The Effects of Radial Growth Rate on Wood Properties and Anatomical Characteristics and an Evaluation of the Xylem Maturation Process in a Tropical Fast-Growing Tree Species, *Gmelina arborea*

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Abstract

The aim of this study was to evaluate the effects of radial growth on wood properties and anatomical characteristics and to clarify the xylem maturation process in *Gmelina arborea*. Stem diameter, tree height, and stress-wave velocity were investigated for 54 5-year-old *G. arborea* trees planted in Indonesia. In addition, radial variations of wood properties (basic density and compressive strength parallel to the grain in green condition) and anatomical characteristics (fiber and vessel morphologies) were investigated for nine trees selected from three different radial growth categories (fast, medium, and slow growing). Stem diameter was positively significantly correlated with stress-wave velocity and compressive strength parallel to the grain in green condition. In addition, compressive strength and anatomical characteristics, except for wood fiber diameter, differed significantly among the radial growth categories. Radial variations of the wood properties and anatomical characteristics gradually increased, and then they showed constant values toward the bark. It is thought that the xylem maturation of *G. arborea* begins at approximately 5 cm from the pith. In addition, in a fast-growing tree species, such as *G. arborea*, the trees with faster stem diameter do not always form wood with low strength properties.

Gmelina arborea Roxb. ex Sm. is one of the fast-growing species. It is regarded as a promising species because of its ease and low cost of plantation establishment, rapid growth, and wood suitable not only for pulp and paper production but also for solid wood products (Dvorak 2004, Rasineni et al. 2010). Therefore, it is extensively planted in Southeast Asia, Latin America, India, Africa, and elsewhere (Dvorak 2004).

The effects of radial growth rate on wood properties and anatomical characteristics have been investigated for *G. arborea* (Moya Roque 2004, Moya Roque and Tomazello Fo 2007, Moya Roque et al. 2007, Moya and Tomazello Fo 2008, Kojima et al. 2009a). Moya Roque and Tomazello Fo (2007) reported that a pronounced decrease in fiber length and an increase in intra-ring wood density with increase in growth rate were presented. However, they also pointed out that the coefficient of determination between intra-ring wood density and growth rate was very low, indicating that growth rate is not a good parameter for intra-ring wood density prediction. Kojima et al. (2009a) also reported that in 3.5-, 7-, and 12-year-old *G. arborea* trees, the lateral growth rate and cambium age did not significantly affect the

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longitudinal released strain of the growth stress, wood density, or microfibril angle at the outermost surface of the secondary xylem. To use the wood resources from fast-growing *G. arborea* trees, however, further research is needed to clarify the effects of radial growth rate on wood properties and anatomical characteristics.

To use the wood resources from a fast-growing tree species, it is important to know whether xylem maturation depends on cambium age or tree diameter, and when the maturation process occurs. Understanding the maturation process is crucial not only for forest management, but also to avoid problems for manufacturers and consumers (Kojima et al. 2009b). It has been reported that the xylem maturation of some fast-growing species, such as *Acacia mangium*, *Falcataria moluccana*, and others, depends on diameter growth (Honjo et al. 2005, Kojima et al. 2009b, Makino et al. 2012, Ishiguri et al. 2016). In contrast, the xylem maturation of *Eucalyptus* spp., *Shorea acuminatissima*, and *Tectona grandis* depends on cambial age (Kojima et al. 2009b, Ishiguri et al. 2012, Hidayati et al. 2014, Wahyudi et al. 2015). However, the mechanism of xylem maturation in *G. arborea* remains unclear.

In the present study, stem diameter, tree height, and stress-wave velocity were determined for 5-year-old *G. arborea* trees planted in Indonesia. In addition, nine trees with different radial growth rates were used to determine wood properties (basic density and compressive strength parallel to the grain in green condition) and anatomical characteristics (fiber and vessel morphologies). The objectives of this study were to clarify the effects of radial growth on wood properties and anatomical characteristics and to investigate the xylem maturation process in *G. arborea*.

Materials and Methods

A total of 54 *G. arborea* trees aged 5 years old were surveyed in the present study. These trees were planted in the Educational Forest of Wanagama, which is managed by the Faculty of Forestry of Gadjah Mada University in Yogyakarta, Indonesia (07°54′S, 110°32′E). The environmental conditions of the plantation site were as follows: average temperature, 27.7°C; annual precipitation, 1,954 mm/yr; relative humidity, 80 to 85 percent; altitude, 214 m above sea level; soil, Mediterranean; and topography, flat. The seedlings were initially planted with 1.5 by 3.0-m spacing (initial planting density = 2,222 trees per ha). Unfortunately, the seed source and silvicultural management before this survey were unknown.

The stem diameter at 1.3 m above the ground and tree height were measured for all 54 trees. The trees were categorized into three groups according to radial growth rate (Ishiguri et al. 2012): fast-growing (larger than the mean + standard deviation), medium-growing (within the mean ± standard deviation), and slow-growing (smaller than the mean − standard deviation). The trees were categorized into three groups according to mean and standard deviation of the stem diameter (d): fast growth ($d > 16.6$ cm), medium growth ($9.6 \leq d \leq 16.6$ cm), and slow growth ($d < 9.6$ cm).

The stress-wave velocity of the stem was measured using a commercial, handheld stress-wave timer (Fakopp Microsecond Timer, Fakopp Enterprise) according to the method previously described in Ishiguri et al. (2007) and Hidayati et al. (2013a, 2013b). Start and stop sensors were set at 150 and 50 cm from ground level, respectively. The start sensor was hit with a small hammer to create a stress wave. After the stress wave was received by the stop sensor, the stress-wave propagation time between the two sensors was recorded. Ten measurements of stress-wave propagation time were obtained for each tree, and the mean value was calculated for each tree. Stress-wave velocity was calculated by dividing the distance between the sensors (100 cm) by the average stress-wave propagation time.

Core samples (5 mm in diameter) were collected from three trees in each group to measure the wood properties (basic density and compressive strength parallel to the grain in green condition) and anatomical characteristics (wood fiber cell diameter, wood fiber cell wall thickness, wood fiber length, vessel diameter, and vessel element length). Three core samples from pith to bark were obtained using a core borer (Haglöf) at 1.3 m above the ground for the nine selected trees. From these three core samples, two core samples were used for determination of compressive strength parallel to grain at green condition and basic density (as soon as possible after getting the core sample). The remaining core sample was used for determination of anatomical characteristics.

To determine the wood properties and anatomical characteristics (except for compressive strength), the core samples were cut into 1-cm segments at every 1 cm from the pith. For the compressive strength test, the core was cut at 5-mm intervals from the pith.

To determine basic density, the green volume of each segment was measured by the water displacement method, and then the ovendry weight was determined. Basic density was calculated by dividing the ovendry weight by the green volume.

Compressive strength parallel to the grain in green condition was measured using a core sample testing machine (Fractometer II, IML) in accordance with the method described by Matsumoto et al. (2010). A specimen was placed in the testing machine and a load was applied in the longitudinal direction. The compressive strength value indicated by the testing machine was recorded for each specimen. The mean value of compressive strength at 1-cm intervals was calculated before the analysis of radial variation.

Transverse sections (20 μm in thickness) were obtained from each 1-cm segment with a sliding microtome (ROM-380, Yamato Koki). The sections were stained with safranin, dehydrated, and mounted in bioleit. Digital images of the transverse sections were obtained by a microscope (BX51, Olympus) equipped with a digital camera (E-P3, Olympus) and analyzed with ImageJ software (National Institutes of Health, version 1.45S). The tangential and radial diameters were measured for 50 wood fibers and 30 vessels in each 1-cm segment, and the mean values were calculated. The double wall thicknesses of 50 wood fiber cells were measured, and then one-half of the double wall thickness was defined as the fiber wall thickness. Small strip specimens were macerated with Schulze's solution to measure wood fiber length and vessel element length. In total, 30 vessel elements and 50 wood fibers were measured using a microprojector (Nikon, V-12) and a digital caliper (Mitutoyo, CD-15CP).

To detect the differences among the radial growth categories, an analysis of variance test was conducted by using spreadsheet software (Microsoft, Excel for Mac 2011) and statistical software (AnalystSoft, StatPlus:mac LE Version 2009).

Results and Discussion

Growth characteristics and stress-wave velocity of trees

Table 1 shows the stem diameter, tree height, and stress-wave velocity of the trees. The mean and standard deviation of the stem diameter of the 54 trees were 13.1 and 3.5 cm, respectively.

In other fast-growing tree species, stress-wave velocity values were at 3.59 and 3.75 km s^{-1} for 5- and 7-year-old *A. mangium,* respectively (Makino et al. 2012), 3.08 km s^{-1} for 13-year-old *F. moluccana* (Ishiguri et al. 2007), and 3.45 km s^{-1} for 4-year-old *Eucalyptus camaldulensis* (Ishiguri et al. 2013). Thus, it is considered that the stress-wave velocity values of *G. arborea* may be relatively lower than those in other tropical fast-growing tree species. This phenomenon might be caused by the differences of anatomical characteristics and basic density of the species.

Figure 1 shows the relationships between the stem diameter and tree height and also stem diameter and stress-wave velocity values of the stem. A positive significant correlation was found between the stem diameter and tree height. High correlation coefficients between the stem diameter and tree height have also been observed in other hardwood species (Callister and Collins 2008; Monteuuis et al. 2011; Hidayati et al. 2013a, 2013b). On the other hand, no correlations have been reported between the growth characteristics and stress-wave velocity values in some other hardwood species (Dickson et al. 2003; Ishiguri et al. 2007, 2012; Makino et al. 2012; Hidayati et al. 2013a, 2013b). In the present study, a positively significant correlation was also observed between stem diameter and stress-wave velocity (Fig. 1), indicating that even faster growing trees show higher stress-wave velocity. Our results of the relationship between stem diameter and stress-wave velocity are inconsistent with those of previous studies. As described below, although no significant differences among growth categories were found in basic density, mean values of basic density gradually increased with increase of radial growth rate. Therefore, stress-wave velocity might increase with increasing stem diameter. From our results, we determined that the faster growing characteristics of this species do not always lead to lower strength properties of wood.

Wood properties

The mean values of basic density in the fast, medium, and slow growth categories were 0.49, 0.48, and 0.46 g cm^{-3}, respectively (Table 2). The radial variation of basic density increased up to 5 cm from the pith and then

Table 1.—Stem diameter, tree height, and stress-wave velocity of 54 trees of G. arborea.[a]

	Mean (SD) value			
Characteristic	Fast growing (n = 7)	Medium growing (n = 43)	Slow growing (n = 4)	Total (n = 54)
Stem diameter (cm)	20.0 (3.6)	12.5 (1.8)	8.5 (0.8)	13.1 (3.5)
Tree height (m)	14.6 (2.3)	12.2 (2.4)	9.8 (1.9)	12.4 (2.6)
SWV (km s^{-1})	2.84 (0.31)	2.84 (0.24)	2.61 (2.61)	2.83 (0.25)

[a] n = number of trees; SD = standard deviation; SWV = stress-wave velocity.

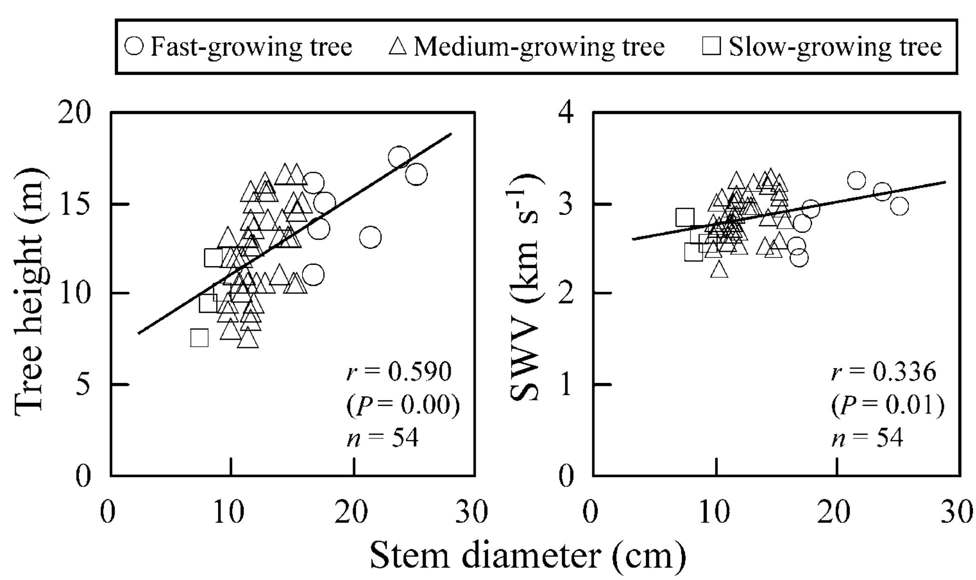

Figure 1.—Relationships between stem diameter and tree height or stress-wave velocity (SWV) in 54 trees of G. arborea. *r = correlation coefficient; P = probability; n = number of trees.*

became almost constant (Fig. 2). Espinoza (2004) reported that wood density measured by X-ray densitometry was 0.43 g cm^{-3} for 5-year-old *G. arborea* trees planted in Venezuela. Kojima et al. (2009a) reported that the wood density values of 3.5-, 7-, and 12-year-old *G. arborea* trees planted in Indonesia were 0.56, 0.58, and 0.52 g cm^{-3}, respectively. Our data on basic density were 0.49, 0.48, and 0.46 g cm^{-3} for three categories, which is within the ranges of these previous results (Espinoza 2004, Kojima et al. 2009a). The results might be in the same range because the trees are almost same age. On the other hand, no significant difference in basic density was found among the three radial growth categories (Table 2). When *G. arborea* wood samples were investigated from trees at different ages (3.5, 7, and 12 years old), Kojima et al. (2009a) found no relationships between growth rate and wood density. Our results are in agreement with those of the previous study by Kojima et al. (2009a). Ohbayashi and Shiokura (1990) reported that ovendry density slightly increased from pith to bark in 15-year-old *G. arborea* trees planted in the Philippines. Wood density measured by X-ray densitometry increased from pith to bark in 5-year-old *G. arborea* trees planted in Venezuela (Espinoza 2004). Our result of the radial variation in basic density (Fig. 2) is inconsistent with those of previous studies (Ohbayashi and Shiokura 1990, Espinoza 2004, Moya Roque 2004).

Compressive strength parallel to the grain ranged from 25.9 to 32.1 MPa, and significant differences were found among the categories (Table 2). Soerianegara and Lemmens (1994) reported that compressive strength parallel to grain in standard size specimens ranged from 23 to 39 MPa in 12 to 17 percent moisture content. In the present study, compressive strength parallel to grain was deter-

Table 2.—Tree characteristics, wood properties, and anatomical characteristics of nine selected trees.[a]

Characteristic	Mean (SD) value			F value (P value)
	Fast growing ($n = 3$)	Medium growing ($n = 3$)	Slow growing ($n = 3$)	
Tree				
Stem diameter (cm)	20.8 (3.6)	12.1 (1.1)	8.2 (0.6)	25.597 (0.00)
SWV (km s^{-1})	2.94 (0.38)	2.67 (0.24)	2.64 (0.19)	1.071 (0.40)
Wood				
Basic density (g cm^{-3})	0.49 (0.01)	0.48 (0.02)	0.46 (0.02)	2.059 (0.21)
Compressive strength (MPa)	31.9 (2.1)	29.5 (2.2)	26.1 (1.6)	6.338 (0.03)
Anatomy				
Wood fiber				
Cell diameter (μm)	20.9 (1.5)	20.7 (0.4)	20.4 (1.3)	0.155 (0.86)
Cell wall thickness (μm)	2.1 (0.1)	2.0 (0.1)	1.9 (0.1)	8.586 (0.02)
Length (mm)	1.40 (0.04)	1.26 (0.03)	1.24 (0.03)	22.426 (0.00)
Vessel element				
Diameter (μm)	168 (20)	142 (8)	137 (6)	5.277 (0.05)
Length (mm)	0.24 (0.01)	0.21 (0.02)	0.19 (0.01)	21.347 (0.00)

[a] n = number of trees; SD = standard deviation; SWV = stress-wave velocity.

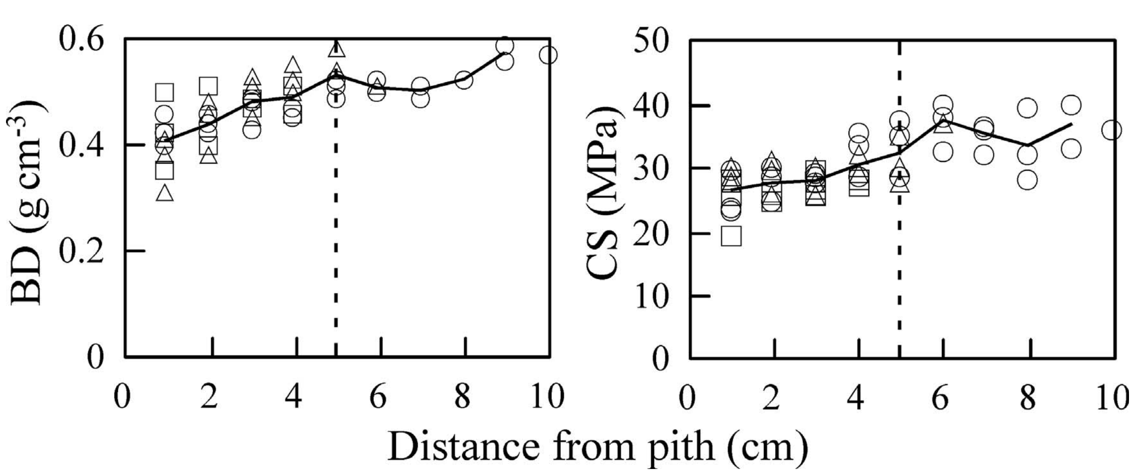

Figure 2.—Radial variations of basic density (BD) and compressive strength (CS) parallel to the grain in green condition of nine selected trees from three different radial growth categories. For explanation of symbols, refer to Figure 1. Solid and dotted lines indicate the mean values of the nine trees and position at 5 cm from the pith, respectively.

mined at green condition. Thus, compressive strength values in Soerianegara and Lemmens (1994) were converted to the values at green condition by the method described by Kollmann and Côté (1984). The resulting values ranged from about 10 to 20 MPa. These results suggest that our values are similar to or relatively higher than those described in Soerianegara and Lemmens (1994). A similar radial variation pattern with basic density was also observed in compressive strength (Fig. 2). The values of compressive strength parallel to the grain tended to increase with the increase of the radial growth rate. This trend is also recognized in Figure 3, in which there is a significant positive correlation between stem diameter and compressive strength. These results suggest that the *G. arborea* trees with faster growth in stem diameter result in high compressive strength. This tendency was also true for the relationship between stem diameter and stress-wave velocity, as shown in Figure 1. These results might be also related to the relatively higher basic density values in fast-growing categories, although a significant difference among growth categories was not found in basic density.

Anatomical characteristics

Moya Roque et al. (2007) reported that in 9- to 12-year-old *G. arborea* trees planted in Costa Rica, the mean values of wood fiber diameter, wood fiber double wall thickness, and wood fiber length were 30.7 μm, 4.0 μm, and 1.29 mm, respectively. Ogata et al. (2008) reported that *G. arborea* trees had wood fiber that was 1.1 mm long, a tangential diameter of 18 to 30 μm and thickness of 2.0 to 3.5 μm, and vessel elements with a maximum tangential diameter of 210 to 260 μm. In the present study, the mean values of cell diameter, cell wall thickness, wood fiber length, and vessel diameter ranged from 20.4 to 20.9 μm, 1.9 to 2.1 μm, 1.24 to 1.40 mm, and 137 to 168 μm, respectively (Table 2). Our results are similar to those of other studies, except for wood fiber diameter and vessel diameter (Moya Roque et al. 2007, Ogata et al. 2008).

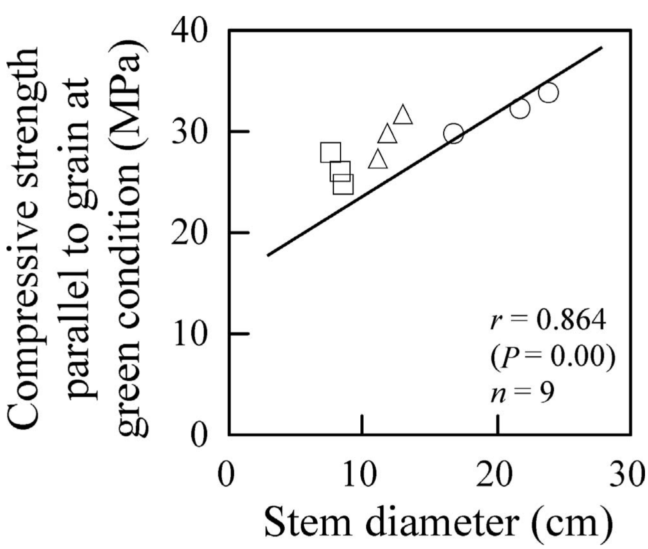

Figure 3.—Relationship between stem diameter and compressive strength parallel to the grain in green condition in the nine selected trees from three different radial growth categories. r = correlation coefficient; p = probability; n = number of trees. For explanation of symbols, refer to Figure 1.

Ohbayashi and Shiokura (1990) reported that fiber length increased rapidly, and then the increasing rate became very small at 6 to 8 cm from the pith. They also found that vessel element length increased from the pith up to 5 to 6 cm and then became more or less constant toward the bark, and vessel diameter increased up to 4 to 5 cm from the pith and then became constant toward the bark. In the present study, the radial variations of the measured anatomical characteristics were almost consistent with those of the previous study (Ohbayashi and Shiokura 1990). Kojima et al. (2009a) reported that in the 3.5-year-old plantation, a positive correlation at the 5 percent level was observed between the lateral growth rate and wood fiber length. However, in the 7-year-old plantation, the lateral growth rate did not significantly affect wood fiber length. They also found that the 3.5-year-old smaller diameter trees had not produced mature wood yet. In addition, fiber length of *G. arborea* trees planted in Indonesia was 1.20, 1.35, and 1.29 mm for 3.5-, 7-, and 12-year-old trees, respectively (Kojima et al. 2009a). In the present study, the mean values of wood fiber length were 1.40, 1.26, and 1.24 mm for fast-, medium-, and slow-growing categories, respectively, whereas length of vessel element ranged from 0.19 to 0.24 mm (Table 2). In addition, the radial variations of all anatomical characteristics were gradually increased and then became almost constant toward the bark (Fig. 4). Our results are similar to those of Kojima et al. (2009a).

The mean values of the vessel diameter were 168, 142, and 137 μm for fast-, medium-, and slow-growing trees (Table 2). A similar tendency was also recognized in 35-year-old *Shorea acuminatissima* (Ishiguri et al. 2012). Based on these results, it is thought that the mean values of the anatomical characteristics from pith to bark were influenced by the radial growth rate.

Xylem maturation

With a few exceptions, the radial variations of almost all wood properties and anatomical characteristics gradually increased up to 5 cm from the pith, and then they became almost constant to the bark (Figs. 2 and 4), suggesting that a boundary exists around 5 cm from the pith between unstable wood (like juvenile wood in softwoods) and stable wood (like mature wood in softwoods). As shown in Table 3, significant differences were found in mean values of wood properties and anatomical characteristics within 5 cm from pith and after 5 cm from pith to bark side. In addition, this boundary was recognized in the trees of all radial growing categories. It was reported that the xylem maturation process in some fast-growing trees, such as *A. mangium, F. moluccana,* and others, depends on diameter growth (Honjo et al. 2005, Kojima et al. 2009b, Makino et al. 2012, Ishiguri et al. 2016). Therefore, it is thought that the xylem maturation process in *G. arborea* may depend on diameter growth rather than cambial age. Based on these results, to obtain a higher yield of wood with stable quality, the enhancement of volume yield by silvicultural practice should be conducted for tree stem diameters reaching more than 5 cm.

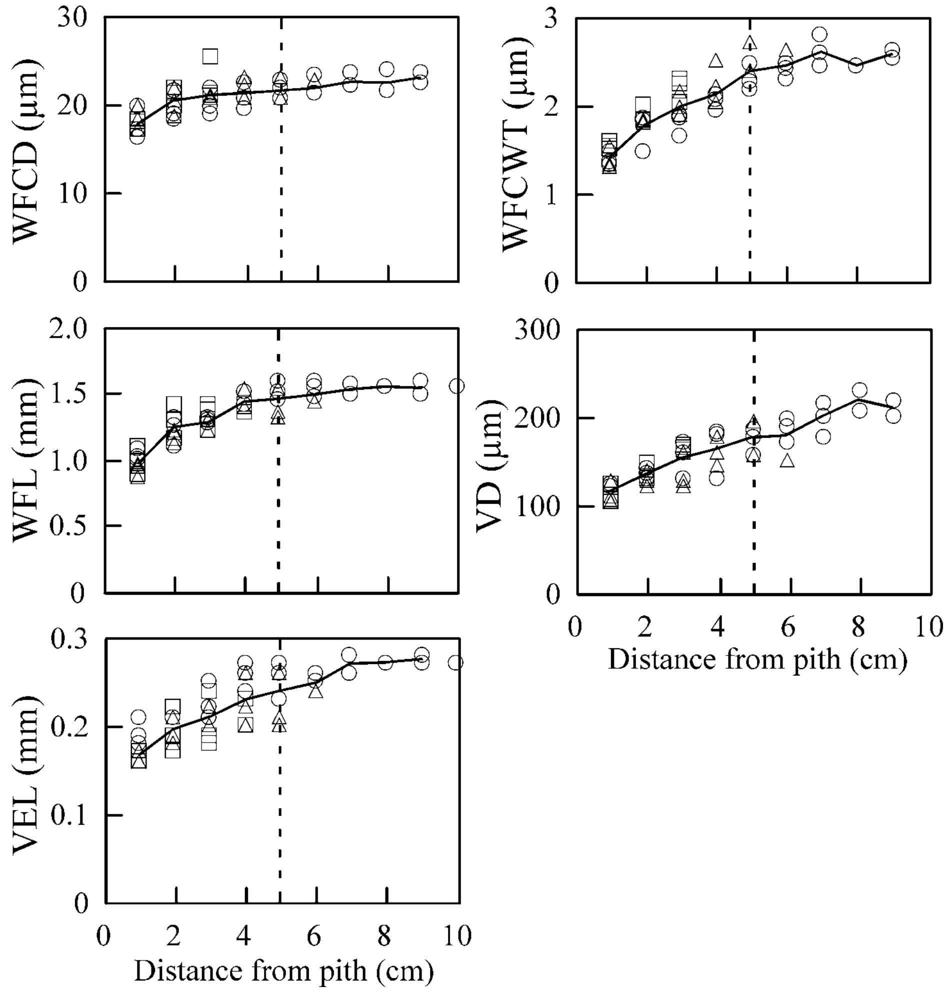

Figure 4.—Radial variations of the anatomical characteristics in the nine selected trees from three different radial growth categories. WFCD = wood fiber cell diameter; WFCWT = wood fiber cell wall thickness; WFL = wood fiber length; VD = vessel diameter; VEL = vessel element length. For explanation of symbols, refer to Figure 1. Solid and dotted lines indicate the mean values of the nine trees and position at 5 cm from the pith, respectively.

Table 3.—Mean values of wood properties and anatomical characteristics within 5 cm from pith and after 5 cm from pith to bark side.[a]

Characteristic	Within 5 cm from pith		After 5 cm from pith to bark side		
	n	Mean (SD)	*n*	Mean (SD)	*t* value (*P* value)
Wood					
Basic density (g cm^{-3})	41	0.47 (0.06)	11	0.53 (0.03)	−3.371 (0.00)
Compressive strength (MPa)	41	28.4 (3.5)	13	35.4 (3.7)	−6.039 (0.00)
Anatomy					
Wood fiber					
Cell diameter (μm)	38	20.3 (1.9)	11	22.5 (1.0)	−3.547 (0.00)
Cell wall thickness (μm)	38	1.9 (0.4)	11	2.5 (0.1)	−5.572 (0.00)
Length (mm)	41	1.27 (0.19)	11	1.54 (0.05)	−4.520 (0.00)
Vessel element					
Diameter (μm)	38	144 (25)	11	196 (23)	−6.076 (0.00)
Length (mm)	41	0.21 (0.03)	11	0.26 (0.01)	−5.651 (0.00)

[a] *n* = number of specimens; SD = standard deviation.

Conclusions

The objective of this study was to clarify the effects of radial growth on wood properties, anatomical characteristics, and the xylem maturation process of *G. arborea* trees. Growth characteristics and stress-wave velocity were measured for 54 *G. arborea* trees at 5 years old. The trees were classified into three growth categories (fast-, medium-, and slow-growing trees) based on the mean stem diameter and standard deviation, and three trees in each category were selected to determine wood properties and anatomical characteristics. A significant positive correlation was found between stem diameter and stress-wave velocity, suggesting that the trees with fast-growing characteristics do not always result in wood with lower strength properties. Although no significant differences among the radial growth categories were found in basic density, compressive strength increased with an increase in radial growth rate. Among the radial growth categories, differences were found in all anatomical characteristics, except for wood fiber diameter. With a few exceptions, almost all wood properties and anatomical characteristics increased up to around 5 cm from the pith. Although radial growth rate differed, the tendency was the same for all sample trees, suggesting that the xylem maturation of *G. arborea* starts around 5 cm from the pith.

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