宇　大　演　報
第 58 号（2022）論 文

Bull. Utsunomiya Univ. For.
No. 58 (2022) Article

Effects of radial growth rates on wood properties and xylem maturation manner in *Eucalyptus urophylla*

*Eucalyptus urophylla*における肥大成長速度が木材性質に及ぼす影響および木部成熟様式

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ABSTRACT

The growth characteristics, stress-wave velocity of stem, green moisture content, and basic density were investigated for 24-year-old *Eucalyptus urophylla* trees planted in Indonesia. The effects of radial growth rate on the wood properties, and the manner of xylem maturation were evaluated through the selection of the best mixed-effect model. Logarithmic and quadratic functions were fitted as the best model for radial variations in green moisture content and basic density, respectively. By the variance component analysis, effects of radial growth rate on stress wave-velocity and basic density were minimal. The mean absolute error values for the models with the fixed part for radial variation in basic density in relation to relative distance from pith were smaller than those in relation to distance from pith, suggesting that the manner of xylem maturation in *E. urophylla* depended on the cambial age rather than diameter growth.

Keywords: stress-wave velocity, basic density, mixed-effects model, radial growth rate, xylem maturation

要　旨

インドネシアに植栽された 24 年生 *Eucalyptus urophylla* の成長特性，樹幹の応力波伝播速度，生材含水率および容積密度を測定した．得られた結果より，肥大成長速度が木材性質に及ぼす影響および木部成熟様式を混合効果モデルにより評価した．対数式および二次式を基にした混合効果モデルは，生材含水率および容積密度の半径方向変動を説明するために最適であった．選択された混合効果モデルから推定された分散成分から，肥大成長が樹幹の応力波伝播速度および容積密度に及ぼす影響は小さいことが明らかとなった．また，容積密度の半径方向変動モデルにおける平均絶対誤差は，髄からの距離で算出した値と比較して髄から樹皮までの相対距離で算出した値の方が小さい値を示した．このことから，本種における木部成熟様式は，直径成長よりもむしろ形成層齢に依存している可能性が示唆された．

キーワード：応力波伝播速度，容積密度，混合効果モデル，肥大成長速度，木部成熟

1. Introduction

Eucalyptus urophylla S. T. Blake naturally distributes Lesser Sunda Island (Timor, Wetar, Flores, Adonara, Lomblem and Alor) and planted in many tropical parts of the world (Soerianegara and Lemmens 1994). The chief characteristics of *E. urophylla* are its rapid growth, and good form (FAO 1979). This species has grown well at low altitudes and there are significant provenance differences (Hillis and Brown 1984). Wood of this species widely used for heavy construction, pulp production, and others (FAO1979; Soerianegara and Lemmens 1994). This species can produce hybrids with *E. alba* and other species. Studies on fundamental wood properties and relationship between growth characteristics and wood properties in this species are important for producing and utilizing the wood from this species as well as producing high qualities wood from the hybrids.

Understanding the effects of radial growth rate on wood properties is important in sustainable forestry. The forest managers are worried about that increase of tree growth rate might result in productions of lower quality wood. Especially for fast-growing tree species, many people consider that the trees might produce lower quality of wood. In tropical broad-leaved tree species, the effects of radial growth rate on wood properties have been investigated (Ohbayashi and Shiokura 1990; Bhat et al. 2001; Kojima et al. 2009a,b; Quang et al. 2010; Ishiguri et al. 2012, 2016; Wu et al. 2013; Pertiwi et al. 2017, 2018; Prasetyo et al. 2017; Nezu et al. 2021). In 9-year-old *E. urophylla* planted in Indonesia, stem diameter was significantly positive correlated with stress-wave velocity (Prasetyo et al. 2017). *Eucalyptus urophylla* at age 96 months in southern China, no significant correlation coefficients were reported between basic density and stress-wave velocity of stems (Wu et al. 2013). However, the sampled tree was young with less than 15 cm in diameter (Wu et al. 2013; Prasetyo et al. 2017), and it is necessary to study radial growth rate on wood properties in sample with larger diameter for obtaining high value-added wood products from this species.

Xylem maturation manner should be also considered in addition to growth rate-wood properties relationships. The tendency of xylem maturation manner is not the same among tropical broad-leaved tree species and it has been reported that two different types of xylem maturation manner were found: anatomical characteristics and wood properties stabilized in relation to diameter growth (Honjo et al. 2005; Chowdhury et al. 2009; Kojima et al. 2009a,b; Makino et al. 2012; Ishiguri et al. 2016; Hidayati et al. 2017; Pertiwi et al. 2017, 2018) and cambial age (Bhat et al. 2001; DeBell et al. 2001; Kojima et al. 2009b; Ishiguri et al. 2012; Nezu et al. 2021). Thus, xylem maturation process should be evaluated in more detail at species level because the strategy of silvicultural managements may be differed among the types: promotion of radial growth in trees in which xylem maturation process depending on diameter growth results in increase of stable wood volume, but opposite results may be obtained in trees in which xylem maturation process depending on cambial age. To effectively utilize wood resources of *E. urophylla*, the effect of radial growth rate on wood properties should be clarified.

When wood properties were obtained using hierarchical structure data, a mixed-modeling has been applied especially for conifers (Fujimoto and Koga 2010; Auty et al. 2013; Dahlen et al. 2018). However, less statistical methodologies based on hierarchical structure data in wood properties have been adopted for clarifying the effect of radial growth rate on wood properties and xylem maturation manner in tropical broad-leaved tree species (Nezu et al. 2021). Therefore, novel findings may be obtained by the modeling approach.

In the present study, growth characteristics, stress-wave velocity of stem, and wood properties (green moisture content and basic density) were preliminary investigated for 24-year-old *E. urophylla* trees planted in Indonesia. Based on the results, effects of radial growth rate on wood properties and xylem maturation manner in this species were discussed.

2. Materials and methods

An experimental plantation of *Eucalyptus urophylla* S.T. Blake was in Gunung Nona, Education Forest, Pattimura University, Ambon, Maluku, Indonesia (3°43'S, 128°11'E, 265m above sea level). Thirty 24-year-old *E. urophylla* trees planted in the plantation were selected for the experiments. Stem diameter at 1.3 m above ground level, tree height, and stress-wave velocity of stem were measured by the same methods described in our previous study (Wahyudi et al. 2015).

To determine the green moisture content and basic density, trees were classified into three categories based on the mean (μ) and standard deviation (σ) of stem diameter (d) (Ishiguri et al. 2012; Wahyudi et al. 2015; Nezu et al. 2021): slow growth ($d \leq \mu - \sigma$), medium growth ($\mu - \sigma < d < \mu + \sigma$), and fast growth ($\mu + \sigma \leq d$). As the results, slow-, medium-, and fast-growth categories were $d \leq 16.8$ cm, 16.8 cm $< d <$ 23.8 cm, and $d \geq 23.8$ cm. Core samples (5 mm in diameter) of 2 cm from cambium toward pith were collected from 4, 5, and 5 trees in each category at 1.3 m above ground. In addition, to determine radial variation of green moisture content and basic density, a core sample (5 mm in diameter) were collected from pith to cambium in a tree within each growth category. Basic density was calculated by dividing the oven-dry weight by the green volume.

Statistical analyses were conducted using R software version 4.0.2 (R Core Team 2020). The effects of radial growth rate on each property were evaluated by an intercept-only linear mixed-effects model by the lmer function in the lme4 package (Bates et al. 2015). For clarification of the effect of radial growth rate on each property, the variance component was estimated by the following model:

$$y_{ij} = \mu + Category_i + e_{ij} \quad (1)$$

where y_{ij} is the observation values of the jth individual tree of the *i*th growth category, μ is the fixed-effect parameter, $Category_i$ is the random-effect parameter of the growth category *i*, and e_{ij} is the residual. The significant level of the fixed-effect parameter was evaluated (Bates et al. 2015). The ratio of the variance component for the growth category to the total variance ($Ratio_{cat}$) was calculated by the following formula (Nakagawa and Schielzeth 2010):

$$Ratio_{cat}\ (\%) = V_{cat} / (V_{cat} + V_{res}) \cdot 100 \quad (2)$$

where V_{cat} is the variance component of the growth category and V_{res} represents residual variance. The ratio of the variance component for the growth category to the total variance could not calculated, when equation 1 was not converged.

The radial variation of green moisture content and basic density in relation to distance from pith were determined by the linear or nonlinear mixed-effects models using the lmer function in the lme4 package (Bates et al. 2015) and the nlme function in the nlme package (Pinheiro and Bates 2000) expressed as the following:

$$y_{ij} = \alpha_0 + (\alpha_1 + Tree_i)\, D_{ij} + e_{ij} \quad (3)$$
$$y_{ij} = \alpha_0 + \alpha_1 \cdot D_{ij} + Tree_i + e_{ij} \quad (4)$$
$$y_{ij} = \beta_0 + (\beta_1 + Tree_i) \ln D_{ij} + e_{ij} \quad (5)$$
$$y_{ij} = \beta_0 + \beta_1 \cdot \ln D_{ij} + Tree_i + e_{ij} \quad (6)$$
$$y_{ij} = \gamma_0 + \gamma_1 \cdot D_{ij} + (\gamma_2 + Tree_i)\, D_{ij}^2 + e_{ij} \quad (7)$$
$$y_{ij} = \gamma_0 + (\gamma_1 + Tree_i)\, D_{ij} + \gamma_2 \cdot D_{ij}^2 + e_{ij} \quad (8)$$
$$y_{ij} = \gamma_0 + \gamma_1 \cdot D_{ij} + \gamma_2 \cdot D_{ij}^2 + Tree_i + e_{ij} \quad (9)$$

where y_{ij} is the observed value for the *j*th cm position from pith in the *i*th individual tree, D_{ij} is the *j*th cm position from pith in the *i*th individual tree, α_0, α_1, β_0, β_1, γ_0, γ_1, and γ_2 are the fixed-effect parameters, $Tree_i$ is the random-effect parameter of the ith individual tree, and e_{ij} is the residual. Applied function were linear function (equations 3 and 4), the logarithmic function (equations 5 and 6), and the quadratic function (equations 7 to 9). The models with low significant level ($p > 0.05$) of the fixed-effect parameter was not used. Then, the best model was selected using the Akaike Information Criterion: The model with minimum the AIC value was considered the best model (AIC, Akaike 1998). If quadratic function was selected as the best model, distance from pith ($D_v = -\gamma_1/2\gamma_2$) and each property value ($Y_v = \gamma_0 - \gamma_1^2/4\gamma_2$; *Y* is value of moisture content or basic density) were calculated at the vertex of quadratic function with only fixed-effect parameters.

To clarify xylem maturation manner in this species (depending on diameter growth or cambial age), radial variation of basic density in relation to relative distance from pith to cambium was calculated by the method described by Chowdhury et al. (2009). For radial variation modeling of basic density in relation to relative distance from pith, the function (linear [equations 3 and 4], logarithmic [equations 5 and 6], and quadratic [equations 7 to 9]) in the best model for radial variation in relation to distance from pith was applied after modification of the explanatory variables from 'distance from pith' to 'relative distance from pith'. The modified formula was as follows:

$$BD_{ij} = \alpha_0 + (\alpha_1 + Tree_i)\, RD_{ij} + e_{ij} \quad (10)$$
$$BD_{ij} = \alpha_0 + \alpha_1 \cdot RD_{ij} + Tree_i + e_{ij} \quad (11)$$
$$BD_{ij} = \beta_0 + (\beta_1 + Tree_i) \ln RD_{ij} + e_{ij} \quad (12)$$
$$BD_{ij} = \beta_0 + \beta_1 \cdot \ln RD_{ij} + Tree_i + e_{ij} \quad (13)$$
$$BD_{ij} = \gamma_0 + \gamma_1 \cdot RD_{ij} + (\gamma_2 + Tree_i)\, RD_{ij}^2 + e_{ij} \quad (14)$$
$$BD_{ij} = \gamma_0 + (\gamma_1 + Tree_i)\, RD_{ij} + \gamma_2 \cdot RD_{ij}^2 + e_{ij} \quad (15)$$
$$BD_{ij} = \gamma_0 + \gamma_1 \cdot RD_{ij} + \gamma_2 \cdot RD_{ij}^2 + Tree_i + e_{ij} \quad (16)$$

where BD_{ij} is the observed value for the *j*th% position from pith in the *i*th individual tree, D_{ij} is the *j*th% position from pith in the *i*th individual tree, α_0, α_1, β_0, β_1, γ_0, γ_1, and γ_2 are the fixed-effect parameters; $Tree_i$ is the random-effect parameter of the ith individual tree; and e_{ij} is the residual. Among the models (equations 10 to 16), the model with minimum AIC was selected as the best model for radial variation in basic density in relation to relative distance from pith. In addition, the significant level was confirmed in the fixed-effect parameter in the selected model.

For the best models in relation to distance from pith and relative distance from pith, mean absolute error (MAE) was carried out from the fixed part of each model (Willmott and Matsuura 2005). The MAE is expressed as the following:

$$\mathrm{MAE} = n^{-1} \Sigma \left| y_{obs,k} - y_{pred,k} \right| \quad (17)$$

where the *n* is total number of samples, $y_{obs,k}$ is the observed value for the *k*th cm position from pith or the *k*th % position from pith, and $y_{pred,k}$ is the predicted value from the model for the *k*th cm position from pith or the *k*th % position from pith. A smaller MAE value is considered the best model between two models in relation to distance from pith or relative distance from pith for basic density.

Pearson's correlation coefficients were determined for clarifying the relationships between stem diameter and stress-wave velocity.

3. Results and discussion

3.1 Stress-wave velocity of stem

Table 1 shows stem diameter, tree height and stress-wave velocity of stem. Values of Mean ± standard deviation in each growth category in stem diameter, tree height, and stress-wave velocity of stem of 30 trees in the stand were 20.3 ± 3.5 cm, 15.5 ± 2.4 m, and 3.65 ± 0.21 km/s. Similar mean values and standard deviation were also obtained in 15 trees collected samples. Prasetyo et al. (2017) reported that stem diameter, tree height and stress-wave velocity of stem of 9-year-old *E. urophylla* planted in Indonesia were 13.1 cm, 12.1 m, and 3.18 km/s, respectively. In other *Eucalyptus* species, stress-wave velocity was 3.45 km/s for 4-year-old trees of *E. camaldulensis* grown in Thailand (Ishiguri et al. 2013), 3.23 km/s for 26-year-old *E. alba* trees planted in the same place with this study (Wahyudi et al. 2015), and 3.18 to 3.36 km/s for 13-year-old *E. nitens* trees of three different races planted in Australia (Blackburn et al. 2010). The results of stress-wave velocity obtained in the present study showed relatively higher values compared to those in other *Eucalyptus* species.

3.2 Wood properties

Moisture content at green condition and basic density for 2 cm from the cambium in 15 selected trees in slow, medium, and fast-growth category were 57.1, 58.3, and 57.8% and 0.72, 0.68, and 0.68 g/cm^3 (Table 1). The basic density values were 0.506 and 0.535 g/cm^3 in fast- and slow-growing *E. urophylla* families at age 10 from a progeny trial in Vietnam (Quang et al. 2010). In 9-year-old *E. urophylla* planted in Indonesia, the basic density was 0.46 g/cm^3 (Prasetyo et al. 2017). Thus, the basic density value obtained in the present studies is high compared to those in these previous studies, although tree age is differed among the studies.

Table 2 shows a comparison of AIC values of seven models for radial variations of green moisture content and basic density in relation to the distance from pith. The logarithmic function showed the minimum AIC values for green moisture content (equation 6). On the other hand, radial variation for basic density was fitted for quadratic function (equation 7). The radial variations in green moisture content and basic density in relation to distance from pith are shown in Figures 1 and 2. Solid curve indicates regression curve based on the best model with fixed-effect parameters in each property (Table 3). Moisture content decreased and then became stable toward the cambium. On the other hand, the vertex of quadratic function of the best model with only fixed-effect parameters of radial variation for basic density was 0.74 g/cm^3 at around 6 cm from pith (Figure 2). Therefore, basic density increased up to 6 cm from the pith, and it decreased toward bark side.

Prasetyo et al. (2017) reported that basic density almost constant up to 3 cm from the pith, and then it gradually increased toward the bark. In other *Eucalyptus* species, oven-dry density in *E. saligna* and basic density in *E. alba* increased slightly from pith to bark (Ohbayashi and Shiokura 1990; Wahyudi et al. 2015). The results of radial profile of *E. urophylla* in the present study were different from those in previous studies (Ohbayashi and Shiokura 1990; Prasetyo et al. 2017; Wahyudi et al. 2015). Further investigation is needed for clarifying the factors which affected on the decreasing trend of basic density after 6 cm from pith to bark side.

3.3 Effects of radial growth rate on wood properties

To clarify the effect of radial growth rate on each property, the intercept-only linear mixed-effects model with the growth category as the random effect was developed using mean values of the property at individual tree level. The ratio of the variance component for the growth category was based on the developed model in each property (Table 4). The variance component ratio in stem diameter and tree height were 88.3 and 14.2%. On the other hand, the mixed-effects models of stress-wave velocity, green moisture content, and basic density were singular fitting; variances of one or more linear combinations of effects close to zero

Table 1 Statistical values of growth characteristics, stress-wave velocity of stem, and wood properties of specimens obtained in 2 cm from cambium.

Property	Slow	Medium	Fast	Mean/total
*n*1	6	20	4	30
Stem diameter (cm)	15.7 (1.4)	20.6 (2.0)	26.0 (1.4)	20.3 (3.5)
Tree height (m)	14.0 (0.8)	15.6 (2.7)	17.1 (1.9)	15.5 (2.4)
Stress-wave velocity (km/s)	3.73 (0.31)	3.63 (0.17)	3.67 (0.23)	3.65 (0.21)
*n*2	5	6	4	15
Stem diameter (cm)	15.5 (1.4)	20.7 (1.6)	26.0 (1.4)	19.2 (2.0)
Tree height (m)	13.9 (0.9)	14.8 (1.0)	17.1 (1.9)	15.1 (0.2)
Stress-wave velocity (km/s)	3.81 (0.26)	3.60 (0.15)	3.67 (0.23)	3.69 (0.22)
Green moisture content (%)	57.1 (12.2)	58.3 (5.5)	57.8 (4.6)	57.8 (7.6)
Basic density (g/cm^3)	0.72 (0.07)	0.68 (0.09)	0.68 (0.07)	0.69 (0.07)

Note: *n*1, number of trees in the stand; *n*2, number of trees collecting core samples. The value in parenthesis indicates standard deviation.

Table 2 Comparison of AIC value of mixed-effect model for radial variation of green moisture contents and basic density in relation to distance from the pith.

Function	Equation	Green moisture content	Basic density
Linear	3	246.445	-
	4	234.495	-
Logarithmic	5	240.866	-
	6	**229.231**	-
Quadratic	7	247.985	**− 49.339**
	8	247.985	− 43.455
	9	235.754	-

Note: -, Model was not converged because of not significant of fixed-effect parameters ($p < 0.05$). Bold values in AIC indicate the minimum AIC values in each property in relation to distance from pith.

Table 3 Parameter estimates, associated standard errors, *p*-values, and the random effects parameters for the selected model of radial variation in each property in relation to distance from pith.

Property	Equation	Fixed effects					Random effects		
		Parameter	Estimates	SE	*t*-value	*p*-value	$Tree_{Slow}$	$Tree_{Medium}$	$Tree_{Fast}$
Green moisture content	6	β_0	82.835	5.564	14.888	<0.001	− 8.998	1.037	7.961
		β_1	− 13.827	2.007	− 6.891	<0.001			
Basic density	7	γ_0	0.5985	0.3648×10^{-1}	16.407	<0.001	-0.2176×10^{-3}	-0.8328×10^{-3}	0.1050×10^{-2}
		γ_1	0.4498×10^{-1}	0.1350×10^{-1}	3.333	0.003			
		γ_2	-0.3573×10^{-2}	0.1228×10^{-2}	− 2.910	0.007			

Note: SE, standard error; *p*-value, significant level for each fixed-effect parameter. $Tree_{Slow}$, $Tree_{Medium}$, and $Tree_{Fast}$, random-effect parameter of each category.

(Bates et al. 2015). Thus, the effect of the radial growth rate on these properties was minimal. Correspondingly, the mean values of these properties showed similar values among growth categories (Table 1). In addition, no significant correlation coefficients were found in stem diameter and basic density or stress-wave velocity of trees (Figure 3), suggesting that these wood properties might be independent from stem diameter. Therefore, the wood of faster radial growth rate would not always show lower wood quality in *E. urophylla*.

3.4 Xylem maturation

The model of radial variation in basic density in relation to relative distance from pith was applied using the same function selected as the best model for radial variation in relation to distance from pith (equations 14 to 16). The results of AIC values of developed models were shown in Table 5. The AIC value was minimum in equation 14. The radial variations in basic density in relation to relative distance from pith are shown in Figure 2. The regression curve in the Figure 2 indicates the fixed part of the best model in basic density (Table 6). Based on the results, we considered the xylem maturation manner. If the models of radial variation in relation to distance from pith were fitted, we regard as the xylem maturation depending on diameter growth. In the present study, the MAE was used as a criterion to compare the models (Figure 2). A smaller MAE value was found in the relative distance from pith for basic density compared to distance from pith, suggesting that basic density varied depending on cambial age rather than diameter growth. The results might be also related to the tendency of no significant relationship between radial stem diameter and basic density as shown in Figure 3. In addition, the vertex of quadratic function of best model with only fixed-effect parameters was 0.77 g/cm^3 in basic density and about 63% in relative distance from pith, respectively. Thus, peak values of basic density might be showed at the cambial age of 15 years (24 years old [tree age] × 0.63 [relative distance from pith] = around 15 years old), suggesting that the tree of this species should be harvested after 15 years old when the final products of the wood from this species are required high density.

It has been reported that xylem maturation of tropical fast-growing tree species, such as *Acacia mangium*, *Falcataria moluccana*, *Gmelina arborea* and others, depends on diameter growth: when cambium reaches to a certain diameter, tree produces xylem with stable quality in wood fibers, wood density, and others (Honjo et al. 2005; Chowdhury et al. 2009; Kojima et al. 2009a,b; Makino et al. 2012; Ishiguri et al. 2016; Hidayati et al. 2017; Pertiwi et al. 2017, 2018). On the other hand, cambial age dependency was found in xylem maturation of several *Eucalyptus* species, such as *E. grandis*,

Table 4 Variance components of the linear mixed-effect model for each property.

Property	$Ratio_{cat}$	V_{res}	V_{cat} (%)
Stem diameter	25.566	3.396	88.3
Tree height	0.9148	5.5458	14.2
Stress-wave velocity	-	-	-
Green moisture content	-	-	-
Basic density	-	-	-

Note: V_{cat}, variance component of growth category; V_{res}, the residual variance; $Ratio_{cat}$, The ratio of the variance component for the growth category to the total variance. The number of trees in this data is 30 for growth characteristics and stress-wave velocity, and 15 trees for green moisture content and basic density, respectively.

Table 5 Comparison of AIC value of mixed-effect model for radial variation of basic density in relation to relative distance from pith.

Function	Equation	AIC
Quadratic	**14**	**− 39.798**
	15	− 38.703
	16	− 39.262

Note: Bold value in AIC indicates the minimum AIC values among quadratic models in basic density in relation to relative distance from pith.

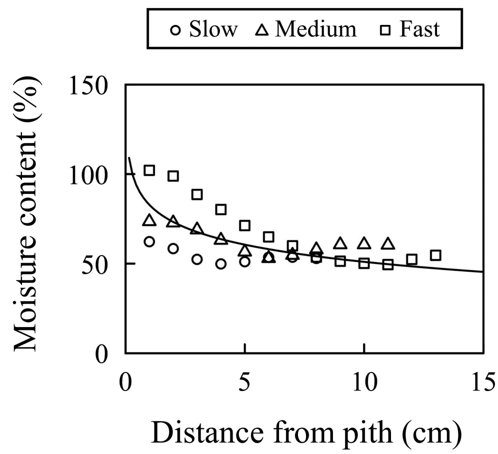

Figure 1 Radial variations in green moisture content in relation to distance from pith based on the best model.

Note: Circles, triangles, and squares indicate slow-, medium-, and fast-growing trees. Solid curve indicates the regression curve based on the best model with fixed-effect parameters.

Table 6 Parameter estimates, associated standard errors, *p*-values, and the random effects parameters for the selected model of radial variation in basic density in relation to relative distance from pith.

Property	Equation	Fixed effects					Random effects		
		Parameter	Estimates	SE	*t*-value	*p*-value	$Tree_{Slow}$	$Tree_{Medium}$	$Tree_{Fast}$
Basic density	14	γ_0	0.5697	0.3564 × 10^{-1}	− 3.742	<0.001	− 0.1013 × 10^{-5}	− 0.4855 × 10^{-5}	0.5868 × 10^{-5}
		γ_1	0.6395 × 10^{-2}	0.1488 × 10^{-2}	4.297	<0.001			
		γ_2	− 0.5070 × 10^{-4}	− 0.1356 × 10^{-4}	15.985	<0.001			

Note: SE, standard error; *p*-value, significant level for each fixed-effect parameter. $Tree_{Slow}$, $Tree_{Medium}$, and $Tree_{Fast}$, random-effect parameter of each category.

E. globulus, and *E. alba* (DeBell et al. 2001; Kojima et al. 2009b; Wahyudi et al. 2015). In the present study, xylem maturation manner can be clarified in tropical broad-leaved tree species using new modelling approach: model selection from two mixed-effects models of radial variation for wood properties with explanatory variables as distance from pith and relative distance from pith (or cambial age), and random effect as individual trees. As the results, xylem maturation in *E. urophylla* also depended on cambial age rather than diameter growth based on the model selection of radial variation in basic density. Further research is needed for clarifying that what kind of factors affects on xylem maturation manner and how the manner controls at genus level.

4. Concluding remarks

To clarify the effects of radial growth rate on wood properties and the manner of xylem maturation, mixed-effect models were fitting for wood properties in 24-year-old *E. urophylla* trees planted in Indonesia. The best models that represent the radial variations of green moisture contents and basic density were logarithmic and quadratic functions, respectively. The mixed-effects models of stress-wave velocity, green moisture content, and basic density were singular fitting. In addition, no significant correlation was found between stem diameter and stress-wave velocity or basic density, suggesting that the effect of the radial growth rate on these properties was minimal. Therefore, the faster radial growth rate did not always produce a lower quality of wood respect to production of solid wood for construction. By the model selection between distance from the pith and relative distance from pith as the explanatory variables, models with relative distance from pith was selected for basic density, suggesting that xylem maturation depend on cambial age in *E. urophylla*. In the future, xylem maturation manner in the other tropical broad-leaved tree species also should be clarified by the model selection among two mixed-effects models of radial variation for wood properties with explanatory variables as distance from pith and relative distance from pith (or cambial age), and random effect as individual trees.

Acknowledgements

The authors thank to Kazuko Makino, Student, School of Agriculture, Utsunomiya University, for assisting field experiments in Indonesia and laboratory experiments in Japan.

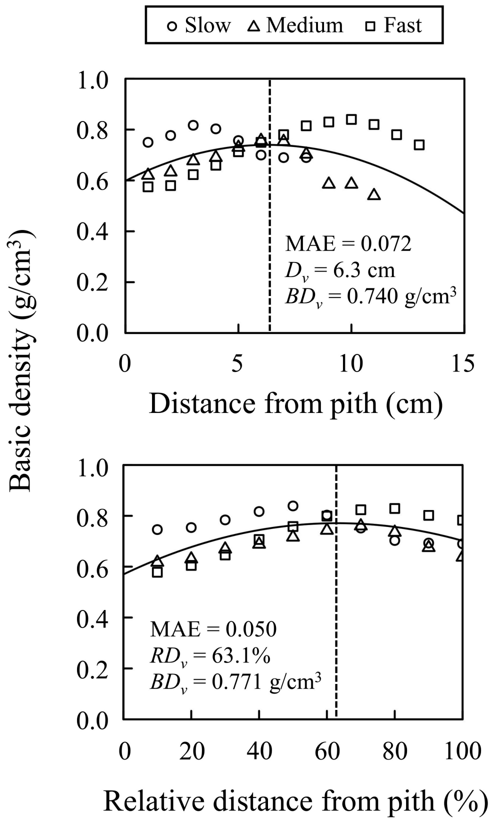

Figure 2 Radial variations in basic density in relation to distance from pith or relative distance from pith based on the best model.

Note: MAE, mean absolute error; D_v, RD_v, and BD_v, distance from pith, relative distance from pith, and basic density of vertex estimated from the best model with fixed-effect parameters (Tables 3 and 6). Circles, triangles, and squares indicate fast-, medium-, and slow-growing trees. Solid curve indicates the regression curve based on the best model with fixed-effect parameters. Dashed line indicates the vertex of the best model with fixed-effect parameters.

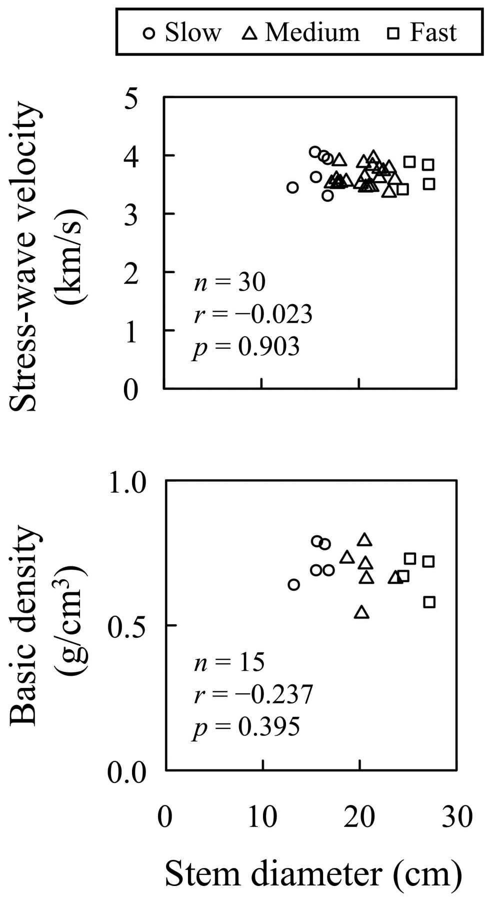

Figure 3 Relationship between stem diameter and stress-wave velocity of stem or basic density.

Note: n, number of sample trees; r, correlation coefficient; p, p-value of a correlation coefficient.

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