Growth Characteristics and Wood Properties of Two Interspecific *Eucalyptus* Hybrids Developed in Indonesia

Agung Prasetyo Haruna Aiso-Sanada Futoshi Ishiguri
Imam Wahyudi I. Putu G. Wijaya Jyunichi Ohshima
Shinso Yokota

Abstract

The aim of this study was to clarify the wood properties of two interspecific *Eucalyptus* hybrids, *Eucalyptus grandis* × *Eucalyptus pellita* (G×P) and *E. grandis* × *Eucalyptus urophylla* (G×U), developed in Indonesia. The growth characteristics and stress-wave velocity (SWV) were evaluated for 102 trees from three clones of the G×P hybrid and 105 trees from three clones of the G×U hybrid. Wood properties, such as basic density, shrinkage, compressive strength, modulus of elasticity, and modulus of rupture, were evaluated from nine selected trees of each clone. The G×U hybrid had better tree growth and SWV compared with those of the G×P hybrid. No negative correlation coefficients were observed between growth characteristics and SWV, indicating that the selection of clones for increased wood volume does not reduce their mechanical properties. Hybridizations between *E. grandis* and *E. pellita* or *E. urophylla* showed that *E. grandis* dominated the growth characteristics with some refinements in the wood properties, especially compressive strength, in the G×P hybrid. Selection based on the superior clones for tree growth would result in higher wood productivity for timber use in these two hybrids.

The interspecific hybridization of *Eucalyptus* species has been conducted to produce hybrids with desirable characteristics, such as faster growth, higher disease resistance, and higher environment adaptability. For example, Wessels et al. (2016) found that fast growth and drought tolerance are two key benefits of *Eucalyptus* hybridization in South Africa. In addition, growth characteristics, adaptability for a wider range of altitudes, and frost tolerance are breeding objectives for a *Eucalyptus globulus* × *Eucalyptus nitens* hybrid in Chili (Carillo et al. 2017). Furthermore, the development of a *Eucalyptus grandis* × *Eucalyptus urophylla* (G×U) hybrid was conducted in China for its ability to survive in a wide range of altitudes (Wu et al. 2012). To date, many interspecific hybrids between *E. grandis* and *E. urophylla*, *Eucalyptus pellita* or other *Eucalyptus* species have developed, and they have been planted as valuable wood resources for both paper and solid wood production in Brazil, China, and South Africa (Gwaze et al. 2000, Carvalho et al. 2004, Wu et al. 2012, Madhibha et al. 2013, Sseremba et al. 2016).

Successes in obtaining good wood resources from these hybrids have influenced the development of interspecific *Eucalyptus* hybrids in other countries, including Indonesia. The developments of interspecific hybrids between *E. grandis* and *E. urophylla* or *E. pellita* produce genetic improvements that are useful for these hybrids in high-elevation plantations in Sumatra, Indonesia (Brawner et al. 2010). Although the hybrids are mainly used for producing pulpwood, using the hybrids for timber should also be considered to gain more economic benefits and to reduce the degradation of natural forests due to the excessive production of commercial timber. Therefore, knowledge of

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The authors are, respectively, PhD Student, Researcher, and Associate Professor, Utsunomiya Univ., Utsunomiya, Japan (agungprstyo42@gmail.com, haiso@cc.utsunomiya-u.ac.jp, ishiguri@cc.utsunomiya-u.ac.jp [corresponding author]); Professor, Bogor Agric. Univ., Bogor, Indonesia (imyudarw16@yahoo.com); Business Continuous Improvement Department Head, PT Toba Pulp Lestari, Tbk, North Sumatra, Indonesia (Putu_Wijaya@tobapulp.com); and Lecturer and Professor, Utsunomiya Univ., Utsunomiya, Japan (joshima@cc.utsunomiya-u.ac.jp, yokotas@cc.utsunomiya-u.ac.jp). This paper was received for publication in September 2017. Article no. 17-00049.

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the growth characteristics and wood properties of interspecific hybrids developed in Indonesia is critical.

In the present study, the growth characteristics (i.e., stem diameter and tree height), stress-wave velocity (SWV), and wood properties (i.e., basic density, shrinkage, microfibril angle of wood fiber, compressive strength, modulus of elasticity, and modulus of rupture) were evaluated for 4-year-old *E. grandis* × *E. pellita* (G×P) and G×U hybrids. The data on the two hybrids in the present study were also statistically compared with those obtained from the parental species (Prasetyo et al. 2017) to discuss the hybridization's effects on wood properties.

Materials and Methods

Experimental stand

Two 4-year-old, interspecific hybrids, G×P and G×U, were used in the present study. The pulp and paper company PT, Toba Pulp Lestari, Tbk (Indonesia) developed these hybrids. The seed sources of the parental species originated from Australia for *E. grandis*, Papua New Guinea for *E. pellita*, and East Timor for *E. urophylla* (Prasetyo et al. 2017). The plantation site was located in Habinsaran, Toba Samosir, Medan, North Sumatra, Indonesia (ca. 2°17′N, 99°13′E, 1,300 m above sea level [asl]). The temperature in the plantation site varies from 24°C to 32°C and rarely falls below 22°C or exceeds 34°C. Rainfalls range from 2,200 to 2,900 mm yr^{-1}, with the least amount of rain in June, averaging about 90 mm, and the most rain in November, averaging about 340 mm. In the present study, three clones of each hybrid were used (G×P1, G×P2, G×P3, G×U1, G×U2, and G×U3). Cuttings of the clones were planted with an initial spacing of 2.6 by 2.6 m. No silvicultural treatments were applied, except for fertilizing three times before harvesting. Data on the wood properties from the pith up to 6 cm that were obtained from the parental species and described in a previous report (Prasetyo et al. 2017) were used as local controls for evaluating the wood properties of the two hybrids used in the present study.

Growth characteristics and SWV of trees

The growth characteristics and SWV of trees were measured for 102 trees from three clones of the G×P hybrid and 105 trees from three clones of the G×U hybrid. D (stem diameter) was measured at 1.3 m above the ground using a diameter tape. TH (tree height) was measured using an ultrasound height meter (Vertex IV, Haglöf). The SWVs of the trees were calculated from the stress-wave propagation time on the stem, which was determined by a stress-wave timer (Fakopp microsecond timer, Fakopp Enterprise; Fig. 1). The two sensors were set on the stem with a distance of 100 m between the sensors (Fig. 1). By tapping the start sensor with a small hammer, stress-wave propagation time was recorded using the stress-wave timer. The data were recorded six times, and the average values were used to determine the SWV. The SWV was calculated from the average values divided by the stress-wave propagation time.

Wood properties

In total, 18 trees (three trees for each clone) were selected on the basis of stem form, health condition, and D (with mean values) for measuring wood properties, such as basic density (BD), microfibril angle (MFA) of wood fibers, radial and tangential shrinkages per 1 percent change in moisture content (RS and TS, respectively), compressive strength parallel to grain (CS), modulus of elasticity (MOE), and modulus of rupture (MOR). After harvesting the selected trees, 30-mm-thick discs were obtained at 1.3 m above the ground as samples for BD and MFA, and logs with 10-cm lengths were also obtained at the same position for measuring shrinkage and mechanical properties (Fig. 1).

The BD and MFA were measured at 1-cm intervals from pith to bark. BD was calculated as the ratio of ovendry weight to green volume using water displacement method (Barnett and Jeronimidis 2003). The MFA was measured using the iodine method (Senft and Bendtsen 1985). Radial sections (20 μm in thickness) were prepared by a sliding microtome (REM-710, Yamato Koki) from pith to bark. The sections were treated with Schulze's solution and then dehydrated in a graded ethanol series. Finally, an iodine–potassium iodide solution and 60 percent nitric acid were dropped onto the dehydrated sections. MFA was measured from photomicrographs of 30 fibers in each radial position using an image analysis software (ImageJ, National Institutes of Health).

For measurements of the shrinkage and three mechanical properties (CS and static bending test), the measurement procedures were following the Japanese Industrial Standard, while the specimen sizes were not made standard due to the limitation on the tree size.

For shrinkage, samples (10 by 10 by 10 mm; longitudinal [L] by radial [R] by tangential [T]) were successively prepared from pith to bark. A digital screw micrometer (MDC-25M, Mitutoyo) was used for measuring the dimensional changes at air-dry and ovendry (105°C) conditions. The formula for calculating RS and TS was described in our previous article (Japanese Standard Association [JIS Z2101] 2009, Istikowati et al. 2014). The ratio between the RS and TS (T/R ratio) was also calculated.

Small-clear specimens of 65 by 10 by 4 mm and 40 by 10 by 10 mm (L by R by T) were prepared for static bending and CS tests, respectively. Before testing, the small-clear specimens were kept at 21°C and 65 percent relative humidity until equilibrium moisture content was reached. The static bending test with three points loading was conducted using a universal testing machine (MSC-5/500-2, Tokyo Testing Machine) with a 45-mm span and a 0.5-mm min^{-1} loading speed. The data on load and deflection were recorded in a personal computer and were used for calculating MOE and MOR following Shmulsky and Jones (2011). For the CS test, the maximum load was obtained using a universal testing machine (RTF-2350, A&D) with a loading speed of 0.5 mm min^{-1}. The CS was determined by dividing the maximum load by the transverse section area of the specimen (Kollmann and Côté 1984).

Data analysis

Wood properties improvement could be achieved in a tree breeding program using appropriate selection of plus-tree. This selection could be made only for trees that performed significantly different in a specific wood property from the others. Therefore, to investigate the significant differences in each investigated property, A Tukey's honestly significant difference (HSD) test at a level of 5 percent was applied. In addition, to clarify the differences between the two hybrids for each investigated property, a *t* test at the level of 5 percent was also used. On the other hand, Pearson's correlation analysis and multiple regression

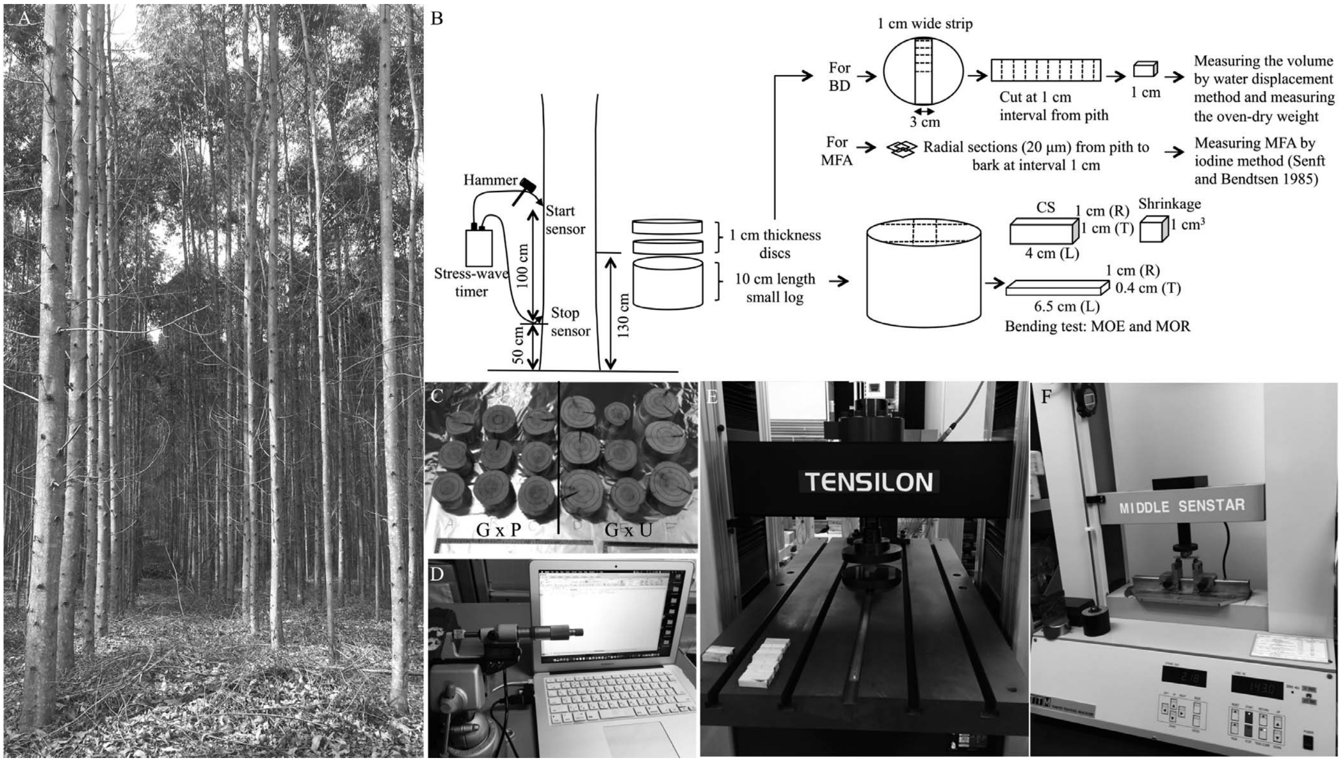

Figure 1.—Photographs of (A) the tree stand, (B) schematic sampling illustration, (C) small logs of two Eucalyptus *hybrids, (D) shrinkage measurement, (E) compressive strength testing, and (F) bending testing. BD = basic density; MFA = microfibril angle; CS = compressive strength parallel to grain; MOE = modulus of elasticity; MOR = modulus of rupture. G×P =* Eucalyptus grandis × Eucalyptus pellita*; G×U =* E. grandis × Eucalyptus urophylla.

analysis were applied to analyze the relationships between two measured wood properties and to explain the relationships between two independent variables with one dependent variable of wood properties, respectively.

Data on wood samples at intervals of 1 cm from the pith up to 6 cm near the bark were used for analyzing the relationships between wood properties (Table 1). Data from the previous article (Prasetyo et al. 2017) on the wood properties of the parental species at intervals of 1 cm from the pith up to 6 cm were statistically compared using the Tukey HSD test at a 5 percent level (Table 2). For all these statistical data analysis, the open-source statistical software package R (R Core Team 2016) was used.

Results

The mean values of D, TH, and SWV were 12.8 cm, 16.4 m, and 3.01 km s^{-1} for the G×P hybrid and 14.6 cm, 18.9 m, and 3.19 km s^{-1} for the G×U hybrid (Table 3). Significant

Table 1.—Relationships of AD, MFA, or AD+MFA with other wood properties.[a]

	E. grandis × *E. pellita* (*n* = 54)			*E. grandis* × *E. urophylla* (*n* = 54)		
Property	AD	MFA	AD+MFA[b]	AD	MFA	AD+MFA[b]
RS	0.24	−0.35**	0.45**	0.16	−0.07	0.17
TS	−0.16	0.02	0.14	0.16	−0.22	0.28
T/R	−0.35**	0.33*	0.48**	−0.17	−0.06	0.17
CS	0.09	−0.24	0.26	0.29*	−0.43**	0.53**
MOE	0.31*	−0.65**	0.71**	0.19	−0.60**	0.67**
MOR	0.39**	−0.62**	0.73**	0.43**	−0.35**	0.61**

[a] *n* = number of samples from 18 trees (three trees × three clones in a hybrid); AD = air-dry density; MFA = microfibril angle of S_2 layer in wood fibers; RS and TS = radial and tangential shrinkages per 1 percent change in moisture content, respectively; T/R = ratio of tangential shrinkage to radial shrinkage; CS = compressive strength parallel to grain; MOE = modulus of elasticity; MOR = modulus of rupture; *, ** = significantly different at 5 and 1 percent levels, respectively.

[b] Results from multiple regression analysis.

Table 2.—Multiple comparisons among parental species and their hybrids.[a]

Property	*E. grandis*	*E. pellita*	G×P	*E. grandis*	*E. urophylla*	G×U
BD	B	A	B		NS	
RS		NS			NS	
TS	A	A	B		NS	
MFA	A	AB	B		NS	
CS	B	AB	A	B	A	B
MOE	AB	A	B	B	A	B
MOR		NS		AB	A	B

[a] Different capital letters indicate significant differences among the parental species and a hybrid based on the Tukey's honest significant difference test at a 5 percent level. Comparison data were collected from each radial position at 1-cm intervals from the pith to 6 cm toward the bark of parental species (Prasetyo et al. 2017) and the hybrids. BD = basic density; RS and TS = radial and tangential shrinkages per 1 percent change in moisture content, respectively; MFA = microfibril angle of S_2 layer in wood fibers; CS = compressive strength parallel to grain; MOE = modulus of elasticity; MOR = modulus of rupture; NS = not significant.

Table 3.—Statistical values of D, TH, and SWV of two Eucalyptus *hybrids.*[a]

	E. grandis × *E. pellita*				*E. grandis* × *E. urophylla*				
Property	G×P1 (*n* = 33)	G×P2 (*n* = 34)	G×P3 (*n* = 35)	Mean	G×U1 (*n* = 36)	G×U2 (*n* = 35)	G×U3 (*n* = 34)	Mean	Two hybrids (*n* = 3)[b]
D (cm)	11.9 (2.8)	13.5 (3.0)	13.0 (2.9)	12.8 (3.0)	15.3 (2.9) A	12.6 (2.2) B	15.9 (3.0) A	14.6 (3.0)	0.31
TH (m)	15.8 (2.6) B	14.6 (2.0) B	18.8 (3.0) A	16.4 (3.1)	18.0 (1.9) B	16.6 (2.1) B	22.3 (3.5) A	18.9 (3.5)	0.04
SWV (km s^{-1})	2.94 (0.16) B	2.98 (0.14) B	3.09 (0.14) A	3.01 (0.16)	3.19 (0.14)	3.16 (0.12)	3.23 (0.17)	3.19 (0.12)	0.04

[a] Values are means (standard deviations). Different capital letters indicate significant differences among clones in each hybrid (Tukey's honestly significant difference test at a 5% level). *n* = number of trees; D = stem diameter; TH = tree height; SWV = stress-wave velocity.

[b] *P* value from *t* test at a 5 percent level.

differences were obtained on the TH and SWV values between the two hybrids (*t* test, 5% level): G×U clones showed better performance in their TH and SWV compared with G×P clones. Significant differences were found among the clones of each hybrid, except for the D of the G×P hybrid and SWV of the G×U hybrid.

The BD in both G×P and G×U hybrids showed almost constant values from pith to bark (Fig. 2). The mean values were 0.39 and 0.40 g cm^{-1} for G×P and G×U hybrids, respectively (Table 4). The RS for G×P and G×U hybrids ranged from 0.17 to 0.22 percent and 0.18 to 0.20 percent, respectively (Table 4). The mean values of the TS and T/R ratio were 0.32 percent and 1.7 for the G×P hybrid and 0.30 percent and 1.7 for the G×U hybrid, respectively (Table 4). The RS and TS on both G×P and G×U hybrids showed almost constant values from pith to bark (Fig. 3). In both hybrids, the MFA values showed a general radial pattern: there was a decreasing trend from the pith to bark (Fig. 4). As the results show, the mean values were 12.3° and 9.8° for G×P and G×U hybrids, respectively (Table 4). The mean values of CS, MOE, and MOR for the G×P hybrid were 42.6 MPa, 4.34 GPa, and 74.3 MPa, respectively (Table 4). For the G×U hybrid, these values were 43.8 MPa, 4.57 GPa, and 79.0 MPa (Table 4), respectively. In the two hybrids, CS was almost constant from the pith up to 2 cm, and then it increased toward the bark (Fig. 5). In the G×P hybrid, both MOE and MOR increased from pith to bark (Fig. 6). No significant differences between the two hybrids were found in all the wood properties tested in the present study (Table 4).

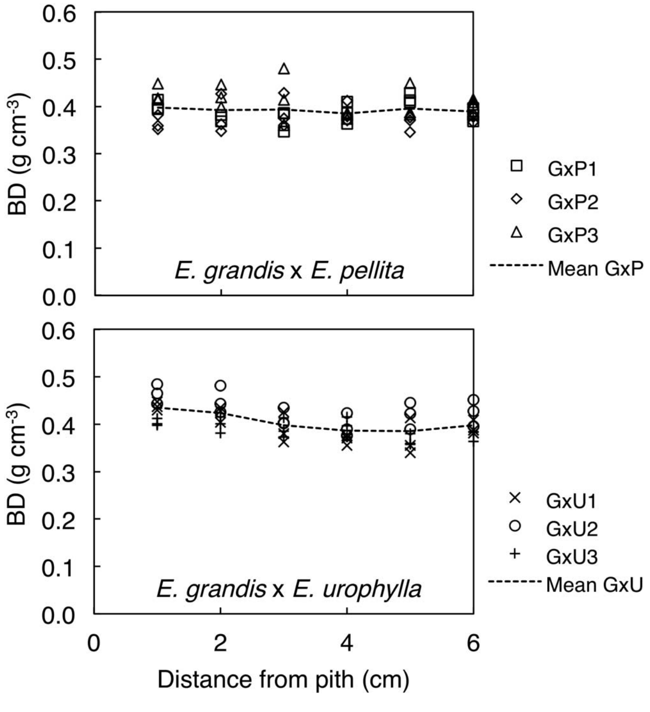

Figure 2.—Radial variation of basic density (BD) in two Eucalyptus *hybrids.*

Discussion

Growth characteristics and wood properties of the hybrids

Gwaze et al. (2000) found that, among the six tested hybrids from *E. grandis*, *E. urophylla*, *E. pellita*, *Eucalyptus camaldulensis*, *Eucalyptus saligna*, and *Eucalyptus tereticornis*, the G×U hybrid is the second most productive hybrid after *E. grandis* × *E. saligna*, and it showed better growth than G×P and other hybrids, such as *E. grandis* × *E. camaldulensis* and *E. grandis* × *E. tereticornis* under high-altitude (1,300 to 1,477 m asl) environmental conditions in Zimbabwe. The G×U hybrid showed 6, 1, and 16 percent increases in diameter, tree height, and volume, respectively, compared with *E. grandis*, whereas the G×P hybrid showed similar growth to *E. grandis* (Gwaze et al. 2000). Clarke et al. (2009) found that *E. grandis* is able to grow well in higher altitudes, whereas *E. pellita* is a species that typically grows faster in the lowland areas. In the present study, plantation was located around 1,300 m asl. Therefore, the G×U hybrid showed better tree height growth compared with the G×P hybrid (Table 3).

SWV ranged from 2.78 to 4.03 km s^{-1} for the 4.3-year-old *Eucalyptus* hybrid clones planted for the pulpwood industry in Southern China (Wu et al. 2011). In a 3-year-old G×U hybrid developed in Brazil, the mean SWV was 3.4 to 4.4 km s^{-1} (Gonçalves et al. 2013). Our results obtained from the G×P and G×U hybrids showed relatively lower SWV values compared with the G×U hybrid developed in Brazil (Gonçalves et al. 2013).

Wu et al. (2011) reported that the mean values of BD ranged from 0.38 to 0.43 g cm^{-3} for a 4.3-year-old G×U hybrid clone developed in southern China. Gardner et al. (2007) found that BD of a 7-year-old G×U hybrid clone planted at two locations in South Africa showed higher values (0.41 to 0.50 g cm^{-3}), which were higher than those of the two hybrids in the present study. Generally, the BD values of *Eucalyptus* spp., such as *E. grandis*, *E. urophylla*, and *E. pellita*, increase from pith to bark (Wu et al. 2006,

Table 4.—Statistical values of wood properties in two Eucalyptus *hybrids.*[a]

Property	*E. grandis* × *E. pellita* G×P1 (*n* = 3)	G×P2 (*n* = 3)	G×P3 (*n* = 3)	Mean	*E. grandis* × *E. urophylla* G×U1 (*n* = 3)	G×U2 (*n* = 3)	G×U3 (*n* = 3)	Mean	Two hybrids (*n* = 3)[b]
BD (g cm^{-3})	0.39 (0.01)	0.38 (0.02)	0.41 (0.02)	0.39 (0.02)	0.40 (0.02) B	0.43 (0.01) A	0.39 (0.01) B	0.40 (0.02)	0.62
RS (%)	0.20 (0.03)	0.17 (0.01)	0.22 (0.02)	0.20 (0.03)	0.18 (0.01)	0.20 (0.04)	0.18 (0.01)	0.19 (0.02)	0.62
TS (%)	0.30 (0.01)	0.32 (0.03)	0.33 (0.03)	0.32 (0.02)	0.30 (0.04)	0.30 (0.03)	0.31 (0.04)	0.30 (0.03)	0.31
T/R	1.6 (0.2)	1.8 (0.2)	1.6 (0.1)	1.7 (0.2)	1.6 (0.1)	1.6 (0.2)	1.8 (0.2)	1.7 (0.2)	0.85
MFA (°)	12.3 (0.7) AB	13.3 (0.1) B	11.4 (0.3) A	12.3 (1.0)	10.2 (0.5)	9.5 (0.4)	9.8 (0.5)	9.8 (0.5)	0.06
CS (MPa)	46.7 (3.7)	39.5 (0.4)	41.6 (4.8)	42.6 (3.7)	40.9 (2.7) B	49.4 (2.2) A	41.3 (0.9) B	43.8 (4.5)	0.82
MOE (GPa)	4.97 (0.33) A	3.75 (0.28) B	4.29 (0.32) AB	4.34 (0.61)	4.44 (0.32)	4.90 (0.26)	4.37 (0.19)	4.57 (0.34)	0.68
MOR (MPa)	84.1 (6.8) A	66.8 (3.7) B	72.0 (3.1) AB	74.3 (8.9)	74.6 (5.6) B	87.6 (2.4) A	74.8 (2.9) B	79.0 (7.3)	0.65

[a] Values are means (standard deviations). Different capital letters indicate significant differences among clones in each hybrid (Tukey's honestly significant difference test at a 5% level). *n* = number of trees; BD = basic density; RS and TS = radial and tangential shrinkages per 1 percent change in moisture content, respectively; T/R = ratio of tangential shrinkage to radial shrinkage; MFA = microfibril angle of S_2 layer in wood fibers; CS = compressive strength parallel to grain; MOE = modulus of elasticity; MOR = modulus of rupture.

[b] *P* value from *t* test at a 5 percent level.

Bailleres et al. 2008, Prasetyo et al. 2017). Our results related to BD were consistent with those of another report for a G×U hybrid tree of the same age (Wu et al. 2006). However, the radial variations in BD in two hybrids were constant from pith to bark, which is in contrast with the results found in other reports (Wu et al. 2006, Bailleres et al. 2008, Prasetyo et al. 2017) on radial variations for BD in *Eucalyptus* species. This result might be explained by the effects of genetic factors on the wood properties, such as BD. In fact, BD of their parent species, *E. grandis* has lesser within- and among-tree variations compared with those *E. urophylla* and *E. pellita* (Prasetyo et al. 2017). Thus, hybridization of these *Eucalyptus* species with *E. grandis* would influence the variation of BD.

The total shrinkages from green to ovendry conditions in the radial and tangential directions and the T/R ratio of the *E. urophylla* × *E. grandis* hybrid clone were reported to be 4.8 percent, 7.8 percent, and 1.7, respectively (Hein et al. 2013). Ishiguri et al. (2017) reported that total shrinkages were 4.9 to 6.9 percent for RS and 9.1 to 12.6 percent for TS in a 4-year-old *E. camaldulensis* planted for pulpwood in Thailand. The total shrinkages in both the radial and

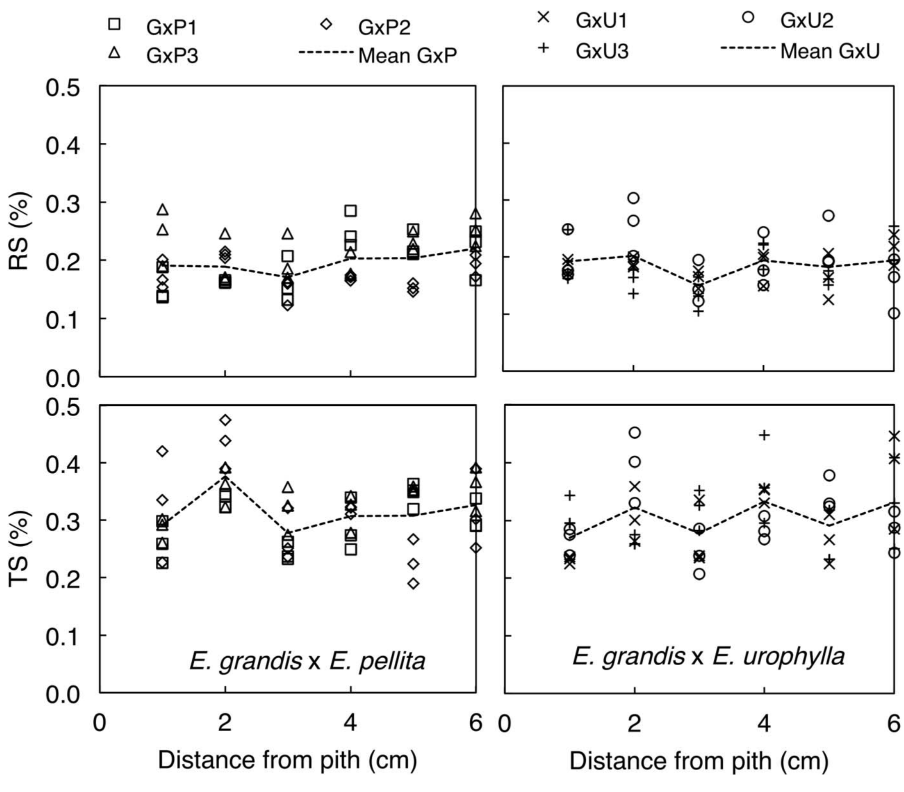

Figure 3.—Radial variation of wood shrinkage per 1 percent change in moisture content in two Eucalyptus *hybrids. RS = radial shrinkage; TS = tangential shrinkage.*

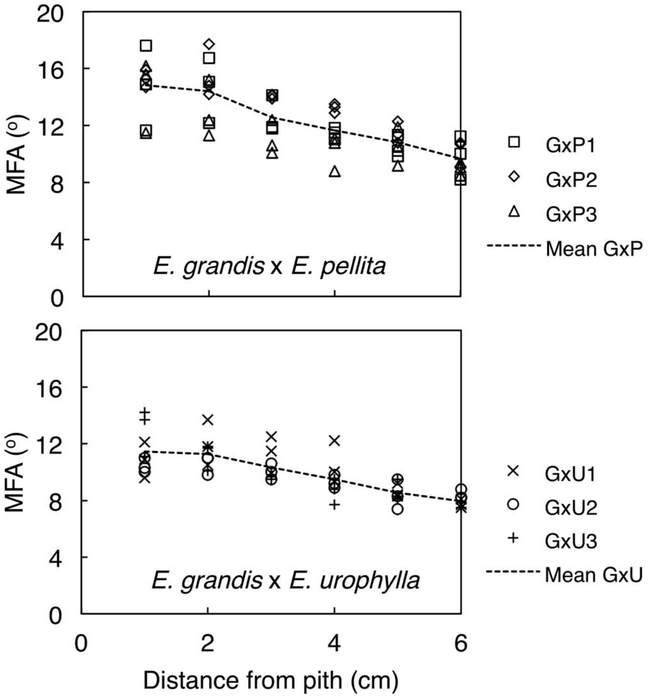

Figure 4.—Radial variation in microfibril angle (MFA) of S_2 layer in wood fibers in two Eucalyptus *hybrids.*

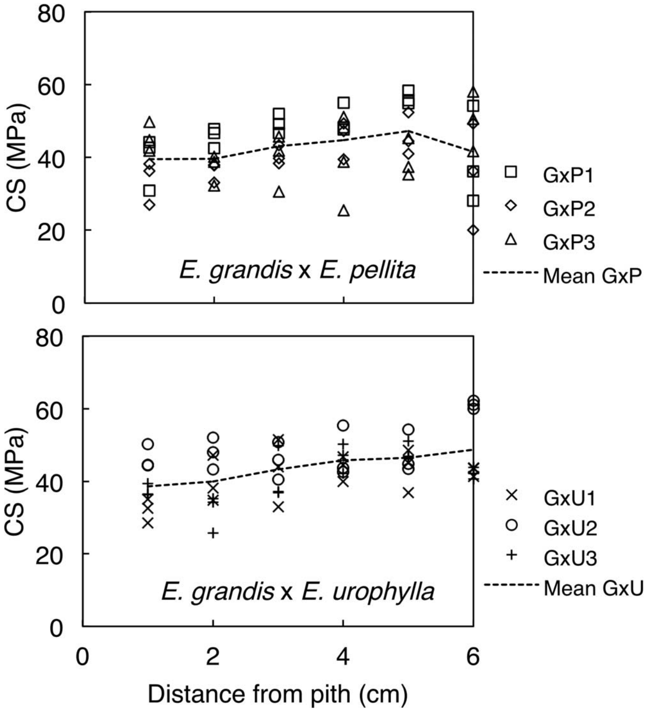

Figure 5.—Radial variation of compressive strength (CS) parallel to grain in two Eucalyptus *hybrids.*

tangential directions for *E. grandis*, *E. urophylla*, and *E. pellita* increased from pith to bark (Wu et al. 2006, Bailleres et al. 2008). The shrinkages obtained in the present study showed almost the same T/R ratio with those of other reports on the *Eucalyptus* hybrids. On the other hand, the radial variations in RS and TS in the present study were in contrast with those of other reports for the *Eucalyptus* species. Similar to BD, the *E. grandis* parent species showed lesser within- and among-tree variation in wood shrinkage compared with those in two other parent species (Prasetyo et al. 2017). Thus, the obtained results of shrinkage in the present study might be influenced by genetic factors.

Although the measurement methods were different, some researchers reported that the mean MFA values of *Eucalyptus* spp. were 12.1° for a 6-year-old *E. urophylla* × *E. grandis* hybrid clone by X-ray diffractometry (Hein et al. 2013) and 14.5° to 15.1° for a 10-year-old *E. pellita* clone by near-infrared (NIR) spectroscopy (Hung et al. 2015). The mean MFA value obtained in the present study was almost the same as that in a 6-year-old *Eucalyptus* hybrid clone (Hein et al. 2013) but was different from that of *E. pellita* as reported by Hung et al. (2015).

In a 7-year-old *E. grandis*, the MOE was 11.2 to 13.0 GPa from heartwood to sapwood (Cademartori et al. 2014). Hein et al. (2013) reported that the mean MOR of a 6-year-old *E. urophylla* × *E. grandis* hybrid clone was 73 MPa. By using NIR spectroscopy, the CS, MOE, and MOR of a 7-year-old *E. urophylla* were 40.1 to 63.6 MPa, 11.1 to 20.2 GPa, and 69.9 to 115.8 MPa, respectively (Andrade et al. 2010). Based on the obtained results in the present study, with the exception of the CS and MOR values, the MOE values of the two hybrids were lower than those reported by other researchers (Andrade et al. 2010, Cademartori et al. 2014). However, as shown in Figures 5 and 6, radial variations of these three mechanical properties showed the general patterns of the *Eucalyptus* species in which the values increase from pith to bark.

Relationships among properties

Figure 7 shows the relationships between growth characteristics (D and TH) and SWV in the two hybrids. In both hybrids, D was positively correlated with TH ($r = 0.67$ and $r = 0.78$ for the G×P and G×U hybrids, respectively). A significant positive correlation coefficient ($r = 0.45$) was also obtained between TH and SWV in the G×P hybrid, but not in the G×U hybrid ($r = 0.13$). In three 9-year-old parental *Eucalyptus* species, positive relationships between TH and SWV were observed ($r = 0.86$ in *E. grandis* and $r = 0.59$ in *E. urophylla*), except for *E. pellita* ($r = 0.39$; Prasetyo et al. 2017). Gonçalves et al. (2013) found significant positive correlations between SWV and MOE in 3-year-old G×U hybrid clones ($r = 0.76$ to 0.81), suggesting that the wood stiffness of G×U hybrid clones can be predicted by SWV values. Therefore, in the two hybrids, it can be concluded that increases in wood volume have no negative impact on mechanical properties.

The relationships between air-dry density (AD) or MFA and other wood properties are presented in Table 1. Significant but relatively lower correlation coefficients were found between the AD and T/R ratio in the G×P hybrid. Similarly, relatively lower and significant correlation coefficients were observed between the MFA and RS or T/R in the G×P hybrid. It was reported that the correlation coefficients between wood density or MFA and shrinkage in *Eucalyptus* species and G×U hybrid clones were relatively lower or nonsignificant values (Yang et al. 2003, Wu et al. 2006, Hein et al. 2013). Therefore, the results obtained in the present study are consistent with those obtained by other researchers (Yang et al. 2003, Wu et al. 2006, Hein et al. 2013). On the other hand, significant correlation coefficients

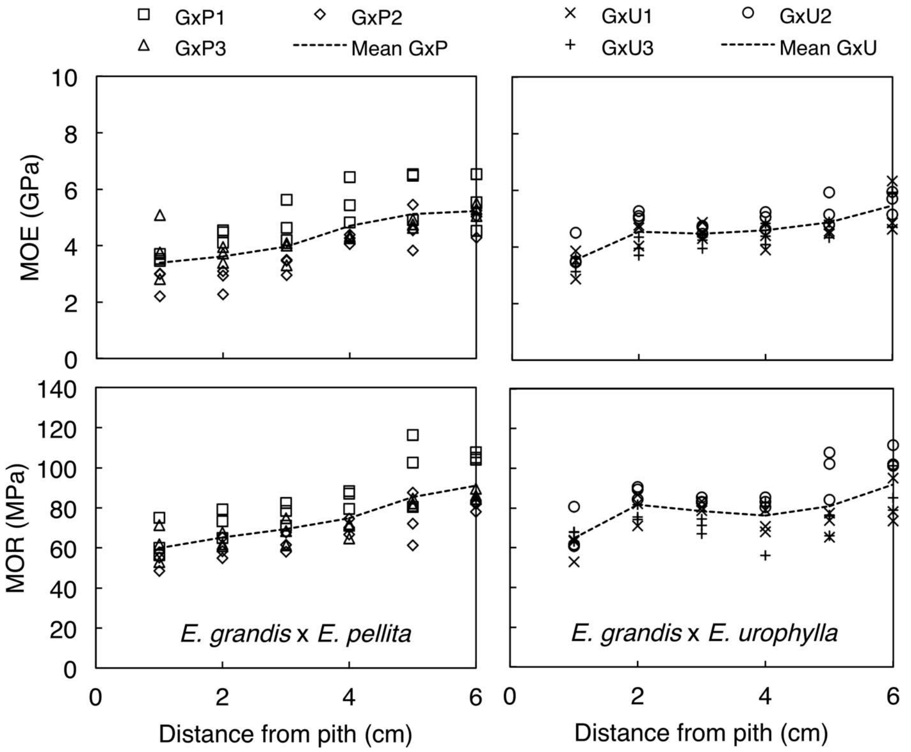

Figure 6.—Radial variations of modulus of elasticity (MOE) and modulus of rupture (MOR) in two Eucalyptus *hybrids.*

were obtained between the AD or MFA and measured mechanical properties, except for CS in the G×P hybrid (Table 1).

Some researchers confirmed that the AD and MFA are good predictors for wood properties in *Eucalyptus* spp. and hybrid clones when AD and MFA are used as an independent variable (Yang et al. 2003, Hein et al. 2013, Wessels et al. 2016). In our previous research, the wood properties of three *Eucalyptus* species were also highly influenced by both BD and MFA ($r = 0.55$ to 0.91; Prasetyo et al. 2017). As shown in Table 1, correlation coefficients increased in the present study when both the AD and MFA were used as independent variables in the multiple regression analysis. The mechanical properties in particular were highly predicted by the AD and MFA values. Thus, it can be concluded that wood properties, especially mechanical properties in these two hybrids, are highly correlated with AD and MFA.

Hybridization effects on wood properties

In the previous study (Prasetyo et al. 2017), we predicted that interspecific hybridizations between *E. grandis* and *E. pellita* or *E. urophylla* would result in better growth characteristics and refinements on the poor wood properties of *E. grandis*. To evaluate the effects of hybridization on wood properties, the data on wood properties obtained in the present study were statistically compared with those of the three *Eucalyptus* species in the previous study (Prasetyo et al. 2017). The results of the comparison are presented in Table 2. In the present study, a positive hybridization effect was only found in the CS of the G×P hybrid. Gwaze et al. (2000) reported that *E. grandis* was dominant to *E. urophylla* and *E. pellita* in growth characteristics when they were hybridized. Using 21 to 55 *E. grandis* × *E. tereticornis* and *E. grandis* × *E. camaldulensis* hybrid families under three different trial conditions (rainfalls and altitudes), *E. grandis* was likely to be a better parent for growth compared with *E. tereticornis* and *E. camaldulensis* under high-altitude and wet hybrid trial conditions in Zimbabwe (Madhibha et al. 2013). For wood properties, the hybridization's effect on BD was negative or close to 0 percent in comparison with the parental species of 2-year-old G×U hybrid clones in Brazil (Bison et al. 2006). Zobel and Jett (1995) also pointed out that, although wood properties are highly inherited, the hybridizations would produce characteristics intermediate to those of the parents. The results in the present study were consistent with the previous findings for hybridization's effect on wood properties (Zobel and Jett 1995, Bison et al. 2006). Breeding for increased uniformity in wood density is valuable regardless of the trait selected, resulting in greater efficiency and better quality control at all stages of the manufacturing process (Zobel and van Buijtenen 1989, Zobel and Jett 1995). The wood properties of the three parental species increased from pith to bark (Prasetyo et al. 2017), with the result that the processing and manufacturing process, especially drying, quality-control, and wood use, would be influenced by the obtained larger variations of wood properties. However, the two hybrids tested here showed greater uniformity in BD and shrinkages from pith to bark, suggesting that hybridization has achieved uniformity in these two wood properties. Furthermore, no negative relationships were found between the growth characteristics and SWV, suggesting that selecting the superior clones of two hybrids could be done based on the tree height (G×P3 and G×U3; Table 3) to produce higher wood productivity for timber use.

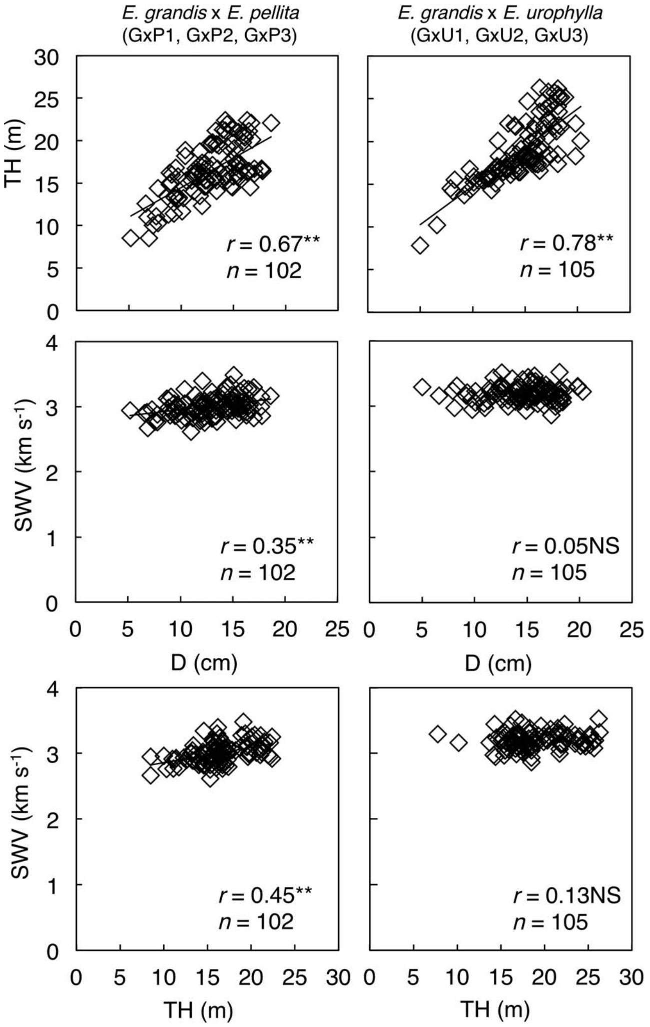

Figure 7.—Relationships between growth characteristics (stem diameter [D] and tree height [TH]) and stress-wave velocity (SWV) in two Eucalyptus *hybrids.* n = *number of trees; ** = significant at a 1 percent level; NS = not significant.*

Conclusions

The present study clarified the growth characteristics and wood properties of two *Eucalyptus*-hybrid clones developed in Indonesia for assessing their possibility for timber resources. The results are as follows:

1. Significant differences in TH and SWV were observed among the G×P hybrid clones, and D and TH in G×U hybrid clones, suggesting that possibility to improve those values through a tree breeding program. In some wood, properties—such as MFA, MOE, and MOR in the G×P hybrid and BD, CS, and MOR in the G×U hybrid—were also significantly different among those clones.
2. Between the two hybrids, the G×U hybrid had better tree growth and SWV than the G×P hybrid, although the wood properties were not significantly different between the two.
3. Positive significant correlation coefficients between growth characteristics and SWV were obtained in the G×P hybrid clones, while no significant correlation coefficients between these values were obtained in the G×U hybrid clones, indicating that an increase in wood volume does not reduce the mechanical properties of the hybrids.
4. The hybridizations might be dominated by *E. grandis* in terms of their growth characteristics but have some refinements in their wood properties, especially CS in the G×P hybrid. Therefore, selection based on the superior clones for tree growth would result in the higher wood productivity for timber use in the hybrids.
5. Considering the uniformity of radial variation in BD and shrinkages, increase of wood strength, and limitation of timber supply in Indonesia, the two hybrids have great potential to be used as timber as well as pulpwood. In addition, improvement on their wood properties are also can be achieved in a tree breeding program.

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