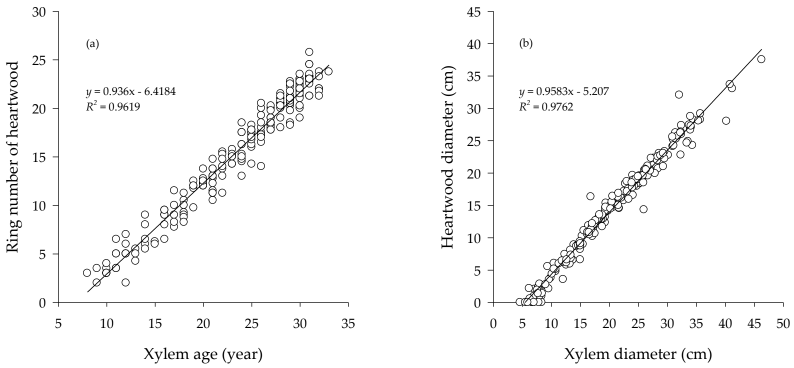

Figure 7. Regression equation of ring number of the heartwood and xylem age (a), heartwood diameter and xylem diameter (b) of dominant trees.

Figure 7a shows that the number of growth rings of the heartwood and the xylem age for teak dominant trees showed a highly significant positive correlation (F value = 4943.5630, $P < 0.01$). The rate of heartwood formation for dominant trees was 0.94, and the initial tree age of heartwood formation was the seventh year (when the number of heartwood growth rings was 0, the xylem age was 6.90). The heartwood diameter and xylem diameter showed a highly significant positive correlation (F value = 7935.9898, $P < 0.01$) (Figure 7b). The transforming width from the sapwood to the heartwood every year was 0.96 cm, and the initial stem diameter of the heartwood was 5.43 cm (when the heartwood diameter was 0, the xylem diameter was the initial stem diameter of the heartwood).

Discussion

According to the ordered clustering of current annual increment (CAI), the growth processes of DBH and tree height were divided into three phases. The tree height in the early growing phase (1–8 years) was 4 years more than the DBH (1–4 years); the duration for the DBH in the middle growing phase (stable growth stage) could last for a long time (5–18 years), more than tree height in the middle growing phase (9–13 years). This indicated that when compared with the DBH, growth of the tree in height was more sensitive to the changes in external factors [18]. Thus, it was speculated that the premature high density led to intensified competition in the stand for light, heat, water and nutrients. Although the first thinning was carried out during 6 - 8 years old, the intensity may not be enough, the increase in competition intensity among stands in the middle and late phases, affected the growth in tree height. In the tree height late growing phase (14–31 years), the minimum value of CAI was only 0.16 m· years $^{-1}$ (23 years old), but after the third thinning (during 27 - 29 years), the CAI of tree height increased to 0.86 m· years $^{-1}$(29 years old). The DBH, tree height, and volume increments were fitted, and the estimated value of the parameter *a* also showed that the extreme growth values of DBH, tree height, and volume were 39.29 cm, 23.17 m, and 1.1831 m^3, respectively. The growth curves of volume and age for the dominant trees showed that the average increment (AI) curve and the CAI curve did not intersect suggested that 31 years teak had not yet reached the age of quantitative maturity, and its increments followed an increasing trend. This was similar to study on the dominant, mean and suppressed teak trees aged about 30 years by Jia [23], who conclude that tending and management were still important at the late stage for high-quality large-sized timber production in this species.

The total number of growth rings for all tree species and the number of heartwood growth rings gradually decreased with the increase in height [22], and the increment for trees with heartwood gradually increased every year with the growth of trees [11]. In this study, the total number of growth rings and the number of heartwood growth rings in the xylems of teak dominant trees followed the trend of decreasing progressively with the increase in tree height. The number of sapwood growth rings had a smaller change with the increase in height compared with that of the heartwood; the growth ring of sapwood for the stem below 16.00 m fluctuated around 8.00 and gradually decreased for that above 16.00 m. The changes in xylem and heartwood and sapwood diameters at different heights showed the same trend as the growth rings. The sapwood diameter for the stem below 22.00 m was also stable and gradually decreased for that above 22.00 m. This was similar to the findings of Yang *et al.* [24] on the sapwood growth of 45 year-old *Cryptomeria japonica* where the number of sapwood growth rings from the stem base to the height of 10.3 m was stably maintained at 20 to 22 and gradually decreased beyond this height.

The study of heartwood and sapwood of precious timbers has important theoretical and practical significance [5]. The growth processes of the heartwood and sapwood of different tree species or different individuals of the same species of the same tree species were affected by genetic factors of trees [25], management measures [12], and other factors. The variation of the percentage of heartwood in teak trees seems to be the main parameter studied in relation to site, geographic localization, and environmental conditions [26]. Pe´rez and Kanninen [27] studied teak trees growing in dry and wet sites in Costa Rica, they found that the proportion of heartwood was significantly higher in dry sites than in wet sites. Varghese *et al.* [28] found that the sapwood proportion was different in nine localities in India. However, Taylor *et al.* [29] showed that the site conditions and management measures, such as intermediate cuttings, pruning, and fertilization, had no significant effect on the number of sapwood growth rings of trees. Kjær *et al.* [30] studying heartwood proportion in teak trees from Puerto Rico, India, Mexico, Indonesia, and Ghana. Found that trees from India and Mexico showed the highest heartwood proportion while those from Indonesia and Ghana presented the lowest heartwood proportions. It can be concluded that the proportion of heartwood varied with the source of the germplasm. The results of this study showed that although the diameter of sapwood of teak dominant trees changed little with tree height, the sapwood area gradually decreased with the increase in tree height due to the effect of the taper of the stem. Therefore, it was necessary to pay attention to the selection and promotion of improved varieties of teak with small tapering grade so as to produce more standing crops and heartwood increment in a unit area.

The initiation of heartwood formation was in the seventh year. The transforming width from the sapwood to the heartwood every year was 0.95 cm, and the initial stem diameter of the heartwood was 5.31 cm. Solo´rzano *et al.* [31, 32] revealed that the proportion of 4 year-old teak heartwood had reached 12%. Fernández-Sólis *et al.* [13] studied the growth process of teak plantations in Costa Rica, found that the heartwood was formed for individual plants of 2 or 3 year-old teak plantations. This study suggested that the number of growth rings of the heartwood and that of the xylem, heartwood diameter, and xylem diameter for the teak dominant trees showed highly significant positive correlations ($P < 0.01$). On the other hand, while fast-growth conditions quickly produce large-diameter logs [33], it also promotes more heartwood formation [34]. Thulasidas and Bhat [35] studied teak trees from wet and dry localities in India, found that trees on wet sites presented larger diameter and heartwood diameter. Therefore, the timely implementation of management measures to promote the growth of trees also promote heartwood formation.

Conclusions

The 31 and 32 years old teak plantations in south China have not reached the maturity level, its current growth and predicted maximum growth are far lower than the cultivation target (breast diameter ≥60 cm). There is a significant positive correlation between heartwood formation and diameter growth. More attention should be paid to the selection and utilization of teak varieties with small degree of sharpening to increase the volume of individual plants and the amount of heartwood. With the increase of growth competition in plantations, the DBH and tree height growth of the dominant tree in teak plantations began to decrease at 18 and 13 years old, respectively. The plantations should be thinned from 13 years old, to provide growing space for the dominant trees retained in the stand, maintaining fast growth of DBH and tree height, so as to promote formation of heartwood and achieve the goal of efficient cultivation of teak plantation for large-diameter timbers.

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