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Growth process and heartwood formation for planted teak (*Tectona grandis*) in South China

Wachstum und Kernholzbildung von Teak (*Tectona grandis*) in Plantagen Süden Chinas

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Keywords: *Tectona grandis* L. f., dominant tree, stem analysis, growth process, heartwood, sapwood, allometry, monitoring

Schlüsselbegriffe: *Tectona grandis*, Mittelstamm, Stammanalyse, Baumwachstum, Kernholz, Splintholz, Allometrie, Monitoring

Abstract

Tree growth processes and heartwood formation characteristics of teak (*Tectona grandis* L. f.) are important for the efficient management of teak plantations. We analyzed the stems of 17 dominant trees from 31- and 32-years old stands in Guangxi, South China. We measured annual increment, heartwood and sapwood dimensions for each disc on average 13 stem discs per tree (total 226 discs). Four function types (Weibull, Richards, Logistic and Gompertz) were used for testing their performance in reproducing diameter at breast, height and individual volume increment. The results showed that, both current annual increments of diameter at breast height under bark and the tree height showed similar growth trends with tree age. They increased in the first several years after planted and then decreased with tree age. The increasing current annual increment of tree height lasted a longer time than that of increase of diameter at breast height, and tree height growth had a higher variability and sensi-

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tivity. The teak has not reached the maximum mean annual increment of individual volume at 31- and 32-years old. The optimal growth fitting equations for DBH under bark, height and individual volume under bark of teak were Weibull (R^2 = 0.9074), Gompertz (R^2 = 0.9090) and Gompertz (R^2 = 0.8019), respectively. The maximum sizes of dominant tree DBH under bark, height and individual volume under bark with the existing stand density were 39.3 cm, 23.2 m and 1.18 m^3, respectively. The diameters of xylem and heartwood and sapwood width at different heights showed the same trend as their ring numbers; the sapwood width below 22 m was stable, and decreased gradually above 22 m. The area of heartwood was larger than sapwood at the lower stem section (< 10 m), but smaller at the upper stem section (> 10 m). There was a significant positive correlation between the number of heartwood rings and xylem age and also between diameter of heartwood and xylem diameter ($p < 0.01$). The rate of heartwood formation was 0.94 and the initial age and diameter of heartwood formation were 7 years old and 5.31 cm, respectively. The rate of transformation from sapwood to heartwood was 0.96 $cm \cdot yr^{-1}$. The results provided guidance for forest management and timber harvesting to maximize the plantation profits from the viewpoints of tree growth process and heartwood formation at local as well as in the main distribution zones of teak in south China.

Zusammenfassung

Baumwachstum und die Bildung von Kernholz sind wichtig für eine erfolgreiche und effiziente Bewirtschaftung von Teak Plantagen Teak (*Tectona grandis* L. F.). Hier analysierten wir 17 Probestämme von 31- und 32-jährigen Beständen in Gungxi im Süden Chinas. Wir haben den jährlichen Zuwachs (Durchmesser, Baumhöhe) sowie Kernholz und Splintholzanteile für 13 Stammscheiben pro Baum gemessen (insgesamt 226 Scheiben). Für die Modellierung von Brusthöhendurchmesser, Baumhöhe und Volumenzuwachs wurden vier Funktionstypen (Weibull, Richards, Logistic und Gompertz) getestet. Unsere Ergebnisse zeigen, dass der Zuwachs von Durchmesser unter Rinde und Baumhöhe ähnlichen Mustern folgt und an das Baumalter gekoppelt ist. In den ersten Jahren nahmen Durchmesser und Baumhöhe zu, während es zu einem nachlassenden Wachstum ab etwa 25 Jahren kam. Das Höhenwachstum hielt dabei länger an als das Durchmesserwachstum, zeichnete sich aber durch hohe Variabilität aus. Der hier untersuchte Teak-Bestand hat im Alter von 31 bzw. 32 Jahren noch nicht den maximale mittleren Volumenzuwachs erreicht. Die am besten geeigneten Funktionen für Durchmesser, Baumhöhe und Volumen waren Weibull (R^2 = 0.907), Gompertz (R^2 = 0.909) and Gompertz (R^2 = 0.802). Die größten gemessenen Werte waren 39,3 cm Brusthöhendurchmesser, 23,2 m Baumhöhe und 1,18 m^3 Stammvolumen. Die Durchmesser des Xylems, der Kernholz- und Splintholzbreite zeigten dieselben Trends wie die Jahrringanzahl, wobei die Splintholzbreite unter 22 m Höhe stabil war und darüber abnahm. Der Anteil des Kernholzes war entsprechend größer als der Anteil des Splintholzes in den unteren Stammabschnitten bis < 10 m und geringer darüber. Wir haben einen signifikanten Zusammenhang ($p < 0.01$) zwischen der Anzahl der Kernholzjahrringe und der Jahrringanzahl sowie zwischen Kernholzbreite und

Xylembreite beobachtet. Ab einem Alter von 7 Jahren kam es zu Kernholzbildung bei einem durchschnittlichen Brusthöhendurchmesser von 5,3 cm. Die Umwandlung von Splintholz in Kernholz lag bei durchschnittlich 0,96 cm pro Jahr. Diese Studie gibt Hinweise für Bewirtschaftung und Ernte mit dem Ziel der Profitmaximierung für Teak-Plantagen unter Berücksichtigung der Wachstumsprozesse und Kernholzbildung für das Hauptverbreitungsgebiet von Teak-Plantagen im Süden Chinas.

1 Introduction

Teak (*Tectona grandis* L.f.) is one of the most valuable and popular tropical hardwoods in the world due to its high wood quality, aesthetic appearance and extensive use. The increasing population and economy also cause a substantial demand for high quality teak timbers. 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 (White 1991 and Huang *et al.* 2016). However, teak logs produced from plantations are not as large and high quality as those harvested from natural forests, since it is usually planted at a high density (*e.g.* 2500 stems ha^{-1}) and the rotation is also much shorter than that in natural forests. High-quality (logs having high percentage of heartwood) and large-sized teak timber (DBH ≥ 60 cm) is especially in short supply (Zhang 2008) all over the world. Hence, the efficient cultivation of high-quality and large-sized timber is urgent now.

Tree growth process is a direct manifestation of their growth at different ages. Studying the growth process of forest trees, especially the pattern of growth and formation of the heartwood, has important theoretical and practical significance for devising rational silviculture managements of plantation forests (Liu *et al.* 2014). Stem analysis is an intuitive technique for studying the growth process of forest trees (Perez, 2008; Machado *et al.* 2010 and Liao *et al.* 2018). Based on the technique, Novaes *et al.* (2017) used total and partial stem analysis data from permanent teak plots to construct site index curves and growth and production models both at individual and stand levels. Perez (2008) modelled the growth equations of diameter at breast height (DBH), tree height and volume for teak. Koirala *et al.* (2017) fitted a suitable height-diameter equation as well as localized and generic volume equations for teak in central lowland, Nepal.

Heartwood is desirable for timber applications requiring durability and aesthetic value. Precious timber trees are especially appreciated for their heartwood. The demand and the price of logs for valuable tree species vary greatly with heartwood content all over the world (Jayawardhane *et al.* 2016). Therefore, an increase in heartwood formation through forest management measures would be valuable for plantation forestry. The growth of heartwood is positively correlated with tree age (Wang and Zhang 1998), and also significantly affected by stand density and management measures (Miranda *et al.* 2006). Fernández-Sólis *et al.* (2018) developed predictive models for sapwood thickness, heartwood radius, maximum heartwood height, heartwood percentage and heartwood volume of teak based on randomly sampled trees in each age stage. While dominant trees in the stand have the advantages of high growth rates and prolonged stage of fast growth and are also the crop tree for large-diameter timber cultivation (Li *et al.* 1991). Thus, such a study for dominant trees in a stand can be helpful for the effective management of plantations, especially for crop tree management.

To bridge the information gaps mentioned above, stem analysis of 31 and 32 years old dominant teak trees selected from plantations under traditional management measures was performed to study the growth process, heartwood formation and their relationships. The findings could provide basic data and theoretical instructions for the efficient cultivation of high-quality and large-sized log both in local teak plantations and other plantations with valuable tree species.

2 Materials and Methods

2.1 Study area

The study sites were located at Qingshan (QS) and Baiyun (BY) Experimental Fields, which are next to each other in Experimental Center of Tropical Forestry, Chinese Academy of Forestry, Pingxiang, Guangxi (Figure 1). The sites are at elevations 146 to 350 meters, in the southwest of the south subtropical monsoon climate region and adjacent to the northern margin of the north tropical zone, which belongs to a humid and subhumid climate. The mean annual temperature is 20.5–21.7°C, with maximum temperatures reaching 40.3°C and minimum temperatures as low as -1.5°C. The annual sum of active temperature (≥10°C) is 6000°C–7600°C. The mean annual precipitation is 1200–1500 mm, and the relative moisture is 80%–84% (1981–2013). The main landform types are low mountains and hills. The zonal soil is latosol, with soil thickness more than 1 m.

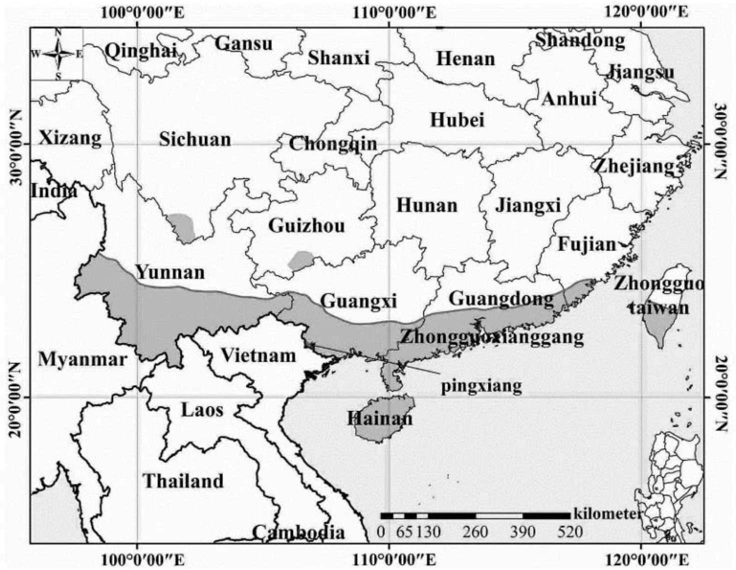

Figure 1: Location of study teak sites in Pingxiang, South China. The light gray area is the planting area of teak in China.

Abbildung 1: Lage der Untersuchungsregion in Pingxian, Süd-China. Grau unterlegt sind die Plantagenregionen von Teak.

Our selected teak plantations were planted at the end of 1981 and the beginning of 1982 with one-year-old seedlings. The planting density was 2500 trees·ha^{-1}. No irrigation and fertilization were conducted on these plantations. 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} (Table 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.

2.2 Materials

The diameter at breast height over bark, tree height, height to crown base, and crown diameters in four directions for all trees in each sample plot were measured. DBH is diameter at breast height over bark, measured at 1.3 m above ground. The mean basal area, diameter at breast height over bark, tree height, height to crown base and crown diameter of the eight sampled stands were 17.66 – 26.56 m^2·ha^{-1}, 23.71 – 28.48 cm, 16.93 – 22.23 m, 6.61 – 12.75 m and 4.93 – 7.80 m respectively. According to the results, 2–3 dominant trees were sampled for stem analysis in each plot (17 trees in total). Tree growth performance of the stand and sampled dominant and codominant trees were shown in Table 1.

Table 1: Growth performance (mean diameter at breast height (DBH) over bark and tree height) of teak in eight plots from Baiyun (BY) and Qingshan (QS) Experimental Fields. Standard deviations are provided in brackets.

Tabelle 1: Bestandeskennzahlen und Wachstum (Brusthöhendurchmesser über Rinde und Baumhöhe) für acht Probeflächen in Baiyun (BY) und Qingshan (QS) Forschungsbeständen. Standardabweichung ist in Klammern angegeben.

Plot	Stand Density (trees·ha^{-1})	Stand Age (year)	DBH (cm)	Height (m)	Number of sampled trees	Sampled dominant trees	
						DBH (cm)	Height (m)
BY1	400	32	27.05 (0.81)	18.90 (0.50)	2	32.4, 32.4	22.3, 23.4
BY2	417	32	25.91 (1.26)	16.93 (0.84)	2	31.9, 32.9	22.2, 21.9
BY3	417	32	28.48 (1.01)	18.77 (1.53)	3	32.3, 31.7, 32.3	22.6, 22.4, 22.5
QS1	400	31	23.71 (0.81)	16.94 (0.58)	2	31.5, 32.2	22.3, 21.9
QS2	433	31	26.07 (0.86)	19.40 (0.68)	2	30.9, 31.1	23.6, 23.2
QS3	417	31	25.46 (0.90)	19.97 (0.62)	2	31.9, 31.4	22.9, 22.9
QS4	417	31	25.17 (0.59)	22.23 (1.39)	2	33.1, 32.9	25.4, 24.9
QS6	400	31	27.57 (1.51)	19.42 (0.80)	2	31.7, 32.5	22.8, 22.9

2.3 Field measurement

Before the sampled trees were cut down in January 2014, their trunks were marked at east and north directions. After felled, stem discs with thickness of 5 cm were cut at the heights of 0.3, 1.3, and 2 m and then every 2 m until the tree top. The height and north orientation were marked for each disc. The discs were taken back to the laboratory and then the working face of each disk was polished and scanned with a high-definition scanner (UNIS M2900, Beijing, China). The scanned images were opened in Adobe Acrobat Professional 7.0 software, the number of heartwood, sapwood and xylem rings were identified (Figure 2), the over-bark, xylem and heartwood radii, sapwood width and the distance from each growth ring to the pith of the four cardinal directions for each disk were measured using the measuring tool in the software menu (Tang *et al.* 2015). The bark thickness ranged from 0.25 cm to 1.24 cm along stem tip to base.

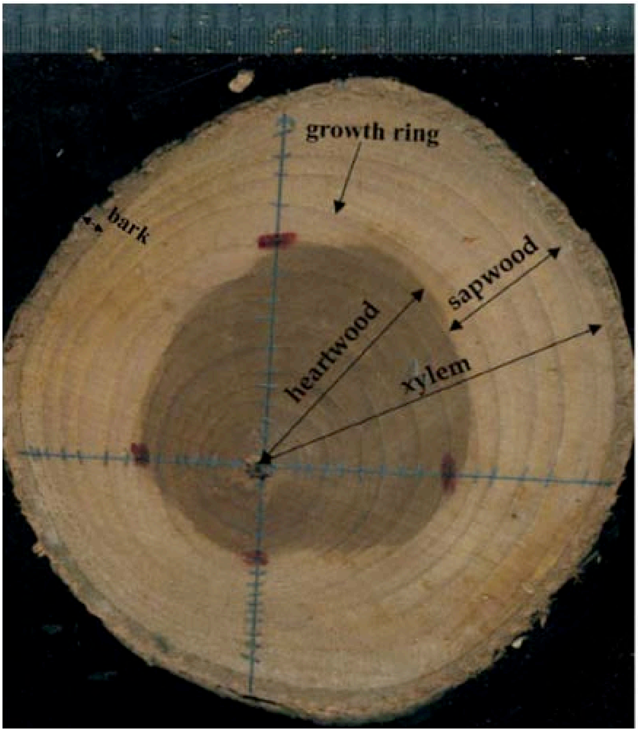

Figure 2: Sapwood, heartwood, xylem, growth ring and tree bark of teak (the first sampled dominant tree from BY1).

Abbildung 2: Splintholz, Kernholz, Xylem, Jahrringe und Rinde einer Teak Stammscheibe (von Fläche BY1).

2.4 Data processing

The ForStat 2.2 software (Li *et al.* 2004; Liu *et al.* 2013) was used to analyze the growth data of trees. The current annual increment, mean annual increment and cumulative increment of tree height, diameter at breast height under bark and individual volume were calculated by the software directly. The individual volume was the volume of stem bole under bark and excluding the stump (0.3 m in height). We assumed that the shapes of xylem and heartwood in each disc were circles. The diameters of heartwood and xylem and sapwood width were calculated as two times of the mean observations at four cardinal directions. The xylem and heartwood area were calculated as the area of its circle. The individual volume was calculated on the basis of each stem section (2 m in length). Four representative mathematical models including Weibull, Richards, Logistic, and Gompertz were used to fit growth regression equations of DBH under bark, tree height and individual volume under bark with tree age for the dominant teak trees in DPS 16.05 (Data processing system). The fitted models were further evaluated with the coefficient of determination (R^2), root mean square error (*RMSE*), and model parameter test *P* value.

Relationships between ring number of heartwood and the xylem age as well as xylem diameter were determined by regression analysis for dominant trees. Based on the regression curve, the xylem age with the heartwood ring number being 0 was defined as the initial age of heartwood formation, and the slope of regression curve indicated the rate of the heartwood formation (Pinto *et al.* 2004; Knapic and Pereira 2005; Longuetaud *et al.* 2006). 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 (Wang *et al.* 2008).

3 Results

3.1 Growth process of teak dominant trees

The average increment (AI) of DBH under bark maintained a sharp increasing trend in the first 3 years after planted, and then a slow increasing rate was observed in the following 6 years. It reached nearly 1.00 cm year^{-1} at the ninth year. After that, the AI of DBH under bark presented a mild decreasing trend with tree age and decreased much quicker after 27 years. However, it was still higher than 0.80 cm year -1 even at the time of harvest (Figure 3a). The average increment (AI) of the tree height increased from 0.93 m year^{-1} to 1.20 m year^{-1} in the first 6 years after planted and then decreased to 0.76 m year^{-1} at the 31th year (Figure 3b).

The current annual increment (CAI) of DBH under bark and tree height also increased sharply at the first several years after planted, and then decreased quickly with tree age, especially for tree height, which also showed a higher variability than DBH.

Additionally, at the late growth period (from 23 years to 29 years old), there was an obvious recovery for CAI of tree height. The highest CAI of DBH under bark and tree height both exceeded 1.4 cm year^{-1} in the third year and 1.4 m year^{-1} in the fourth year (Figure 3a, b).

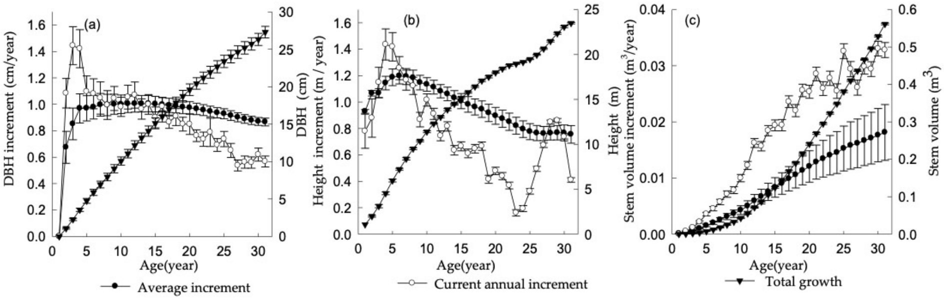

Figure 3: Observed growth of diameter at breast height under bark (DBH, a), height (b) and individual volume under bark (c) from the 17 sampled dominant trees from teak plantations in South China, the data are the means ± standard errors.

Abbildung 3: Beobachteter Zuwachs von Brusthöhendurchmesser (a), Baumhöhe (b) und Stammvolumen unter Rinde (c) von 17 Probestämmen dominanter Bäume in Teakplantagen Süd Chinas. Wir zeigen Mittelwerte ± Standardfehler.

The average increment (AI) curve of the volume under bark showed a steady growth trend and did not intersect with the current annual increment (CAI) curve. The CAI of the volume under bark 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 year^{-1}) appeared in the 25th and 30th year, respectively (Figure 3c).

3.2 Fitting of the growth process of teak dominant trees

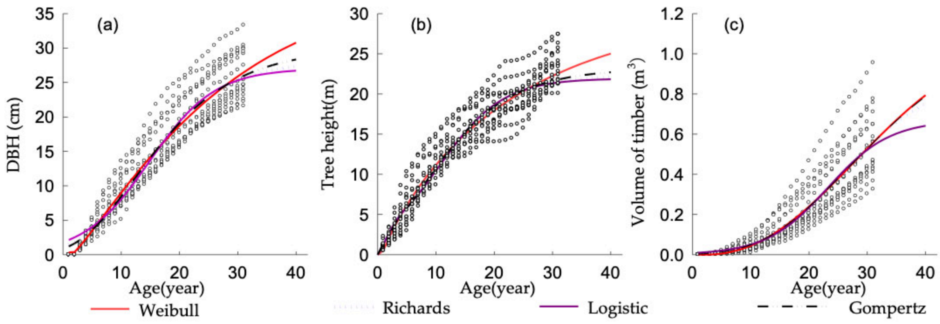

Figure 4: Fitted curves of diameter at breast height under bark (DBH, a), tree height (b) and individual volume under bark (c) for the 17 sampled dominant teak trees using Weibull, Richards, Logistic and Gompertz models.

Abbildung 4: Angepasste Wachstumskurven für Brusthöhendurchmesser (a), Baumhöhe (b) und Stammvolumen unter Rinde (c) von 17 Probestämmen unter Verwendung von Weibull, Richards, Logistic und Gompertz Modellen.

The selected Weibull, Richards, Logistic, and Gompertz models were used for fitting diameter at breast height under bark, tree height and individual volume under bark of the sampled 17 trees, 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 ($P < 0.01$) of these four equations, the optimal-growth-fitting equation for DBH under bark was Weibull equation ($R^2 = 0.9074$, $RMSE = 2.6983$). The optimal-growth-fitting equation for both tree height and individual volume under bark was the Gompertz equation ($R^2 = 0.9090$, $RMSE = 2.6983$; $R^2 = 0.8019$, $RMSE = 0.0815$). From the fitting equations (parameter 'a' asymptotes), we could conclude that the potential DBH under bark, tree height, and volume under bark of dominant teak trees under the present site conditions and stand management were 39.3 cm, 23.2 m, and 1.18 m^3, respectively.

Table 2: Parameters estimation (in brackets, P value), the coefficient of determination (R2) and root mean square error (RMSE) of the four growth models based on sampled 17 teak trees.

Tabelle 2: Parameter, deren P-Werte (in Klammer), Bestimmtheitsmaß (R^2) und root mean square error (RMSE) der vier getesteten Wachstumsmodelle.

Factor	Model	Sample number	Parameter estimation				R^2	*RMSE*
			a	*b*	*c*	*d*		
Diameter at breast height under bark	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
Individual volume under bark	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

3.3 Distribution characteristics of the heartwood for dominant teak trees

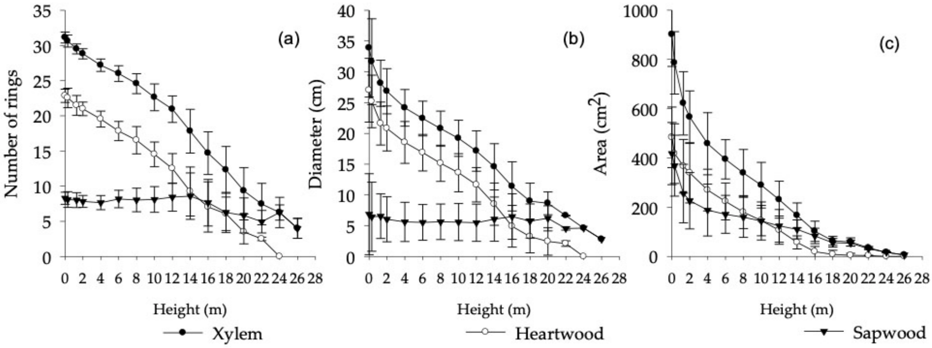

Figure 5: Variation of xylem, heartwood and sapwood for the sampled 17 dominant teak trees regarding number of rings (a), diameter or width (b) and area (c). The data are the means ± standard errors.

Abbildung 5: Variation von Xylem, Kernholz und Splintholz entlang der Stammachse für die 17 dominanten Teak Bäume hinsichtlich der Anzahl der Jahrringe (a), Durchmesser (b) und Fläche (c). Wir zeigen Mittelwert ± Standardfehler.

The number of sapwood growth rings stabilized around 8 below the stem height of 16.00 m and gradually decreased with tree height above 16.00 m (Figure 5a). A similar trend was also observed for sapwood width (Figure 5b), but significant decreasing trend was found for sapwood area (Figure 5c). The number of xylem and heartwood rings, the diameter of xylem and heartwood as well as the area of heartwood and xylem all had the same changing trend with the increment of stem height. They all decreased obviously with the increasing stem height (Figure 5a, b and c). The intersections of sapwood and heartwood for ring number, diameter and area were found at about 15 m, 15 m and 10 m, respectively.

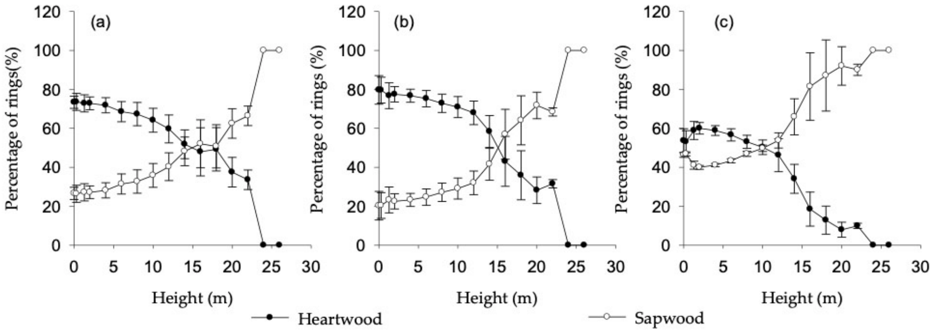

Figure 6: Percentages of ring number (a), diameter / width (b) and area (c) of sapwood and heartwood with tree height for the sampled 17 dominant Teak trees. The data are the means ± standard errors.

Abbildung 6: Prozentsatz der jahrringe (a), Durchmesser / Breite (b) und Fläche (c) von Kernholz und Splintholz enlang der Stammachse für die 17 dominanten Teak Bäume. Wir zeigen Mittelwert ± Standardfehler.

The percentages of growth ring number for heartwood and sapwood to xylem between 0 m and 15 m showed slow decreasing and increasing trends, respectively. The percentages of the heartwood and sapwood growth ring numbers between 18 m and 24 m significantly decreased to 0% and increased to 100%, respectively (Figure 6a). The percentages of heartwood diameter and sapwood width to xylem diameter showed decreasing and increasing trends (Figure 6b), respectively, with the increment of stem height, which intersected at about 15 m. The percentages of heartwood and sapwood area showed increasing and decreasing trends between 0 m and 2 m, and generally decreasing and increasing trends between 2 m and 24 m, respectively. The equal size was observed at about 9 m (Figure 6c).

3.4 Growth characteristics of the heartwood of teak dominant trees

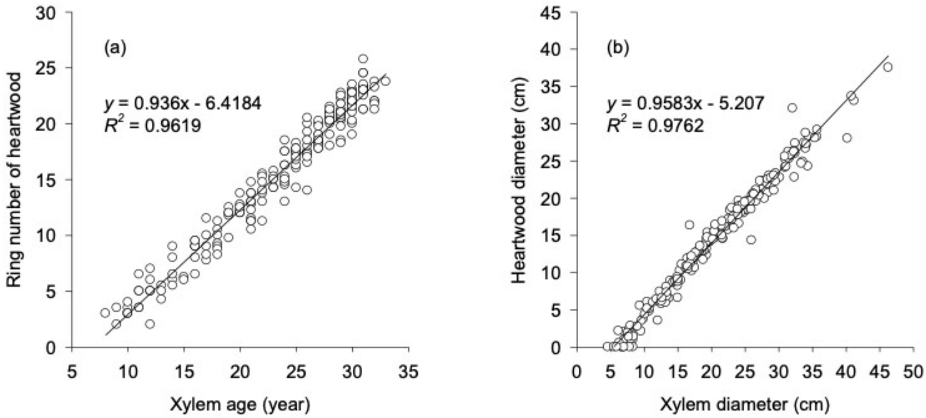

Figure 7: Regression correlations between ring number of heartwood and the xylem age (a) as well as xylem diameter (b) for dominant trees.

Abbildung 7: Regressionen zwischen Kernholzjahrringe und Baumalter (a) und Xylemdurchmesser und Kernholzdurchmesser (b).

Figure 7a showed that the number of heartwood rings and the xylem age for dominant teak trees, which presented 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 year seven (when the number of heartwood growth rings was 0, the xylem age was 6.90). The heartwood diameter also showed a highly significant positive correlation with xylem diameter (F value = 7935.9898, $P < 0.01$) (Figure 7b). The transforming rate from sapwood to heartwood was 0.96 cm year^{-1}, and the initial stem diameter for forming heartwood was 5.43 cm.

4 Discussion

4.1 Growth and rotation

In the present study, the increments of DBH under bark, tree height, and individual volume under bark for sampled dominant teak trees were fitted with tree age, and the estimated value of the parameter *a* also showed that the mean DBH under bark, tree height, and individual volume under bark of dominant trees at stand level could reach 39.3 cm, 23.2 m, and 1.18 m^3, respectively.

The growth curves of individual volume under bark and tree age for the dominant trees showed that the average increment (AI) curve and the current annual increment (CAI) curve did not intersect. These suggested that 31 years old teak had not yet reached the maximum mean annual increment of individual volume under bark (biological rotation), so its mean annual increment of individual volume under bark was still increasing. This was in accordance with Jia's (2019) study on about 30 years old dominant, mean and suppressed teak trees, where he suggested that tending and management were still important at the present stage for high-quality and large-sized timber production for this species. However, the results were quite different from previous studies from Ecuador (Cañadas-L *et al.* 2018), Costa Rica (Bermejo *et al.* 2004), Panama (Griess and Knoke 2011) and other countries, they illustrated that the maximum mean annual increment in volume occurred between 9 and 26 years from different productive sites and plantations. The large differences from our studies were mainly caused by climate condition, since their mean annual temperature and precipitation were far higher than those of our study region and mean monthly temperature was found the most significant factor affecting tree growth (Kokutse *et al.* 2010). In addition, CAI of tree height was more variable than that of DBH under bark in this study, this indicated that CAI of tree height was more sensitive to external factors. Our results on each CAI change of tree height after thinning also verified the viewpoint, especially for the latest thinning treatment. The results also demonstrated the importance of tending in efficient cultivation of valuable tree species.

4.2 Heartwood distribution

It is well known that the total number of growth rings for all tree species and the number of heartwood growth rings gradually decreased with the increasing stem height, and the amount of heartwood gradually increased every year with the growth of trees (Wang *et al.* 2008). This was also observed in this study, where the numbers of xylem rings and heartwood rings of dominant teak trees followed the trend of decreasing progressively with the increasing stem height. The number of sapwood growth rings had a smaller change with the stem height; the number of sapwood rings 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 diameters and sapwood width at different heights showed the same trend as the growth rings. The results were similar to the findings of Yang *et al.* (1994) on 45-year-old *Cryptomeria japonica* where the number of sapwood 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. Taylor *et al.* (2002) also showed that the number of sapwood growth rings was not significantly affected by site conditions, intermediate cuttings, pruning, fertilization and other management measures. However, although the sapwood width of dominant teak trees changed little with tree height, the sapwood area gradually decreased with the increasing stem height due to the effect of the taper of the stem. Therefore, it was necessary to pay attention on the selection and promotion of improved teak varieties with small tapering grade. The percentages of growth ring number for heartwood and sapwood to xylem decreased and increased with tree height, respectively. This can be explained by our above results that the number of sapwood rings, sapwood width and area changed marginally with tree height, while those of xylem and heartwood decreased with tree height. With regard to the variation of the percentage of heartwood and sapwood in the first two meters (Figure 6c), the reason may be correlated with the irregular shape of both trunk and heartwood at the base of teak trees. Furthermore, geographic localization (Kjær *et al.* 1999; Varghese et al. 2000), social status of trees (Kokutse *et al.* 2010) and environmental (Moya *et al.* 2014) and site (Pérez and Kanninen 2003), conditions were also illustrated affecting heartwood proportion. It can be concluded that the proportion of heartwood was codetermined by both inner genetic factors and external environment and management factors.

4.3 Heartwood formation

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 under bark of the heartwood formation was 5.31 cm. The result was different from previous studies on young teak plantations. Solórzano *et al.* (2012a; b) found that the proportion of 4-year-old teak heartwood had reached 12%. Fernández-Sólis *et al.* (2018) found that the heartwood was formed for individual plants of 2-or 3-year-old from the growth process of teak in Costa Rica. This may be highly correlated with the differences of heritage, site and climate conditions. In addition, the present study suggested that the number of growth rings and diameter for heartwood showed closely significant positive correlations ($P < 0.01$) with those of xylem for the dominant teak trees. The result is in coincide with Kokutse *et al.* (2010)'s study in Togo, where heartwood formation was higher in larger trees and highly correlated with stem cross-sectional area. That is to say, good site conditions produce large-diameter logs in a short rotation, and also promote more heartwood formation (Morataya *et al.* 1999; Perez 2005; Thulasidas and Bhat 2009). Therefore, increased heartwood volume can be produced by planting on good site conditions, and by timely implementation of management measures to promote the growth of trees, especially for the crop trees.

5 Conclusions

Dominant trees in the 31- and 32-year-old teak plantations in south China have not reached the maximum mean annual increment of individual volume under bark. Both the current growth and potential maximum growth are far lower than the cultivation target (DBH ≥60 cm), and the target diameter at breast height and rotation length at local should be modified to match our asymptote predictions on tree diameter at breast height under bark. There was a significant positive correlation between heartwood formation and stem diameter growth; fast diameter growth produces more total heartwood volume. More attentions should be paid both on the selection of teak varieties with small stem taper, early heartwood formation and high heartwood proportion as well as silvicultural measures (*e.g.* thinning at age 13) to promote tree growth, especially for crop trees. The results of the present study provide instructions on forest management and timber harvesting to maximize the plantation profits from the viewpoints of tree growth process and heartwood formation at local as well as in the main distribution zones of teak.

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Conflicts Interest

The authors declare that there are no financial or personal relationships with other people or organizations that could inappropriately influence this work, and that there are no professional or other personal interests of any nature or in any product, service and/or company, which could influence the positions presented herein or affect the review of the manuscript.

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