# TREE RING CHARACTERISTICS OF 30-YEAR-OLD *SWIETENIA MACROPHYLLA* PLANTATION TREES

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**Abstract.** Ring characteristics of mahogany (*Swietenia macrophylla* K.) plantation trees grown in Taiwan were explored. Significant differences in average ring width (RW) and ring density (RD) occurred among three tree-diameter classes and three radial stages of ring numbers. RW in the radial direction decreased from the pith outward to the bark and followed a distinctive three-stage variation pattern (juvenile, transition, and mature zones). RD in the radial direction increased slowly from the pith outward to the bark. Wider tree rings and lower density are associated with juvenile wood close to the pith, whereas narrower tree rings and higher density are typical for mature wood outward toward the bark. RD in overtopped trees was higher than that in dominant trees. However, RW in dominant trees was wider than that in intermediate and overtopped trees. Earlywood density, latewood density, maximum density, and minimum density were the most important factors determining overall RD. There was a weak relationship between RW and RD, indicating that it is unlikely for growth rates of mahogany plantation trees to have a significant impact on wood density.

***Keywords:*** Mahogany (*Swietenia macrophylla*), plantation, ring characteristics, ring width, ring density.

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## INTRODUCTION

Big-leaf mahogany (*Swietenia macrophylla* King) has been a highly valuable neotropical timber species for centuries (Verissimo et al 1995; Grogan et al 2005). Grogan and Barreto (2005) indicated that the species gained strengthened regulatory protection from its listing in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). Mahogany plantation trees should become an important timber resource. Dűnisch and Rűhmann (2006) determined that there are no other suitable species available as acceptable substitutes for mahogany, and therefore, there is a strong incentive to cultivate mahogany.

In Taiwan, big-leaf mahogany was introduced in 1899 and has been extensively planted on plains and hills of subtropical climate (Liu et al 1981). Conservation ethics and wood resource shortages have stimulated sustainable forest management to meet multipurpose needs of present and future generations. People concerned with forest conservation and wood use would benefit from knowing tree growth performance (eg ring width [RW]) and wood quality traits (eg ring density [RD]). Stand structure and growth performance of big-leaf mahogany plantations in Taiwan have been examined (Chang 2008, 2010). Mahogany is selected for plantations mainly because of its growth rate and wood properties. Mahogany growth and its timber quality are affected by site and climate conditions (Mayhew and Newton 1998). Some studies have focused on wood properties (Francis 2003; Moya and Muňoz 2010; Langbour et al 2011), but little attention has been paid to ring characteristics. Lieberman et al (1985) indicated that earlywood is not clearly distinguishable from latewood in many hardwood species grown in tropical areas. Dünisch et al (2002) indicated that the high rate of periclinal cell divisions and formation of relatively large vessels observed after a cambial dormancy gave further evidence for this function of terminal parenchyma bands in the adult phase of mahogany trees. Also, formation of vessel bands in juvenile wood of mahogany trees was not correlated with a cambial dormancy and has to be considered false ring formation caused by short-time changes in exogenous input (Schweingruber 1988). However, with X-ray densitometric techniques, there may be an opportunity for ring characteristics to be analyzed by variations in density profile.

Tree ring analysis is widely applied for many purposes (eg dendroarcheology, dendrochronology, and dendroclimatology). RW and RD components can be explored by X-ray densitometric techniques (Lin et al 2010, 2011). Ring characteristics (RW, RD, and latewood percentage [LWP]) are useful indicators of environment, forest management, and product manufacturing because they are strongly correlated with many other traits, such as climate, tree diameter growth, and wood strength properties (Zobel and van Buijtenen 1989; Alteyrac et al 2006). Therefore, both RW and RD are used as indicators of environmental conditions, and information of ring characteristics provides a useful reference for forest ecology, management, and wood use. The purpose of this study was to explore variations in ring characteristics of mahogany plantation trees of different sizes and ring positions.

## MATERIALS AND METHODS

The experimental trees are located in compartment 4, Xinhua Experimental Forest, Tainan County, southern Taiwan, as administered by the National Chung Hsing University, Taichung, Taiwan. Mean annual temperature is 23.9°C, RH is 79%, mean annual precipitation is 2.52 m (2004-2007), and elevation is 35-152 m. The area of this study site was about 2 ha. The mahogany plantation stand was established at a density of 1500 trees/ha$^{-1}$ in 1980, and this stand has not undergone silvicultural treatment so far. Stand structure was investigated in 2007 (Chang 2008). Average forest stand density was 720 trees/ha$^{-1}$, and average diameter at breast height (DBH) and tree height were 265 mm and 20.5 m, respectively. DBH is foundational and important for deciding sample trees and understanding their corresponding wood properties. A total of 31 sample trees selected by randomization represents the mahogany plantation stand.

An increment corer was used to cut 5-mm-diameter cores from sample trees. From the eastern quadrant of each sample tree, we extracted a pith-to-bark increment core specimen at the DBH position (same direction) in late 2010, when specimens were 30 yr old. All core specimens were mounted and processed into slices for X-ray densitometric scanning. A total of 31 core specimens was further examined. Thus, there were 31 trees (31 core specimens) selected and 30 rings (30 yr old) were measured for each tree. However, some rings near the pith at the DBH position were absent (one or two rings), and a total of 886 rings was measured for nine ring characteristics.

An X-ray densitometric technique was used on the slices (cores) to determine ring characteristics. Volatiles of the slices were extracted using distilled water and an alcohol–benzene solution. Conditioned slices were subjected to a direct-reading X-ray densitometer (commercial device, QTRS-01X tree ring analyzer, Quintek Measurement Systems [QMS], Knoxville, TN) for ring characteristics. Each slice (at 12% MC) was scanned and moved through the X-ray machine in the radial direction.

The main case of the QTRS-01X contains both an X-ray source and a high-voltage power supply (25,000 V). The standard collimator supplied with the QTRS-01X analyzer measures approximately 0.038 mm wide and 1.59 mm high at the detector. Sample step size can be adjusted at 0.02-mm increments. Density is determined by the QTRS-01X scanning system according to the relationship between X-ray attenuation and density (QMS 1999).

The tree ring analyzer actually determines radiation absorption from a collimated X-ray beam of a narrowly controlled energy range. That absorption is related to the actual sample density according to basic radiation attenuation principles. The RD boundary was identified by a fixed-density threshold. According to density profiles, the earlywood/latewood boundary in each ring was defined by an average of both maximum (Dmax) and minimum density (Dmin) in the ring. Therefore, the density profile and ring characteristics were confirmed and determined with a tree ring analysis program (attached to the QMS). Ring characteristics included average tree RW, earlywood width (EW), latewood width (LW), RD, earlywood density (ED), latewood density (LD), Dmax, Dmin, and LWP in rings across the sample. All specimens reached approximately 12% MC, and wood density value (at 12% MC) was adopted when ring density components were converted from the degree of X-ray absorption.

## RESULTS

### Ring Characteristics

Figure 1 shows the RD profile for the mahogany plantation sample (Tree no. 5), revealing density variations (profile) inside tree rings caused by earlywood and latewood width and density. All ring characteristics of mahogany trees could be affirmed by tree ring analysis. Table 1 summarizes average ring characteristics of all rings at breast height in all sampled mahogany trees. Average RW, RD, and LWP of mahogany trees were 4.85 mm, 525.0 kg $m^{-3}$, and 24.7%, respectively.

### Ring Width

Difference in average RW, EW, and LW among sampled trees and rings was analyzed using ANOVA. The results are shown in Table 2. As can be seen, significant differences in RW components occurred between trees and rings (except for LW between rings).

For understanding effects of tree sizes on ring characteristics, all 31 sampled trees were classified into three groups according to RW (growth rate or tree diameter classes in this case) of individual trees. They are dominant tree (Tree A, mean RW = 4.56-9.22 mm, n = 11), intermediate tree (Tree B, mean RW = 4.01-4.45 mm, n = 10), and overtopped tree (Tree C, mean RW = 2.72-4.00 mm, n = 10). Differences in average RW, EW, and LW among the three tree diameter groups were analyzed using ANOVA (Table 3). Significant differences in

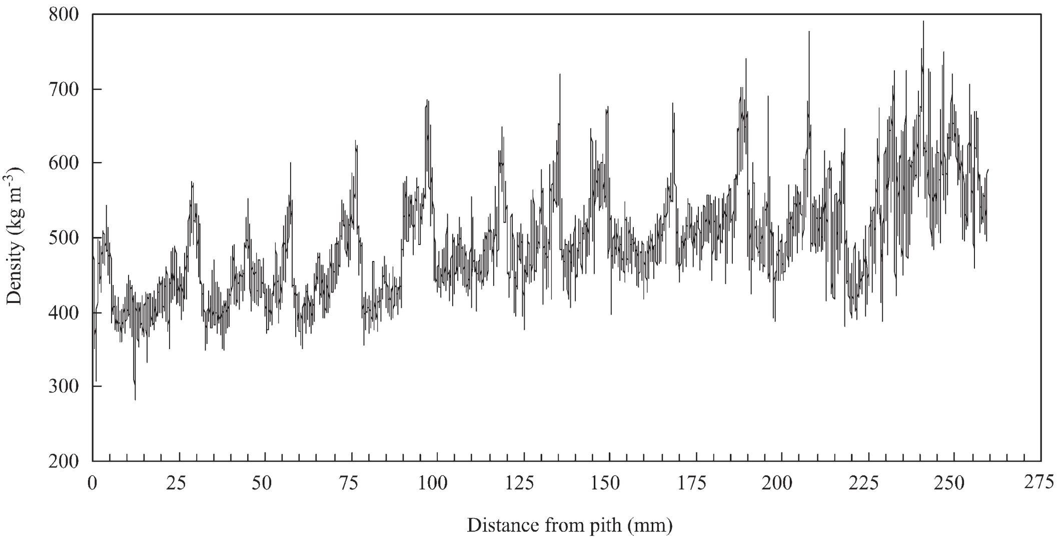


Figure 1. Radial ring density profile of mahogany plantation tree obtained by X-ray densitometric technique (Tree no. 5).

Table 1. Average tree ring characteristics of mahogany plantation trees based on all rings at breast height of all sampled trees (N = 31).[a]

| Components | Value | CV (%) | SE |
|---|---|---|---|
| Width (mm) | | | |
| Ring | 4.85 | 67.5 | 0.11 |
| Earlywood | 3.85 | 76.5 | 0.10 |
| Latewood | 0.99 | 86.3 | 0.03 |
| Density ($kg \cdot m^{-3}$) | | | |
| Ring | 525.0 | 11.1 | 1.95 |
| Earlywood | 491.6 | 9.5 | 1.56 |
| Latewood | 581.8 | 8.0 | 1.57 |
| Lowest | 428.3 | 14.3 | 2.06 |
| Highest | 639.5 | 11.1 | 2.39 |
| LWP (%) | 24.7 | 61.4 | 0.51 |

[a] CV, coefficient of variation; SE, standard error; LWP, latewood percentage.

RW components occurred among the three groups. A comparison of average RW components of mahogany plantation trees is shown in Table 4. According to Tukey test results, average RW in Tree A was significantly larger than that in Trees B and C (6.06 vs 4.56 and 3.78 mm). However, average EW and LW analyzed by Tukey test showed the following trend: Tree A > Tree B > Tree C (Table 4). Therefore, specimens of Tree A (dominant tree) had larger RW than that of Trees B and C (intermediate and overtopped trees).

Interring (radial) variations in RW components of mahogany plantation trees are shown in Fig 2. As can be seen, both RW and EW in the radial direction increased from pith outward to about the 7th ring and then gradually decreased to the 21st and 26th rings, respectively. Finally, they remained almost constant toward the bark. However, there was little change in LW in the radial direction from pith to bark.

For understanding effects of tree ages on ring characteristics, all 30 rings in the radial position at breast height were divided into three groups, namely, Ring A (from the 1st outward to the 7th ring), Ring B (from the 8th outward to the 21st ring), and Ring C (from the 22nd ring outward to the bark). Differences in average RW, EW, and LW among the three radial positions were analyzed using ANOVA (Table 5). Significant differences in RW components occurred among the three radial positions. Average RW and EW analyzed by Tukey test showed the following trend: Ring A > Ring B > Ring C (Table 6). However, average LW in Ring A was significantly larger than that in Rings B and C (1.23 vs 0.96 and 0.90 mm) (Table 6). All rings in the radial position were also separated into three zones, namely, juvenile, transition, and mature. Variations in average RW of the three zones showed the following trend: juvenile > transition > mature zones. Wider tree

Table 2. ANOVA results of differences in ring characteristics of mahogany plantation between trees and rings.[a]

| Variance | Tree | Ring | Residual | Total |
|---|---|---|---|---|
| Degrees of freedom | 30 | 29 | 826 | 886 |
| Width | | | | |
| Ring | | | | |
| Sum of squares | 1,502.4 | 2,591.6 | 5,395.6 | 30,272 |
| Mean square | 50.1 | 89.4 | 6.5 | |
| F value | 7.7* | 13.7* | | |
| Earlywood | | | | |
| Sum of squares | 1,164.5 | 2,264.2 | 4,300.6 | 20,853 |
| Mean square | 38.8 | 78.1 | 5.2 | |
| F value | 7.5* | 15.0* | | |
| Latewood | | | | |
| Sum of squares | 91.0 | 23.6 | 535.5 | 1,524.7 |
| Mean square | 3.0 | 0.8 | 0.6 | |
| F value | 4.7* | 1.3 | | |
| Density | | | | |
| Ring | | | | |
| Sum of squares | 969,264 | 871,573 | 1,169,863 | 2.47E+08 |
| Mean square | 32,308.8 | 30,054.3 | 1,416.3 | |
| F value | 22.8* | 21.2* | | |
| Earlywood | | | | |
| Sum of squares | 838,253 | 365,083 | 707,642 | 2.16E+08 |
| Mean square | 27,941.7 | 12,589.1 | 856.7 | |
| F value | 32.6* | 14.7* | | |
| Latewood | | | | |
| Sum of squares | 832,267 | 345,291 | 76,0271 | 3.02E+08 |
| Mean square | 27,742.2 | 11,906.6 | 920.4 | |
| F value | 30.1* | 12.9* | | |
| Lowest | | | | |
| Sum of squares | 895,109 | 733,277 | 1,686,930 | 1.66E+08 |
| Mean square | 29,837 | 25,285 | 2,042 | |
| F value | 14.6* | 12.4* | | |
| Highest | | | | |
| Sum of squares | 959,730 | 1,035,219 | 2,516,674 | 3.67E+08 |
| Mean square | 31,991 | 35,697 | 3,047 | |
| F value | 10.5* | 11.7* | | |
| LWP[b] | | | | |
| Sum of squares | 2,523.7 | 42,484.0 | 136,282 | 74,167 |
| Mean square | 837.6 | 1,465.0 | 165.0 | |
| F value | 5.1* | 8.9* | | |

[a] Asterisk indicates significance at 5% level by F-test.
[b] LWP, latewood percentage.

rings are associated with juvenile wood close to the pith, whereas narrower tree rings are typical for mature wood toward the bark.

## Ring Density

Differences in average RD, ED, LD, Dmin, and Dmax among sampled trees and rings were analyzed using ANOVA (Table 2). As can be seen, significant differences in RD components occurred among trees and among rings.

Differences in average RD, ED, LD, Dmin, and Dmax among the three tree diameter groups were analyzed using ANOVA (Table 3). Significant differences in RD and Dmin occurred among the three tree-diameter groups. A comparison of average RD components of mahogany plantation trees is shown in Table 4. According to Tukey

Table 3. ANOVA results of differences in ring characteristics of mahogany plantation among three tree diameter classes.[a]

| Components | Groups | Sum of squares | Degrees of freedom | Mean square | F value |
|---|---|---|---|---|---|
| Width | | | | | |
| Ring | Between | 822.5 | 2 | 411.2 | 42.0* |
| | Within | 8,637.6 | 883 | 9.8 | |
| | Total | 9,460.1 | 885 | | |
| Earlywood | Between | 545.3 | 2 | 272.7 | 33.7* |
| | Within | 7,153.0 | 883 | 8.1 | |
| | Total | 7,698.3 | 885 | | |
| Latewood | Between | 28.5 | 2 | 14.2 | 20.2* |
| | Within | 621.8 | 883 | 0.7 | |
| | Total | 650.3 | 885 | | |
| Density | | | | | |
| Ring | Between | 23,275.9 | 2 | 11,638.0 | 3.5* |
| | Within | 2,968,985.9 | 883 | 3,362.4 | |
| | Total | 2,992,261.8 | 885 | | |
| Earlywood | Between | 5,518.3 | 2 | 2,759.1 | 1.3 |
| | Within | 1,906,322.8 | 883 | 2,158.9 | |
| | Total | 1,911,841.0 | 885 | | |
| Latewood | Between | 3,421.9 | 2 | 1,710.9 | 0.8 |
| | Within | 1,933,629.7 | 883 | 2,189.8 | |
| | Total | 1,937,051.6 | 885 | | |
| Lowest | Between | 34,180.4 | 2 | 17,090.2 | 4.6* |
| | Within | 3,281,765.7 | 883 | 3,716.6 | |
| | Total | 3,315,946.2 | 885 | | |
| Highest | Between | 11,458.3 | 2 | 5,729.1 | 1.1 |
| | Within | 4,471,485.4 | 883 | 5,064.0 | |
| | Total | 4,482,943.6 | 885 | | |
| LWP[b] | Between | 1,309.9 | 2 | 654.9 | 2.9 |
| | Within | 201,434.3 | 883 | 228.1 | |
| | Total | 202,744.2 | 885 | | |

[a] Asterisk indicates significance at 5% level by F-test.
[b] LWP, latewood percentage.

test results, average RD and Dmin in Tree C were significantly higher than those in Tree A (532.4 vs 520.8 and 435.7 vs 420.7 kg·m$^{-3}$). However, no significant differences in ED, LD, and Dmax were found among the three tree diameter groups.

Interring (radial) variations in RD components of mahogany plantation trees are shown in Fig 3. As can be seen, RD components in the radial direction increased gradually from pith outward to bark. Differences in average RD, ED, LD, Dmin, and Dmax among the three radial positions were analyzed using ANOVA (Table 5). Significant differences in RD components occurred among the three radial positions. Average RD components analyzed by Tukey test showed the following trend: Ring C > Ring B > Ring A (Table 6). Also, variations in average RD components in the three zones showed the following trend: mature > transition > juvenile. These results displayed that narrower RW and higher RD components were associated with mature wood toward the bark side, whereas wider RW and lower RD components were typical of juvenile wood close to the pith.

## Latewood Percentage

Differences in average LWP among sampled trees and rings were analyzed using ANOVA (Table 2). As can be seen, significant differences in average LWP occurred among all trees and among rings. Differences in average LWP among the three tree diameter groups were analyzed using ANOVA (Table 3). However, no significant differences in LWP occurred among the

Table 4. Comparison of ring characteristics among three tree diameter classes.[a]

| Variables[b] | Tree A | Tree B | Tree C |
|---|---|---|---|
| Width (mm) | | | |
| Ring | 6.06 a | 4.56 b | 3.78 b |
| CV (%) | 60.8 | 64.2 | 68.6 |
| SE | 0.21 | 0.17 | 0.15 |
| Earlywood | 4.85 a | 3.61 b | 2.99 c |
| CV (%) | 69.3 | 74.3 | 78.2 |
| SE | 0.19 | 0.16 | 0.14 |
| Latewood | 1.22 a | 0.96 b | 0.79 c |
| CV (%) | 85.8 | 80.4 | 79.6 |
| SE | 0.06 | 0.05 | 0.04 |
| Density ($kg{\cdot}m^{-3}$) | | | |
| Ring | 520.8 a | 522.3 ab | 532.4 b |
| CV (%) | 10.7 | 10.7 | 10.7 |
| SE | 3.14 | 3.32 | 3.68 |
| Earlywood | 490.1 a | 489.6 a | 495.2 a |
| CV (%) | 8.9 | 9.5 | 10.0 |
| SE | 2.45 | 2.76 | 2.91 |
| Latewood | 581.8 a | 579.3 a | 584.2 a |
| CV (%) | 7.7 | 7.8 | 8.6 |
| SE | 2.52 | 2.70 | 2.95 |
| Lowest | 420.7 a | 429.3 ab | 435.7 b |
| CV (%) | 14.3 | 14.2 | 14.1 |
| SE | 3.38 | 3.64 | 3.63 |
| Highest | 641.1 a | 634.3 a | 642.8 a |
| CV (%) | 10.9 | 11.1 | 11.4 |
| SE | 3.94 | 4.19 | 4.32 |
| LWP (%) | 24.7 a | 25.9 a | 24.5 a |
| CV (%) | 65.6 | 59.2 | 58.9 |
| SE | 0.85 | 0.88 | 0.91 |

[a] Tree A, RW from 4.56-9.22 mm; Tree B, RW from 4.01-4.44 mm; and Tree C, RW from 2.72-4.00 mm. Means with the same superscripts of a, b, and c within a given column show no significant difference ($p \leq 0.05$) as determined by Tukey test.

[b] CV, coefficient of variation; SE, standard error; LWP, latewood percentage.

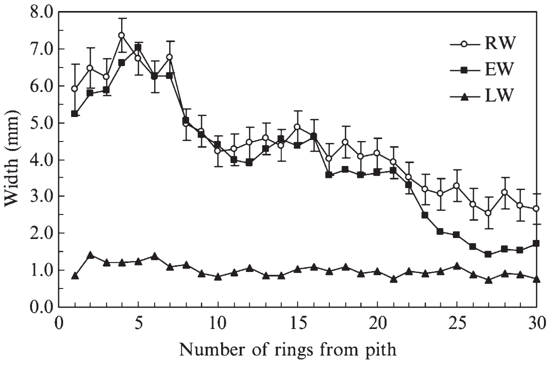


Figure 2. Interring variations in RW components of all rings in sampled trees (I, standard error; EW, earlywood width; LW, latewood width; RW, ring width).

three tree diameter groups (Table 4). This indicates that three tree sizes did not affect LWP.

Interring variations in LWP of mahogany plantation trees are shown in Fig 4. As can be seen, LWP in the radial direction increased gradually from pith outward to bark. Ring width in the radial direction increased from pith outward, decreased to a certain position, and then remained constant toward the bark. However, there is little change in LW from pith to bark. Differences in average LWP among the three radial positions were analyzed using ANOVA (Table 5). Significant differences in LWP occurred among the three radial positions. Average LWP analyzed by Tukey test displayed the following trend: Ring C > Ring B > Ring A (Table 6). Thus, variations in average LWP among the three zones showed the following trend: mature > transition > juvenile.

## Relationships Among Ring Characteristics

Table 7 shows correlation coefficients for all pairwise comparisons of ring characteristics of all rings in sampled trees. As can be seen, both EW and LW (wide components) were the most important factors determining overall RW (coefficients of relationship [$r$] were 0.79 and 0.52, respectively [$p < 0.01$]). Increments of growth (RW) were more concentrated in EW than in LW. Furthermore, ED, LD, Dmax, and Dmin (density components) with $r$ values of 0.90, 0.81, 0.83, and 0.75, respectively ($p < 0.01$) were the most important factors determining overall RD. There was a significant negative relationship between RW and RD. However, coefficients of relationship ($r = -0.36$, $p < 0.05$) were low, indicating a weak relationship between RW and RD, and therefore, it is unlikely for tree growth rates of mahogany plantation trees to have a significant impact on wood density.

### DISCUSSION

Mahogany forms a diffuse porous wood, and growth rings are distinct or indistinct in juvenile wood by stereomicroscope (Fig 5). Axial

Table 5. ANOVA results of differences in ring characteristics of mahogany plantation tree among three radial ring stages.[a]

| Components | Groups | Sum of squares | Degrees of freedom | Mean square | F value |
|---|---|---|---|---|---|
| Width | | | | | |
| Ring | Between | 2,273.8 | 2 | 1,136.9 | 139.7* |
| | Within | 7,186.2 | 883 | 8.1 | |
| | Total | 9,460.1 | 885 | | |
| Earlywood | Between | 1,985.4 | 2 | 992.7 | 153.4* |
| | Within | 5,712.9 | 883 | 6.5 | |
| | Total | 7,698.3 | 885 | | |
| Latewood | Between | 12.3 | 2 | 6.2 | 8.5* |
| | Within | 638.0 | 883 | 0.7 | |
| | Total | 650.3 | 885 | | |
| Density | | | | | |
| Ring | Between | 736,605.2 | 2 | 368,302.6 | 144.2* |
| | Within | 2,255,656.6 | 883 | 2,554.5 | |
| | Total | 2,992,261.8 | 885 | | |
| Earlywood | Between | 298,665.3 | 2 | 149,332.6 | 81.7* |
| | Within | 1,613,175.8 | 883 | 1,826.9 | |
| | Total | 1,911,841.0 | 885 | | |
| Latewood | Between | 286,019.3 | 2 | 143,009.7 | 76.5* |
| | Within | 1,651,032.3 | 883 | 1,869.8 | |
| | Total | 1,937,051.6 | 885 | | |
| Lowest | Between | 577,510.1 | 2 | 288,755.0 | 93.1* |
| | Within | 2,738,436.1 | 883 | 3,101.3 | |
| | Total | 3,315,946.2 | 885 | | |
| Highest | Between | 814,307.8 | 2 | 407,153.9 | 98.0* |
| | Within | 3,668,635.8 | 883 | 4,154.7 | |
| | Total | 4,482,943.6 | 885 | | |
| LWP | Between | 34,213.3 | 2 | 17,106.7 | 89.6* |
| | Within | 168,530.9 | 883 | 190.9 | |
| | Total | 202,744.2 | 885 | | |

[a] Asterisk indicates significance at 5% level by F-test. LWP, latewood percentage.

parenchymatous cells appeared regularly in the vicinity of vessel elements or were sometimes grouped along the initial or terminal parts of annual rings that usually refer to apotracheal banded (or marginal) parenchyma (Carlquist 2001). Dünisch et al (2002) reported that parenchyma and vessel bands as well as bands of resin canals were observed in mahogany trees by anatomical observation, and they discussed that the juvenile phase of mahogany is not suitable for dendroecological studies because of high sensitivity of wood formation to exogenous input and a high portion of increment zones that was not formed annually during the juvenile phase.

In this study, average RW of mahogany trees was 4.85 mm (Table 1). High coefficient of variation (CV) in RW was caused by data points of all trees and rings being collected to calculate average value. CVs of RW in three tree diameter classes and radial ring stages were high (Tables 4 and 6). Dűnisch et al (2003) recorded that mean RW of mahogany plantation trees was 3.49 $\pm$ 1.82 mm (90-170 yr old, CV = 52.1%). Furthermore, average RD of mahogany trees was 525.0 kg $m^{-3}$ (Table 1). All CVs (9.4-11.1%) of RD were low (Tables 1, 4, and 6). Montes et al (2007) reported that CV of wood density was about 6% in *Calycophyllum spruceanum* trees. Some studies reported that wood densities (12% MC) of mahogany plantation trees were 472-549 (Langbour et al 2011), 494 (Francis 2003), and 524 kg/$m^3$ (Moya and Muňoz 2010). However, when measurements were presented by standard error (SE = standard deviation/n), all SE values were low (for RW, SE = 0.11-0.31, and for RD, SE = 1.95-3.68; Tables 1, 4, and 6).

Variations in general radial patterns occur because of juvenile wood presence and its relative

Table 6. Comparison of ring characteristics among three radial ring stages.[a]

| Variables[b] | Ring A | Ring B | Ring C |
|---|---|---|---|
| Width (mm) | | | |
| Ring | 7.42 a | 5.10 b | 2.86 c |
| CV (%) | 55.5 | 52.5 | 71.8 |
| SE | 0.31 | 0.13 | 0.12 |
| Earlywood | 6.19 a | 4.14 b | 1.96 c |
| CV (%) | 59.3 | 59.7 | 83.6 |
| SE | 0.28 | 0.12 | 0.10 |
| Latewood | 1.23 a | 0.96 b | 0.90 b |
| CV (%) | 100 | 76.2 | 78.9 |
| SE | 0.09 | 0.04 | 0.04 |
| Density ($kg \cdot m^{-3}$) | | | |
| Ring | 487.7 a | 514.2 b | 565.0 c |
| CV (%) | 9.8 | 9.7 | 9.4 |
| SE | 3.64 | 2.40 | 3.17 |
| Earlywood | 467.6 a | 484.8 b | 516.9 c |
| CV (%) | 9.9 | 8.4 | 0.4 |
| SE | 3.52 | 1.96 | 2.59 |
| Latewood | 554.1 a | 578.0 b | 604.8 c |
| CV (%) | 7.3 | 7.4 | 7.6 |
| SE | 3.07 | 2.04 | 2.75 |
| Lowest | 400.2 a | 415.9 b | 464.9 c |
| CV (%) | 15.4 | 12.8 | 11.9 |
| SE | 4.69 | 2.56 | 3.31 |
| Highest | 592.4 a | 633.4 b | 678.1 c |
| CV (%) | 9.6 | 10.3 | 9.9 |
| SE | 4.32 | 3.14 | 4.03 |
| LWP (%) | 19.8 a | 23.9 b | 30.1 c |
| CV (%) | 73.9 | 65.0 | 41.0 |
| SE | 0.99 | 0.68 | 0.82 |

[a] Ring A, from 1st outward to 7th ring from pith; Ring B, from 8th outward to 21st ring from pith; and Ring C, from 22nd ring outward to bark. Means with the same superscripts of a, b, and c within a given column show no significant difference ($p \leq 0.05$) as determined by Tukey test.

[b] CV, coefficient of variation; SE, standard error; LWP, latewood percentage.

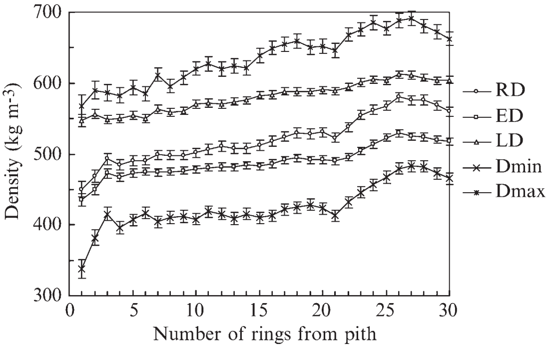


Figure 3. Interring variations in RD components of all rings in sampled trees (I, standard error; ED, earlywood density; LD, latewood density; RD, ring density; Dmin, minimum density in a ring; Dmax, maximum density in a ring).

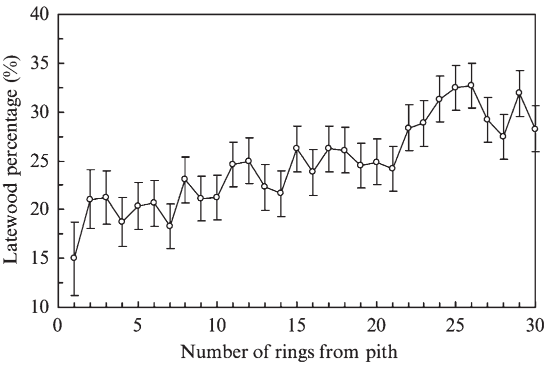


Figure 4. Interring variations in latewood percentage of all rings in sampled trees (I, standard error).

proportion to mature wood (Zobel and Sprague 1998). Rapid change occurred in the juvenile wood zone, whereas mature wood was much more constant (juvenile and mature zones, two-stage pattern). The undefined zone in between them is often referred to as the transition zone, thus forming a distinctive three-stage variation pattern. There are different criteria for determining the juvenile period; for example, RW decreases from pith outward for a number of years and then remains mostly constant (Haygreen and Bowyer 1982; Zobel and Sprague 1998). Researchers generally agree that juvenile wood predominates in the first 5-20 growth rings (Haygreen and Bowyer 1982). In this study, transition between juvenile and mature wood as determined by visual interpretation of graphically plotted radial variation in RW was at about the 8th to 21st ring from the pith (Fig 2). Thus, overall, RW in the radial direction decreased from pith outward to bark and followed a distinctive three-stage variation pattern (juvenile, transition, and mature zones).

In this study, RD components in the radial direction increased gradually from pith outward to bark. Furthermore, higher tree RD components are associated with mature wood toward the bark side, whereas lower tree RD components are typical of juvenile wood close to the pith. Bosman et al (1994) reported that radial variation in wood density of light red meranti (*Shorea leprosula* Miq. and *S. parvifolia* Dyer, two

Table 7. Coefficients of relationships between tree ring characteristics of mahogany plantation of all rings in sampled trees.[a]

| Variable | RW | EW | LW | RD | ED | LD | Dmin | Dmax | LWP |
|---|---|---|---|---|---|---|---|---|---|
| RW | 1.00 | 0.79** | 0.52** | −0.36** | −0.28** | −0.20** | −0.36** | −0.11** | −0.26** |
| EW | | 1.00 | 0.25** | −0.47** | −0.32** | −0.23** | −0.41** | −0.24** | −0.35** |
| LW | | | 1.00 | 0.00 | −0.05 | −0.09** | −0.09** | 0.14** | 0.55** |
| RD | | | | 1.00 | 0.90** | 0.81** | 0.83** | 0.75** | 0.31** |
| ED | | | | | 1.00 | 0.78** | 0.86** | 0.61** | 0.20** |
| LD | | | | | | 1.00 | 0.58** | 0.85** | 0.08* |
| Dmin | | | | | | | 1.00 | 0.47** | 0.20** |
| Dmax | | | | | | | | 1.00 | 0.26** |
| LWP | | | | | | | | | 1.00 |

[a] EW, earlywood width; LW, latewood width; RW, ring width; ED, earlywood density; LD, latewood density; RD, ring density; Dmin, minimum density in a ring; Dmax, maximum density in a ring; LWP, latewood percentage.

* and ** indicate significance at 5 and 1% level by F-test.

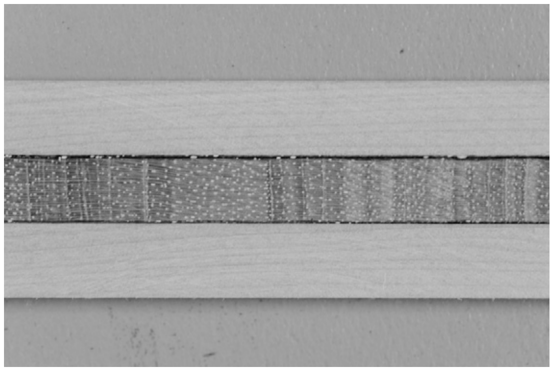

Figure 5. Tree ring in cross section of X-ray specimen obtained from mahogany plantation tree (no. 15).

diffuse porous hardwoods) increased from pith to bark. Montes et al (2007) researched that wood density increased significantly from pith to bark in *Calycophyllum spruceanum* trees. Zobel and Sprague (1998) found that only a moderate relationship between age and wood density occurred in many diffuse porous hardwoods, especially in most eucalypts and poplars. One can generalize for wood density that the middle to high wood density diffuse porous hardwoods generally follow the pattern of low wood density near the pith, then a gradual increase, followed by a leveling off toward the bark. Mayhew and Newton (1998) found that within an individual tree, mahogany wood immediately surrounding the pith was found to be of lowest wood density. Zobel and van Buijtenen (1989) reported an increase in wood density from the pith outward in mahogany trees. Montes et al (2007) found that fast-growing diffuse porous hardwoods exhibited a general increase in density from pith to bark. Also, as tree height increased, trees must also increase their structural stability, and this can be achieved by producing successively denser wood each year. de Castro et al (1993) found that with successive increases in stature, a tree produces new secondary xylem with higher wood density to compensate for structural weakness, and radial increases in wood density are normal.

Generally, growth of natural forest trees was slower than that of plantation trees. Langbour et al (2011) found that wood density of mahogany plantation trees was significantly lower than that of natural forest trees. Observations from natural mahogany forests by Mayhew and Newton (1998) indicated that plantation timber quality can be improved by decreasing growth rates and that growth and timber quality of mahogany plantation trees are affected by site and climatic conditions.

In this study, there was a significant weak negative relationship ($r = -0.36$, $p < 0.05$) between RW and RD. Hence, it is unlikely for growth rates of mahogany plantation trees to have a significant impact on wood density. Zobel and van Buijtenen (1989) and Saranpää (2003) assumed that there were positive and negative relationships, weak correlation, and no relationship between growth rate (or RW) and wood density in diffuse porous hardwoods. Zobel and Jett (1995) found that diffuse porous hardwoods showed little or no relationship between growth rate and wood density. Regarding the relationship of growth rate and wood density in mahogany trees, Zobel and van Buijtenen (1989) found that wood density increased with growth rate but no relationship was found between tree size and wood density. Age-dependent and radius-dependent models were developed to illustrate radial increases in wood density. de Castro et al (1993) summarized that for *Joannesia princes* plantation trees, predictions of the age-dependent determination of wood density were confirmed and predictions of the radius-dependent determination of wood density were rejected. Chowdhury et al (2009) reported that the wood density increment increased up to about 80 mm radial distance from the pith and then was almost constant toward the bark in *Acacia auriculiformis* and variation of wood density was radius-dependent. However, variations in RW and RD were complex and were affected by tree stem positions, cambium ages, growth traits, genetic factors, environmental conditions, and other factors.

## CONCLUSIONS

The purpose of this study was to explore ring characteristics of mahogany plantation trees and compare variations in ring characteristics of different tree growth classes and ring stages. ANOVA results revealed significant differences in RW and RD components among the three tree diameter classes and the three zones in the radial direction. RW in the radial direction increased from pith outward to the 7th ring and then gradually decreased to the 21st ring. Finally, it remained almost constant toward the bark. Such a decrease in RW in the radial direction from the pith outward to bark followed a distinctive three-stage variation pattern (juvenile, transition, and mature zones). Conversely, RD components in the radial direction increased slowly from pith outward to bark. All sampled trees were classified into dominant, intermediate, and overtopped trees according to average RW of individual trees. Average RW in dominant trees was significantly higher than that in intermediate and overtopped trees, whereas average RD in dominant trees was significantly lower than that in overtopped trees. All rings in the radial position were separated into juvenile, transition, and mature zones. Variations in average RW in the three zones showed the following trend: juvenile > transition > mature zones. Variations in average RD components in the three zones showed the following trend: juvenile < transition < mature zones. Both RW and RD in the radial direction were significantly affected by tree age (number and position of rings). ED, LD, Dmax, and Dmin were the most important factors determining overall RD. There was a significant negative relationship between RW and RD, but coefficients of relationship ($r = -0.36$, $p < 0.05$) were low. Hence, it is unlikely for tree growth rates of mahogany plantation trees to have a significant impact on wood density.

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