Wood Properties of Young *Acacia mangium* Trees Planted in Indonesia

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Abstract

This study evaluated the wood properties of 5- and 7-year-old *Acacia mangium* trees planted in West Java, Indonesia. A plot (20 by 20 m) was selected in each stand. The stem diameter and stress-wave velocity (SWV) were measured for all trees ($n = 24$ and 18 for 5- and 7-y-old trees, respectively) in the plots. Core samples were taken from all trees in each plot using an increment borer to measure the basic density (BD) and compressive strength parallel to the grain (CS). The mean ± standard deviation stem diameter was 13.1 ± 3.0 and 21.9 ± 3.8 cm in 5- and 7-year-old trees, respectively. There was no significant correlation between stem diameter and SWV. The mean BD and CS for 5-year-old trees were 0.42 ± 0.02 g cm^{-3} and 30.0 ± 4.4 MPa, respectively, and for 7-year-old trees were 0.45 ± 0.02 g cm^{-3} and 32.8 ± 3.6 MPa, respectively. There was a positive correlation between BD and CS in 5- and 7-year-old trees ($r = 0.790$ and 0.583, respectively). The radial variation patterns for BD and CS were similar in 5- and 7-year-old trees: BD and CS gradually increased to about 6 cm from the pith, after which it was almost constant toward the bark. The results suggest that xylem maturation depends on the growth diameter in *A. mangium*.

Fast-growing tree species have recently attracted considerable attention in tropical areas because they can produce the raw materials for paper, pulp, fuel, and construction in a short time (Wahyudi et al. 1999, Ishiguri et al. 2007, Kojima et al. 2009b). However, fast-growing species produce wood that is low quality because of the presence of juvenile wood, which can cause serious problems (Wahyudi et al. 1999; Kojima et al. 2009a, 2009b).

Acacia mangium Willd. is a fast-growing species found in Southeast Asian countries (Sahri et al. 1993; Wahyudi et al. 1999; Kim et al. 2009, 2011). This species is adaptable to soil types with a wide range of pHs and exhibits rapid growth with a relatively high wood quality (Fujimoto et al. 2002; Kim et al. 2009, 2011). Therefore, large-scale plantations of this species have been established in tropical and subtropical areas, such as Malaysia, Vietnam, Bangladesh, and Indonesia (Fujimoto et al. 2002; Kim et al. 2009, 2011). Wood from *A. mangium* has many uses, including construction, boat building, furniture, cabinet making, veneer, particleboard, and pulp (Soerianegara and Lemmens 1994). Many researchers have studied the wood properties of *A. mangium,* such as its basic density (BD) and strength properties (Sahri et al. 1993, Yamamoto 1998, Wahyudi et al. 1999, Fujimoto et al. 2002, Honjo et al. 2005, Kim et al. 2009, Kojima et al. 2009b, Matsumoto et al. 2010).

In softwood species, the tracheid length increases and the microfibril angle of the S2 layer decreases from the pith to the bark, before they are stabilized at almost the same distance from the pith (Hirakawa and Fujisawa 1995). This point is considered to be the boundary between juvenile and mature wood. Shiokura (1982) determined the boundary based on the radial variation of tracheid length in softwoods. However, the boundary between juvenile and mature wood, as well as the process of xylem maturation, has yet to be fully clarified in hardwood species. Several researchers have recently tried to clarify the process of xylem maturation in tropical fast-growing hardwood species, including *A. mangium, Acacia auriculiformis* A. Cunn. ex Benth., *Eucalyptus globulus* Labill., *Eucalyptus grandis* W. Hill ex Maiden, and *Paraserianthes falcataria* (L.) Nielsen (Honjo et al. 2005; Ishiguri et al. 2007, 2009; Kojima et al. 2009b). Fujimoto et al. (2002) found that *A. mangium* had a significant difference in BD between the wood near the pith and that near the bark. Honjo et al. (2005) studied the radial

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Forest Prod. J. 62(2):102–106.

variation of fiber and vessel length in *A. mangium* to determine the boundary between juvenile and mature wood. They found that the boundary was present from 3 to 4 years of age, after which the fiber length increment was stabilized. More recently, Kojima et al. (2009b) analyzed the relationship between fiber length and distance from the pith in *A. mangium* and concluded that xylem maturation depends on the growth diameter. Thus, the process of xylem maturation in *A. mangium* has been analyzed only in terms of the radial variation of fiber length. However, the effective use of wood from fast-growing species demands the clarification of the process of xylem maturation based on wood property indicators such as BD and compressive strength parallel to the grain (CS).

In the present study, basic wood properties, i.e., BD and CS, were examined using 5- and 7-year-old *A. mangium* trees planted in Indonesia. We also examined the stress-wave velocity (SWV) of stems to estimate the strength property of the wood. The stress-wave technique is considered to be one of the nondestructive tests for evaluating the modulus of elasticity of wood because SWV has a highly positive correlation with the dynamic or static modulus of elasticity (Wang et al. 2004, Yin et al. 2011). The objectives of this study were to clarify (1) the relationship between tree growth and wood properties and (2) the radial variation of wood properties. In addition, the process of xylem maturation based on the results obtained in the present study is also discussed.

Materials and Methods

Experimental stands of 5- and 7-year-old *A. mangium* were located in Parung Panjang, Bogor, West Java, Indonesia (6°24′S, 106°33′E). In both stands, seedlings were planted at a 2 by 3-m spacing. The seed source was unknown. Thinning was conducted at 3 years in both stands and again at 6 years in the 7-year-old stand. A plot (20 by 20 m) was selected in each stand. The stem diameter at 1.3 m above the ground was measured for all trees in each plot (24 and 18 trees for 5- and 7-y-old stands, respectively). We also measured SWV of the stem for all trees in each plot. The stress-wave propagation time for a stem was measured using a commercial handheld stress-wave timer (Fakopp, Fakopp Enterprise). The start sensor and the stop sensor were set on the surface of the xylem at a 45° angle to the longitudinal direction of the stem. The distance between these sensors was 1 m: the start sensor and the stop sensor were set at 150 and 50 cm above the ground level, respectively. The stress-wave propagation time was determined six times at one position on a stem by hitting the start sensor with a small hammer. The SWV of the stem was calculated from the mean value of six stress-wave propagation time measurements using the following formula:

$$\mathrm{SWV}\,(\mathrm{km/s}) = l/t$$

where l is the sensor span (mm) and t is the stress-wave propagation time (μs). Two core samples (5 mm in diameter) were collected from all trees in each plot using an increment borer (Haglöf) to measure BD and CS at 1.3 m above the ground. Because distinct growth rings were not observed, core samples were cut into small pieces at 1-cm intervals from the pith to determine BD. The green volume of each segment was measured using the water displacement method, and the constant weight at 105°C in a laboratory oven (WFO-450ND, Eyela) was determined as the ovendried weight. The BD was calculated by dividing the ovendried weight by the green volume. The CS was measured using a core sample testing machine (Fractometer II, IML) according to the method described by Matsumoto et al. (2010). Core samples were cut into small pieces at 5-mm intervals from the pith. A specimen was placed in the testing machine and a load was applied in the longitudinal direction. The CS of each specimen was recorded as indicated by the testing machine. The mean BD and CS at every 2-cm interval were calculated before analyzing their radial variation. The mean values of BD and CS from the pith to the bark of each tree ($n = 24$ and 18 for 5- and 7-y-old trees, respectively) were calculated for determining the Pearson's correlation coefficients between BD and CS in 5- and 7-year-old trees.

The radial variation of wood properties in relation to the cambial age was calculated for evaluating the maturation process. Figure 1 shows the calculation method described in the previous study (Chowdhury et al. 2009). With this method, radial growth rate was calculated from radial diameter divided by tree age. In total, six selected trees (three trees in each age) with similar diameter were used for calculation.

Results and Discussion

Table 1 shows the wood properties of 5- and 7-year-old trees. The mean ± standard deviation stem diameter was 13.1 ± 3.0 and 21.9 ± 3.8 cm for 5- and 7-year-old trees, respectively. The mean SWV for the stems of 5- and 7-year-old trees was 3.59 ± 0.17 and 3.75 ± 0.23 km s^{-1}, respectively. There was no significant correlation between stem diameter and SWV in 5- and 7-year-old trees (Fig. 2). Dickson et al. (2003) also found no significant correlation between the tree diameter and SWV in 9- and 25-year-old *Eucalyptus dunnii* trees, which matched our results. However, there was a positive correlation between SWV and Young's modulus for logs or lumber (Wang et al. 2004,

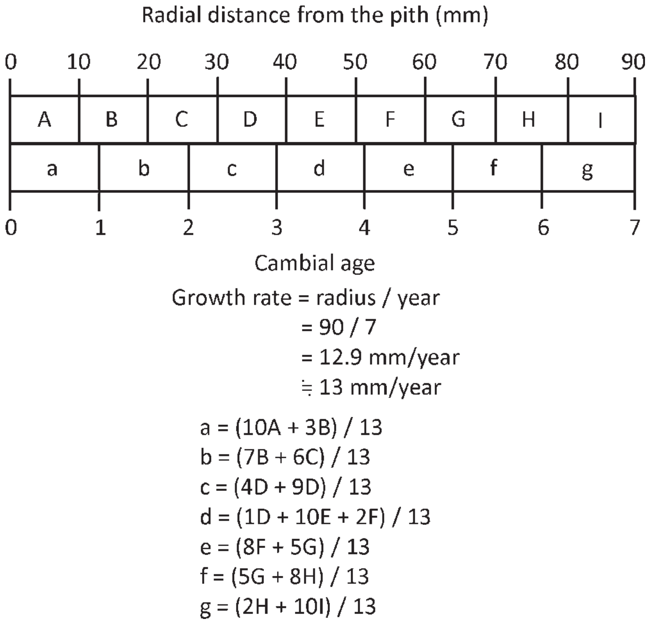

Figure 1.—Calculation method for wood properties with respect to cambial age (Chowdhury et al. 2009). Capital and lowercase letters indicate the measured and calculated values of wood properties, respectively.

Table 1.—Wood properties in 5- and 7-year-old trees.[a]

Age (y)		Stem diameter (cm)	SWV (km s^{-1})	BD (g cm^{-3})	CS (MPa)
5 (*n* = 24)	Maximum	19.0	3.92	0.56	41.3
	Mean (SD)	13.1 (3.0)	3.59 (0.17)	0.42 (0.02)	30.0 (4.4)
	Minimum	8.7	3.17	0.36	21.4
7 (*n* = 18)	Maximum	31.1	4.10	0.54	38.4
	Mean (SD)	21.9 (3.8)	3.75 (0.23)	0.45 (0.02)	32.8 (3.6)
	Minimum	15.3	3.33	0.38	26.5

[a] SWV = stress-wave velocity; BD = basic density; CS = compressive strength parallel to the grain; *n* = number of trees; SD = standard deviation.

Yin et al. 2011). Our finding that there is no significant correlation between stem diameter and SWV suggests that the growth rate is not related to strength properties, such as Young's modulus. Therefore, *A. mangium* trees with a faster growth rate do not always have lower strength properties.

The mean BD for 5- and 7-year-old trees was 0.42 ± 0.02 and 0.45 ± 0.02 g cm^{-3}, respectively (Table 1). The BD of 13- and 30-year-old *A. mangium* trees has been reported to be 0.48 and 0.50 g cm^{-3}, respectively (Yamamoto 1998, Fujimoto et al. 2002). The mean CS for 5- and 7-year-old trees was 30.0 ± 4.4 and 32.8 ± 3.6 MPa, respectively (Table 1). Matsumoto et al. (2010) reported that CS in green conditions was 22.5 ± 2.3 MPa in 4-year-old *A. mangium* trees. Our study indicated a relatively lower BD and a relatively higher CS compared with previous studies (Yamamoto 1998, Fujimoto et al. 2002, Matsumoto et al. 2010). The radial variations in BD and CS for all trees are shown in Figures 3 and 4. The radial variation patterns for BD seemed to change at around 6 cm from the pith: BD gradually increased to about 6 cm from the pith, after which it was stabilized (Fig. 3). Table 2 shows the mean values of coefficient of variance (COV) in BD between core (0 to 6 cm from the pith) and outer (more than 6 cm from the pith to the bark) sections. The COV in the core section was larger than that in the outer section, suggesting that the BD became stable more than 6 cm from the pith. From the obtained results in BD, therefore, the wood can be categorized as core and outer sections. Fujimoto et al. (2002) reported that BD near the pith and near the bark was 0.30 and 0.53 g cm^{-3}, respectively, in 30-year-old *A. mangium*. The radial variation patterns for BD in the present study were similar to those in previous studies (Yamamoto 1998, Fujimoto et al. 2002). In 5- and 7-year-old trees, the radial variation patterns for CS were similar to those for BD: CS gradually increased to about 6 cm from the pith before stabilizing (Fig. 4). In addition, the COV of CS in the core section was also larger than that in the outer section (Table 2). Fujimoto et al. (2002) reported that CS increased from the pith to 5 cm, after which it was almost constant in 30-year-old *A. mangium*. They also reported that the radial variation in CS was very similar to that in BD. Obtained results in the present study were similar to those in previous research (Fujimoto et al. 2002). However, it is well known that CS is highly correlated with BD (Kollmann and Côté 1984). Figure 5 shows a significant positive correlation between BD and CS in 5- and 7-year-old trees (r = 0.790 and 0.583 for 5- and 7-y-old trees, respectively). Therefore, BD can be considered to be a powerful indicator for predicting the mechanical properties

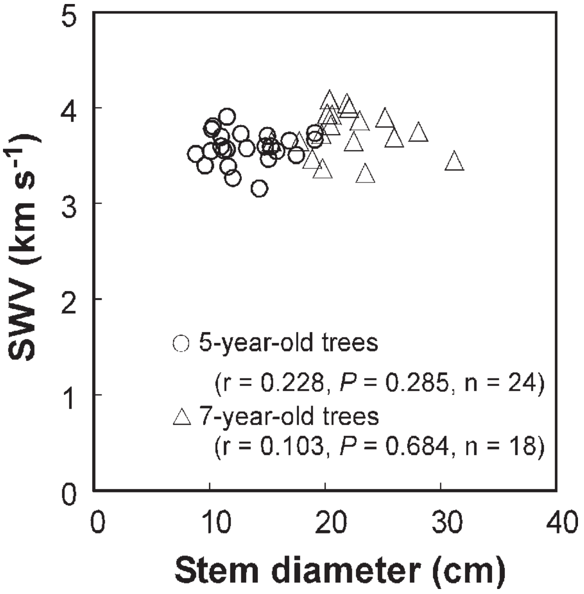

Figure 2.—Relationship between stem diameter and stress-wave velocity (SWV). r = *correlation coefficient;* P = *probability of realization of the null hypothesis (*r = 0*);* n = *number of trees.*

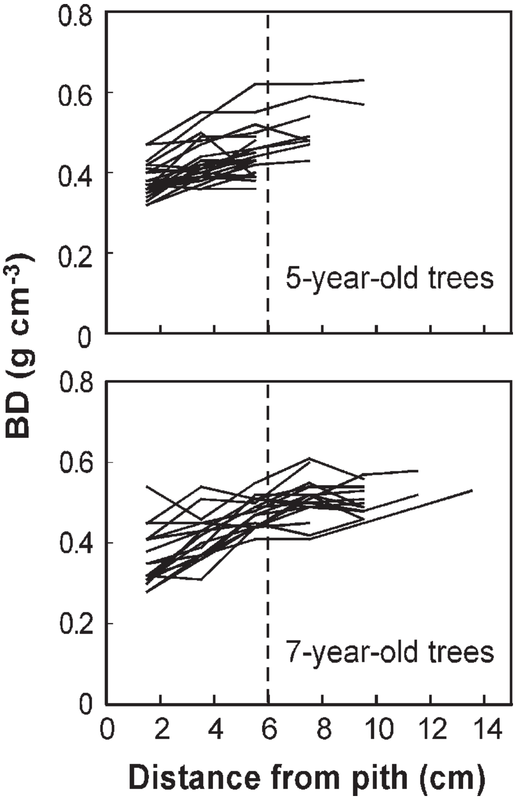

Figure 3.—Radial variation in basic density (BD). Dotted lines indicate the boundary between core and outer sections.

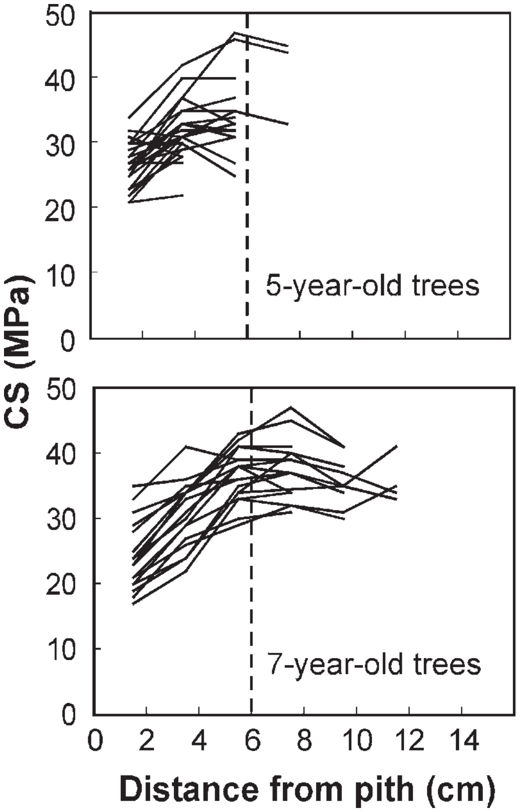

Figure 4.—Radial variation in compressive strength parallel to the grain (CS). Dotted lines indicate the boundary between core and outer sections.

of *A. mangium*. Radial variations of the tracheid length and the microfibril angle of the S2 layer have frequently been used to determine the boundary between juvenile and mature wood in softwood species (Hirakawa and Fujisawa 1995). Although the definition of juvenile wood in hardwood species remains unclear at present, anatomical characteristics, such as vessel diameter, fiber length, and fiber length increment determined by subtracting the vessel element length from the fiber length, have been used to determine the boundary between juvenile and mature wood (Honjo et al. 2005, Kojima et al. 2009b, Tsuchiya and Furukawa 2009). Honjo et al. (2005) studied the radial variation of vessel elements and fiber length in 10- and 13-year-old *A. mangium* trees. They reported that the fiber length increment was stabilized at about 3 to 4 cm from the pith, suggesting that this is the boundary between juvenile and mature wood.

Table 2.—Comparison with mean values of coefficient of variance (COV) in wood properties between core and outer sections.[a]

		Mean values of COV (%)	
Age (y)	Position	BD	CS
5	Core	8.2	13.8
	Outer	3.6	2.6
7	Core	12.1	17.7
	Outer	6.1	4.0

[a] BD = basic density; CS = compressive strength parallel to the grain; core = 0 to 6 cm from the pith; outer = more than 6 cm from the pith to the bark.

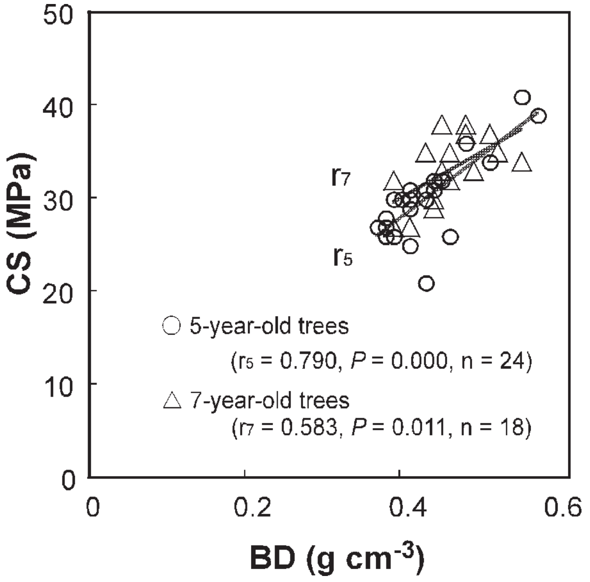

Figure 5.—Relationship between basic density (BD) and compressive strength parallel to the grain (CS). r_5 *= correlation coefficient for 5-year-old trees;* r_7 *= correlation coefficient for 7-year-old trees;* P *=probability of realization of the null hypothesis (r = 0);* n *= number of trees.*

Juvenile wood was present to about 6 cm from the pith when the fiber length was measured in 11-year-old *A. mangium* (Kojima et al. 2009b). Figures 3 and 4 show that BD and CS were stabilized at about 6 cm from the pith in the present study. The boundary obtained from radial variations in BD and CS in our study was similar to that obtained based on the radial variation of fiber length reported by Kojima et al. (2009b). We used trees of two different ages to investigate the radial variation in wood properties. Figure 6 shows the radial variation in BD for six selected trees of two different ages with almost the same diameter as a function of distance from the pith or cambial age. If the wood maturation process depends on cambial age, the BD must be stabilized at the same cambial age even in different tree ages. However, as shown in Figure 6, the BDs of different age trees were stabilized at different cambial ages (stabilized at 3 and 5 y in 5- and 7-y-old trees, respectively). On the other hand, the radial variation of BD in relation to the radial distance from the pith showed almost the same radial profiles in 5- and 7-year-old trees (Fig. 6): the BDs in all trees with almost the same diameter were stabilized at the same distance (6 cm) from the pith irrespective of different age trees. These results suggest that xylem maturation process in *A. mangium* depends on the growth diameter rather than the cambial age. In addition, stable wood with high density might be formed beyond 6 cm from the pith in *A. mangium*. As mentioned above, there is a high, positive correlation coefficient between BD and CS (Fig. 5). Therefore, the wood with a high CS can be also obtained from the outer section beyond 6 cm from the pith. From these results, trees with a stem diameter of more than 12 cm could be used to produce valuable construction timber. Furthermore, trees with a similar stem diameter might have similar wood properties, irrespective of age. The volume of wood with stable properties, i.e., mature wood, may start to increase after the stem diameter reaches 12 cm. This stable wood must have a high density and mechanical properties. Table 1

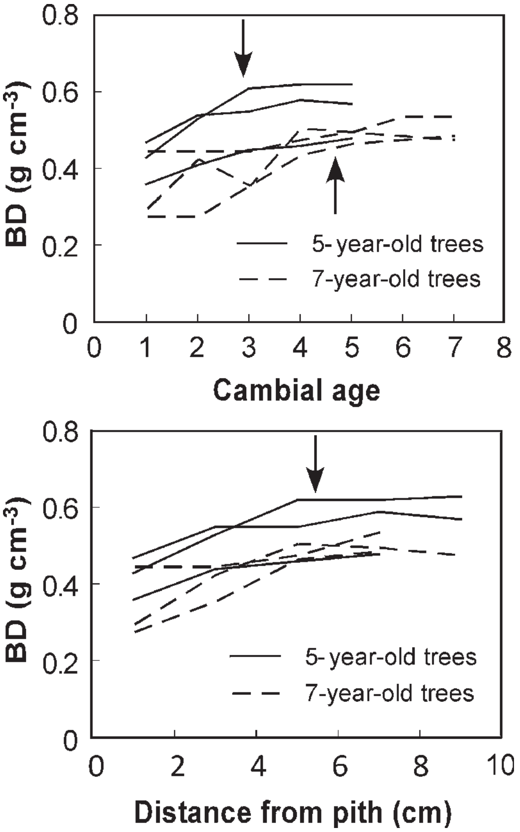

Figure 6.—Radial variation in basic density (BD) for six selected trees from two different age trees with almost the same diameter. Each line indicates an individual tree. The solid and dotted lines indicate 5-year-old (stem diameter = 15.2, 19.0, and 19.0 cm) and 7-year-old (stem diameter = 15.3, 18.8, and 19.6 cm) trees, respectively. The arrows indicate the points after which the values became stable.

shows that the mean stem diameter of 7-year-old trees (21.9 cm) was higher than that of 5-year-old trees (13.1 cm), suggesting that a greater volume of stable wood was present in the stems of 7-year-old trees compared with 5-year-old trees. Therefore, larger mean values for wood properties were obtained with 7-year-old trees (Table 1).

Conclusions

We examined SWV of the stem and basic wood properties (BD and CS) of 5- and 7-year-old *A. mangium* trees planted in Indonesia. The mean stem diameter of 5- and 7-year-old trees was 13.1 and 21.9 cm, respectively. There was no significant correlation between stem diameter and SWV in 5- and 7-year-old trees. BD and CS gradually increased to about 6 cm from the pith in 5- and 7-year-old trees, after which they were stabilized. There were significant positive correlations between BD and CS in 5- and 7-year-old trees ($r = 0.790$ and 0.583, respectively). These results suggest that stable wood with high density and mechanical properties, such as mature wood, is formed beyond 6 cm from the pith in *A. mangium* in this study. Although the distinct growth ring was not observed, our results suggest that xylem maturation depends on the growth diameter in *A. mangium* and that the formation of wood with stable properties commences after the stem diameter reaches 12 cm.

Acknowledgment

The authors express their sincere thanks to Perum Perhutani, Parung Panjang, Bogor, Indonesia, for providing the samples and for assistance with the field experiments.

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