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FIELD NOTE

# Growth characteristics and wood properties of planted *Dryobalanops beccarii* Dyer at a reforestation site with girdling treatment of pioneer trees in Sarawak, Malaysia

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**ABSTRACT** *Dryobalanops beccarii* is an important species for reforestation and produces durable timber in tropical regions. A reforestation site planted with *D. beccarii* was established in Sarawak, Malaysia, in 2005, where logging and shifting cultivation had previously occurred. To promote *D. beccarii* growth, a selective girdling silviculture treatment (debarking below breast height) was experimentally applied to the most dominant pioneer trees, *Macaranga gigantea* in 2012. In this study, the growth characteristics (stem diameter and tree height) and wood properties (basic density and compressive strength parallel to the grain) of 20-year-old *D. beccarii* were investigated approximately a decade after the girdling treatment. *D. beccarii* trees grown in the girdling plot exhibited (1) significantly greater stem diameter and tree height, and (2) similar basic density and compressive strength compared with those in the control plot. In addition, trees with faster radial growth had higher basic density and compressive strength in *D. beccarii*. These findings indicate that the girdling treatment of pioneer trees can enhance the growth performance of planted *D. beccarii* without deteriorating its wood quality.

**Key words:** basic density, compressive strength, girdling treatment, radial growth rate, xylem maturation

## INTRODUCTION

Tropical forests have a variety of ecological services, such as biodiversity conservation, global climate regulation, and soil protection (Whitmore 1984). However, they have been rapidly degraded due to land-use changes mainly caused by expanding human activities, including the establishment of agricultural fields and timber logging, leading to forest fragmentation and disturbances in many tropical regions (Achard et al. 2002; Gustafsson et al. 2016). To prevent further loss of biodiversity in the tropics and restore soil fertility while increasing productivity of poor vegetation stocks, reforestation of the deforested area is considered a practical approach (Chazdon 2008; Wasli et al. 2014, 2020; Gustafsson et al. 2016).

In Southeast Asia, plantation forestry using species of Dipterocarpaceae is a key method for recovering degraded forests (Wasli et al. 2014, 2020; Gustafsson et al. 2016). The genus *Dryobalanops*, one of the smaller genera of Dipterocarpaceae, contains seven species: *D. aromatica* C.F.Gaertn., *D. oblongifolia* Dyer, *D. beccarii* Dyer, *D. fusca* Slooten, *D. keithii* Symington, *D. lanceolata* Burck, and *D. rappa* Becc (Ashton 1982). These species are native to Borneo, Malaya, and Sumatra (Ashton 1982). In particular, *D. beccarii* (locally known as Kapur Bukit) is the most common Dipterocarpaceae species used for reforestation in Sarawak, Malaysia (Wasli et al. 2014, 2020). It is an indigenous species in Malaysia, and its timber is highly economically valued (Wood Technology Division 1967). Therefore, plantation forestry using the *D. beccarii* is also favorable for economic development through the valuable timber production in future Malaysian forestry. In addition, in Sarawak, sustainable forest management of naturally regenerated hill mixed Dipterocarp forests is conducted under Forest Management Plans (FMPs) that prescribe a 25-year cutting cycle, paired with minimum diameter limits to allow regeneration (Diway et al. 2023). Thus, evaluating the wood properties of *D. beccarii* approaching the harvesting cycle is practically important.

Controlling the light condition in the plantation is an important factor influencing the survival and growth of the planted trees (Romell et al. 2009; Gustafsson et al. 2016). In and around gaps formed after logging activities, many species respond differently to changes in light conditions depending on their biological characteristics (Inada et al. 2013). Primary pioneer species such as *Macaranga* spp. often compete with planted seedlings of Dipterocarpaceae in gaps (Inada et al. 2013; Wasli et al. 2020). The seedlings require partial shading but need more light as they grow older (Ashton 1988; Inada et al. 2013). Therefore, silvicultural treatments should be applied to promote the growth of planted Dipterocarpaceae trees where competitive species exist.

Girdling pioneer tree species is one of the methods to improve light conditions for light-demanding planted trees (Romell et al. 2009). This treatment involves removing the outer and inner bark from the tree trunk, usually 50–100 cm above ground, using a knife for the trees (Romell et al. 2009). Girdled trees die more slowly than those cut down by conventional logging, allowing canopy gaps to form gradually and improving light conditions below (Romell et al. 2009). In Sarawak, girdling was applied to *Macaranga gigantea* (Rchb.f. & Zoll.) Müll.Arg. invading the plantation area of *D. beccarii* (Wasli et al. 2020). Wasli et al. (2020) assessed the light intensity and tree growth performance of *D. beccarii* for six years after the girdling treatment. The stem diameter and tree height of *D. beccarii* significantly increased at two and four years after girdling treatment, respectively, suggesting that the gradual canopy opening followed by the girdling treatment on *M. gigantea* might improve growth conditions for planted *D. beccarii* trees (Wasli et al. 2020). However, the effects of girdling on wood properties such as density and strength have not yet been evaluated. To promote both the reforestation of degraded sites and the sustainable production of high-quality timber using *D. beccarii* in the future, wood properties, in addition to growth performance, should be assessed at this site.

In many tropical broad-leaved tree species, two types of xylem maturation have been reported at the species level: diameter growth-dependency and cambial-age dependency (Kojima et al. 2009; Ishiguri et al. 2012; Hidayati et al. 2014, 2017; Nezu et al. 2022, 2023; Yokoyama et al. 2025) (Fig. 1). The former (Fig. 1A) has been observed in fast-growing tree species (e.g., *Acacia* spp. and *Gmelina arborea*) (Kojima et al. 2009; Hidayati et al. 2017; Yokoyama et al. 2025), whereas the latter has been found in relatively slower-growing tree species (e.g., *Tectona grandis* and *Shorea* spp.) (Ishiguri et al. 2012; Hidayati et al. 2014; Nezu et al. 2022). In the species with a diameter-growth dependency, if a wood property increases near the pith and stabilizes at reaching a specific stem diameter, trees with faster radial growth can form wood with a high quality earlier than those with slower radial growth, even at the same tree age (Fig. 1A). Consequently, trees with rapid radial growth might exhibit higher wood quality (Fig. 1A). Conversely, in relatively slow-growing species with cambial-age dependency, such as several Dipterocarpaceae, wood properties were independent from the radial growth rate (Fig. 1B) (Ishiguri et al. 2012; Nezu et al. 2022). Understanding the xylem maturation manner of *D. beccarii* is also important for effective plantation management of this species.

The aim of this study is to evaluate the effect of the girdling treatment to pioneer trees on the growth characteristics and wood properties of the targeted species, *D. beccarii*, in a reforestation site located in Gunung Apeng National Park, Serian Division, Sarawak, Malaysia. The growth characteristics and wood properties were measured for 20-year-old *D. beccarii* trees, for which the girdling treatment was conducted on pioneer species, *M. gigantea*, approximately a decade before. The effects of girdling treatment for pioneer trees on the measured properties of *D. beccarii* were evaluated. In addition, the xylem maturation manner and the relationships between radial growth rate and wood properties in *D. beccarii* are also discussed.

## MATERIALS AND METHODS

### *Study site*

This study was conducted on 20-year-old *Dryobalanops beccarii* Dyer trees planted in Gunung Apeng National Park, Serian Division, Sarawak, Malaysia (Fig. 2A, N00° 55′ 07″, E110° 39′ 43″, 67 m a.s.l.). The study site was relatively steep, with a slope of 5° to 30°. Figure 2 shows the climate conditions in Kuching (N01° 28′ 47″ and E110° 19′ 47″), the nearest meteorological station to the site. The temperature was over 25 °C throughout the year (Fig. 2A). On the other hand, the precipitation varied throughout the year (Fig. 2A): there are wetter and relatively drier seasons, with no distinct dry season.

The study site was previously logged over and had a

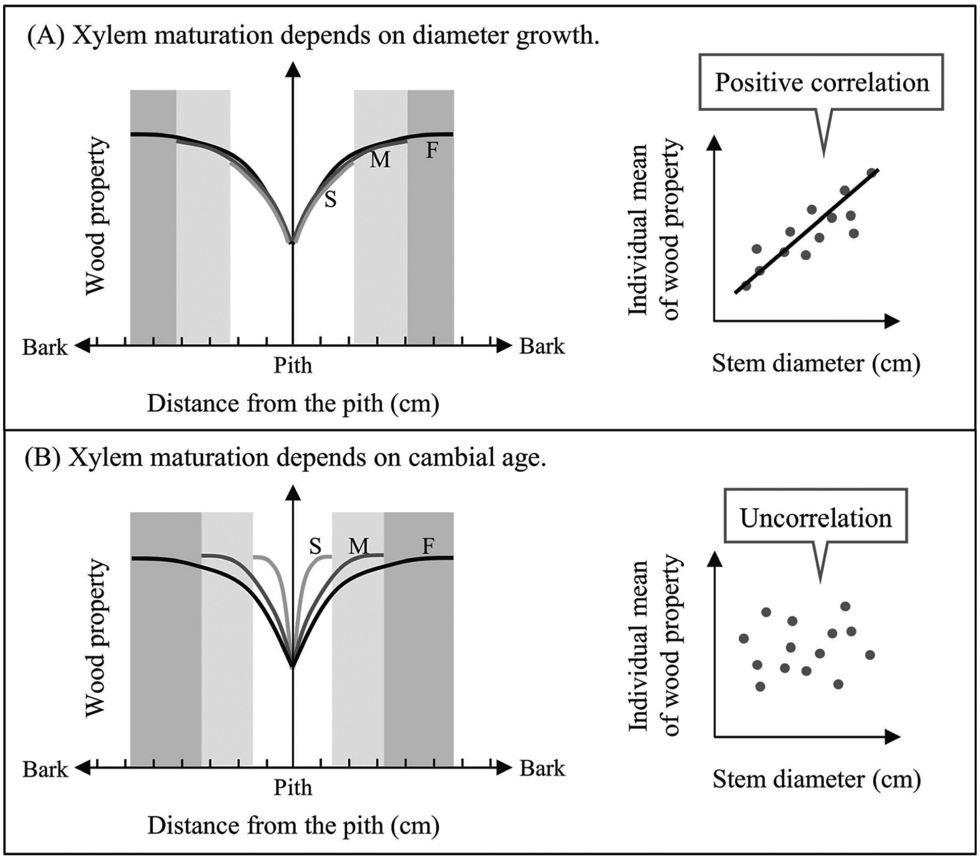


Fig. 1. Schematic diagram of the relationship between radial growth rate and wood properties in relation to the xylem maturation manner in tropical broad-leaved tree species.
Note: (A) and (B) represent diameter-growth dependency and cambial-age dependency, respectively. Left figures in (A) and (B) show the radial variation of a certain wood property in different radial growth rates (S, slow; M, medium; F, fast). Right figures in (A) and (B) represent the relationship between stem diameter and the individual mean values of a certain wood property.

history of shifting cultivation (Wasli et al. 2020). For reforestation, *D. beccarii* seedlings were planted in the site using the line planting technique, with planting lines spaced 5 meters apart (Wasli et al. 2020). The seedlings were planted at 5-meter intervals along each line in 2005 (Wasli et al. 2020). The seed source was unknown. The study site comprises two plots (Plots 1 and 2; the area of 30 m × 50 m in each plot) which are adjacent within a reforestation stand with different silvicultural practices. Plot 1 is a control plot in which the understory was cleared annually after planting in 2005. In Plot 2, the understory was cleared as in Plot 1, and girdling treatment was performed on the most dominant pioneer species, *M. gigantea*, which was growing between or on the planting lines of *D. beccarii* in 2012 (Wasli et al. 2020). Selective girdling was performed manually using a machete by removing bark in a continuous circular band around the *M. gigantea* stem at approximately breast height (Fig. 2B). The debarked band had an approximate vertical width of 30 cm (Fig. 2B). Bark was removed to the full depth necessary to completely interrupt phloem transport. Because bark thickness varies with stem size, the depth of removal naturally differed among individuals: at least 1.3 cm for small trees and between 2.5 and 3.8 cm for larger trees. Only *M. gigantea* individuals with diameter breast height greater than 10 cm and exhibiting dominant crown cover within Plot 2 were selected for girdling. Although minor micro-topographic and edaphic variability may exist within the reforestation stand, no significant differences in the stem diameter and tree height of *D. beccarii* were observed between the two plots prior to the girdling treatment of *M. gigantea* (Wasli et al. 2020). There were 16 and 36 *M. gigantea* trees in Plots 1 and 2, respectively, before 21 *M. gigantea* trees were girdled (Wasli et al. 2020). Following girdling, treated *M. gigantea* individuals gradually died, and no recovery of treated stems was observed (Wasli et al. 2020). Six years after treatment, the number of *M. gigantea* trees was 30 and 39 in Plots 1 and 2, respectively (Wasli et al. 2020). In addition, the number of *M. gigantea* trees with a diameter breast height greater than 20 cm increased in Plot 1 but decreased in Plot 2 during the

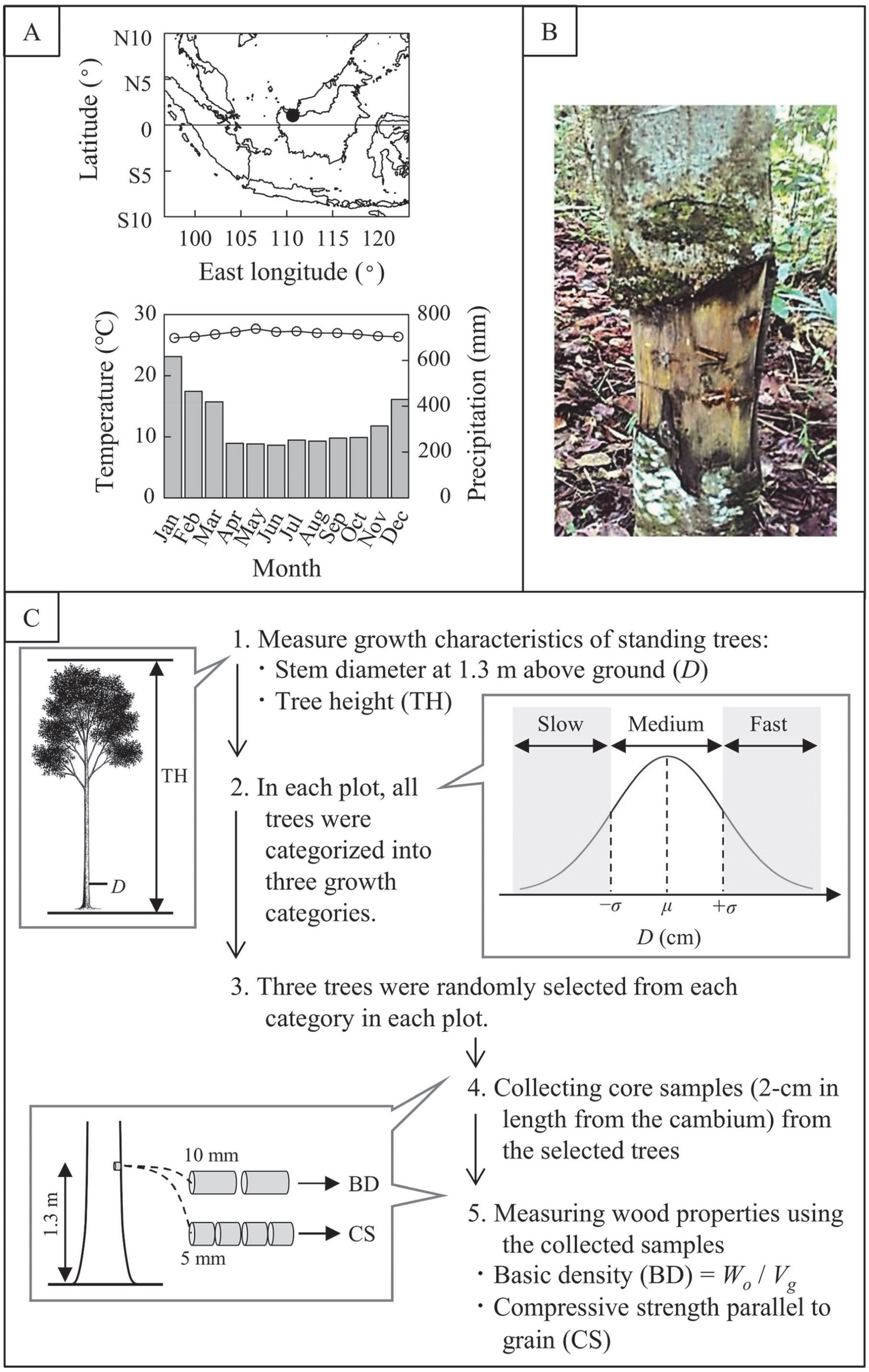


Fig. 2. Location and climatic conditions of the experimental stand (A), a photograph of girdled *M. gigantea* trees (B), and measurement procedure of this study (C).

Note: The circle and solid line in the map indicate an experimental stand and an equator in the upper figure of (A). In the bottom figure of (A), mean monthly precipitation and temperature in Kuching (N1.48° and E110.33°), Malaysia, were calculated by averaging monthly values obtained from the data for the last 5 years (2019 to 2023) provided by the Japan Meteorological Agency. Circle and solid lines indicate mean values of temperature, and bars indicate the mean value of precipitation for the average of 5 years in each month in (A). The photograph of (B) was taken at just after girdling treatment in 2012. The abbreviations of $\mu$, $\sigma$, $W_o$, and $V_g$ in (C) represent the mean, standard deviation, oven-dry weight, and green volume, respectively.

six-year period following girdling (Wasli et al. 2020). In Plot 2, although natural regeneration of *M. gigantea* seedlings and saplings occurred after canopy opening, these individuals did not become sufficient size to restore canopy dominance within the plot during the study period.

### Sample trees

As of February 2024, 48 and 43 *D. beccarii* trees remained in Plots 1 and 2, respectively, except for coppiced trees. The experimental procedures are summarized in Fig. 2C. The stem diameter at 1.3 m above the ground and tree height were measured using a diameter tape (F10−02DM, KDS, Japan) and an ultrasonic height meter (Vertex V, Haglöf, Långsele, Sweden) for all remaining trees in the two plots.

To measure the wood properties, nine trees with different radial growth rates were selected based on the mean values ($\mu$) and standard deviation ($\sigma$) of stem diameter ($D$) in each plot (Fig. 2C). The trees were categorized as slow ($D \leq \mu - \sigma$), medium ($\mu - \sigma < D < \mu + \sigma$), and fast ($\mu + \sigma \leq D$) in each plot (Ishiguri et al. 2012; Nezu et al. 2022). The three trees were randomly selected from each category in each plot. In each tree, two core samples (5 mm in diameter and 2 cm in length from the bark) were obtained using an increment borer (Haglöf) to evaluate the effects of girdling treatment for pioneer trees, *M. gigantea*, on growth and wood properties in *D. beccarii* trees. In both plots, the stem diameter increased more than 2 cm after girdling treatment, suggesting that the core samples collected for evaluating wood properties in the present study were formed after the treatment.

### Wood properties

One core was cut into 1-cm intervals from the cambium to measure the basic density of the two core samples collected in the study site (Fig. 2C). The basic density was measured by dividing the oven-dry weight by green volume using the water displacement method.

The other core was cut into 5-mm intervals from the cambium to measure the compressive strength parallel to the grain at green conditions (Fig. 2C). The compressive strength parallel to the grain of each segment was measured using a core testing machine (Fractometer II, IML, Dortmund, Germany) (Ishiguri et al. 2012). After the segment was clamped in the testing machine, a load was applied in the longitudinal direction. The strength at the time of breaking the segment was recorded as the compressive strength.

### Statistical analysis

All analyses were performed using R (R Core Team 2024). The survival rate was calculated by dividing number of remaining trees by number of planting trees of *D. beccarii* for each plot. The basic density and compressive strength of a tree were determined by averaging the values of 2 cm-length from the bark. A *t*-test was conducted to compare the growth characteristics between the two plots with different silvicultural treatments ($n = 48$ and 43 trees in Plots 1 and 2, respectively). In addition, the effects of girdling treatment of pioneer trees and radial growth rate on the wood properties of planted *D. beccarii* were evaluated using analysis of covariance (ANCOVA), with plot as a fixed factor and stem diameter as a covariate, based on individual mean wood property values ($n = 9$ in each plot). Furthermore, the relationships between measured properties in 18 trees were analyzed using Pearson's product-moment correlation. When a significant correlation ($p < 0.05$) was observed, the line was fitted using the standardized major axis using the R package 'smatr' (Warton et al. 2012).

## RESULTS

The survival rate of 20-year-old *D. beccarii* were 80.0 and 71.7 % in Plots 1 and 2, respectively (Table 1). The mean values of stem diameter and tree height in all *D. beccarii* trees were 12.4 cm and 14.1 m in Plot 1, and 14.3 cm and 15.7 m in Plot 2 (Table 1). For both growth characteristics, significant differences between the plots were found ($p < 0.05$, Table 1).

The basic density and compressive strength of mean values of nine trees were 0.59 and 0.61 g $cm^{-3}$ and 43.1 and 42.7 MPa in Plots 1 and 2, respectively (Table 2). Among the three growth categories, the minimum basic density and compressive strength were 0.54 g $cm^{-3}$ and 35.8 MPa for the slow-growth category in Plot 1 and 0.59 g $cm^{-3}$ and 39.6 MPa for the medium-growth category in Plot 2 (Table 2). On the other hand, the basic density and compressive strength showed the maximum value in the fast-growth category in both plots: 0.63 g $cm^{-3}$ and 48.6 MPa in Plot 1 and 0.63 g $cm^{-3}$ and 46.3 MPa in Plot 2 (Table 2).

Based on the results of ANCOVA (Table 3), girdling treatment had no significant effect on basic density ($p = 0.526$) or compressive strength ($p = 0.694$). In contrast, the covariate, stem diameter, showed a significant effect on basic

Table 1. Statistical values of growth characteristics in *D. beccarii* trees in two plots at the ages of 15 and 20 (six and 11 years after girdling treatment).

| Property | Age (yr) | Plot 1 Mean | Plot 1 SD | Plot 2 Mean | Plot 2 SD | Ratio 1 | Differences between plots $t$ - value | Differences between plots $p$ - value |
|---|---|---|---|---|---|---|---|---|
| Survival rate | 15 | 82.9*1 | | 79.2*1 | | 0.96 | | |
| (%) | 20 | 80.0 | | 71.7 | | 0.90 | | |
| Stem diameter | 15 | 7.5*2 | 2.0*2 | 9.5*2 | 1.5*2 | 1.27 | | $<0.05$*1 |
| (cm) | 20 | 12.4 | 5.0 | 14.3 | 3.8 | 1.15 | −2.117 | 0.037 |
| Ratio 2 | | 1.65 | | 1.51 | | | | |
| Tree height | 15 | 8.3*2 | 1.8*2 | 9.2*2 | 1.4*2 | 1.11 | | $<0.05$*1 |
| (m) | 20 | 14.1 | 1.4 | 15.7 | 3.0 | 1.11 | −2.405 | 0.018 |
| Ratio 2 | | 1.70 | | 1.71 | | | | |

Note: Plot 1, understory clearing; Plot 2, understory clearing with selective girdling of pioneer trees; SD, standard deviation; *1, the data is cited from Wasli et al. (2020); *2, the value was calculated by multiplying annual increment in diameter and height by tree age represented in Wasli et al. (2020). Ratio 1 was calculated by dividing the mean values in Plot 2 by those in Plot 1. Ratio 2 was calculated by dividing the mean values at age 20 by those at age 15.

Table 2. Mean and standard deviation of growth characteristics and wood properties for three growth categories and each experimental plot.

| Plot | Property | Radial growth category: Slow ($n=3$) Mean | SD | Medium ($n=3$) Mean | SD | Fast ($n=3$) Mean | SD | All trees ($n=9$) Mean | SD |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Stem diameter (cm) | 6.0 | 1.1 | 11.3 | 1.0 | 23.2 | 4.9 | 13.5 | 5.7 |
| | Tree height (m) | 10.2 | 1.8 | 13.9 | 0.7 | 19.0 | 2.0 | 14.4 | 4.8 |
| | Basic density (g $cm^{-3}$) | 0.54 | 0.05 | 0.61 | 0.02 | 0.63 | 0.02 | 0.59 | 0.05 |
| | Compressive strength (MPa) | 35.8 | 1.8 | 44.8 | 2.5 | 48.6 | 1.9 | 43.1 | 6.0 |
| 2 | Stem diameter (cm) | 7.7 | 1.3 | 14.8 | 1.7 | 20.2 | 2.3 | 14.2 | 8.0 |
| | Tree height (m) | 10.0 | 1.6 | 16.1 | 1.5 | 20.7 | 1.5 | 15.6 | 4.1 |
| | Basic density (g $cm^{-3}$) | 0.61 | 0.03 | 0.59 | 0.06 | 0.63 | 0.07 | 0.61 | 0.05 |
| | Compressive strength (MPa) | 42.2 | 2.3 | 39.6 | 4.6 | 46.3 | 4.9 | 42.7 | 4.6 |

Note: $n$, number of sample trees; SD, standard deviation; Plot 1, The plot with understory clearing; Plot 2, The plot with understory clearing and selective girdling for *M. gigantea* trees

Table 3. Results of analysis of covariance (ANCOVA) for wood properties.

| Property | Variable | df | Sum of squares | $F$ - value | $p$ - value |
|---|---|---|---|---|---|
| Basic density | Girdling treatment | 1 | 0.0008739 | 0.422 | 0.526 |
| | Stem diameter | 1 | 0.0093769 | 4.527 | 0.050 |
| | Residuals | 15 | 0.0310676 | | |
| Compressive strength | Girdling treatment | 1 | 2.752 | 0.1614 | 0.694 |
| | Stem diameter | 1 | 199.182 | 11.6804 | 0.004 |
| | Residuals | 15 | 255.790 | | |

Note: Number of samples = 18; df, degree of freedom.

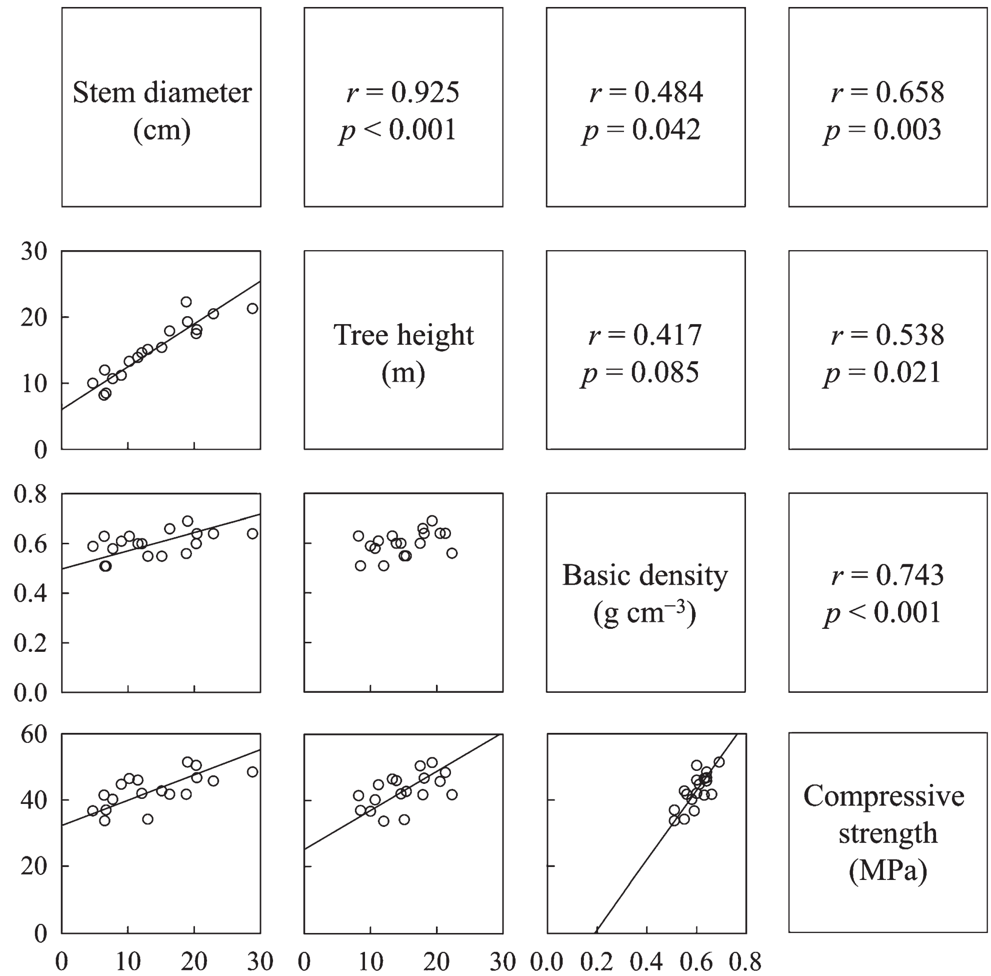


Fig. 3. Relationships between measured properties.
Note: number of trees = 18; *r*, correlation coefficient; *p*, *p*-value.

density ($p = 0.050$) and compressive strength ($p = 0.004$).

Figure 3 shows relationships between measured properties for 18 sample trees. The significant positive correlations were found between stem diameter and tree height ($r = 0.925$, $p < 0.001$), basic density ($r = 0.484$, $p = 0.042$), and compressive strength ($r = 0.658$, $p = 0.003$). Tree height was significantly positively correlated with compressive strength ($r = 0.538$, $p = 0.021$) but not with basic density ($r = 0.417$, $p = 0.085$). Among wood properties, basic density was positively correlated with compressive strength ($r = 0.743$, $p < 0.001$).

## DISCUSSION

### *Comparison of wood properties with* Dryobalanops *spp.*

Table 4 lists wood density and compressive strength of *Dryobalanops* species reported by several researchers (Wood Technology Division 1967; Department of the Environment 1972; Chudnoff 1980; Martawijaya et al. 2005). Although the moisture content at the testing of wood density differed among studies, the basic density of *D. beccarii* used in the present study was the same or smaller than that of *Dryobalanops* spp. in the previous studies. On the other hand, the compressive strength parallel to the grain of *D. beccarii* in this study (approximately 40 MPa) was in the range of that reported in other *Dryobalanops* spp.

### *Effects of girdling treatment for pioneer trees on growth characteristics and wood properties of* D. beccarii

Wasli et al. (2020) evaluated the survival rate and growth characteristics of the *D. beccarii* planted in a reforestation site (the same site as this study) after girdling treatment for the dominant pioneer species, *M. gigantea*. *Macaranga gigantea* is a major species dominating secondary forests that

Table 4. Comparison of wood density and compressive strength with other *Dryobalanops* species.

| Species | Wood density (g cm$^{-3}$) | | | Compressive strength (MPa) | | | Reference |
|---|---|---|---|---|---|---|---|
| | Min. | Mean | Max. | Min. | Mean | Max. | |
| *D. aromatica* | 0.63*1 | 0.81*1 | 0.94*1 | – | 44.9*3 | – | Martawijaya et al. (2005) |
| *D. lanceolata* | | | | | 42.9*3 | | Department of the Environment (1972) |
| | 0.61*1 | 0.74*1 | 1.01*1 | – | 39.8*3 | – | Martawijaya et al. (2005) |
| *D. beccarii* | – | – | – | – | 41.2*3 | – | Department of the Environment (1972) |
| | – | – | – | – | 30.5*3 | – | Martawijaya et al. (2005) |
| | 0.51*2 | 0.60*2 | 0.69*2 | 33.8*3 | 42.9*3 | 51.5*3 | This study (*n* =18) |
| *Dryobalanops* spp. | 0.57*2 | 0.67*2 | 0.76*2 | 44.6*4 | 54.4*4 | 62.8*4 | Wood Technology Division (1967) |
| | | 0.57 to 0.65*2 | | | 41.2*3, 46.7*3 | | Chudnoff (1980) |

Note: Min., minimum; Max., Maximum; *1, air-dry density at 15% moisture content; *2, basic density; *3, compressive strength parallel to the grain under green conditions; *4, compressive strength parallel to the grain at an average moisture content of 15.5%; –, no available data.

develop after logging (Wasli et al. 2020). Most *Macaranga* species have large and lobed leaves that form the main canopy (Romell et al. 2009). Their canopy structure and density can create a dense sub-canopy, which might reduce light for the understory and seedlings (Romell et al. 2009).

In a previous study, Wasli et al. (2020) reported that the survival rate of *D. beccarii* trees in Plot 2 (71.7 %) was slightly lower than that in Plot 1 (79.2 %) at age 15 (six years after girdling treatment) (Table 1). The relatively lower survival rate of *D. beccarii* in Plot 2 at age 15 might be caused by the death of girdled *M. gigantea* during the six-year monitoring period after treatment, as some *M. gigantea* trees fell onto planted *D. beccarii* (Wasli et al. 2020). In the present study, although the trend of survival rate was the same until 20 years old, survivability remained high (> 70 %) in both plots (Table 1). These results suggest that the effect of girdling of *M. gigantea* on the survivability of *D. beccarii* was limited more than a decade after treatment.

The stem diameter and tree height of *D. beccarii* were significantly larger in Plot 2 than in Plot 1 at two and four years after girdling treatment (at *D. beccarii* tree age of 13 and 11 years old), respectively (Wasli et al. 2020). The positive effect on radial and height growth continued until 15 years old (six years after girdling treatment) (Table 1, Wasli et al. 2020). These results indicated that the increase in light availability was attributed to the creation of canopy gaps and growing space following the mortality and eventual fall of the girdled *M. gigantea* trees (Romell et al. 2009; Wasli et al. 2020). Then, improving light conditions for environmental circumstances, even after six years of the girdling treatment, would continuously stimulate the radial and height growth of the remaining *D. beccarii*. These findings suggest that girdling treatment for major dominant pioneer trees, *M. gigantea*, was an effective practice for growing *D. beccarii* in the reforestation site for a relatively long term. In the present study, similar trends were observed for the 20-year-old *D. beccarii* regarding stem diameter and tree height (Table 1). On the other hand, the ratio of mean values between plots (ratio 1) was the same between 15 and 20 years old for tree height, although the ratio in stem diameter at age 20 was relatively lower than that at age 15 (Table 1). In addition, the ratio of the mean values at age 20 to those at age 15 (ratio 2) were almost the same between the Plots for stem diameter and tree height (Table 1). Therefore, the differences in growth characteristics between plots at age 20 (11 years after the girdling treatment) might just reflect the differences at age 15 (six years after the treatment). In contrast, no significant differences in basic density and compressive strength were observed between the two plots in the present study (Table 3). These findings suggest that (1) the positive effect on radial and height growth of *D. beccarii* by girdling treatments for pioneer trees has been maintained for more than a decade, and (2) the quality of wood formed after girdling treatment was not substantially affected by the treatments.

### *Xylem maturation manner and the relationships between radial growth rate and wood properties in* **D. beccarii**

In this study, wood properties of *D. beccarii* were more strongly influenced by stem diameter than by girdling treatment (Table 3). In addition, the faster the radial growth in the category, the higher basic density and compressive strength (Table 2). Furthermore, strong positive correlations were found between growth characteristics and wood properties, except for between tree height and basic density

(Fig. 3). These results indicate that higher basic density and compressive strength were found in *D. beccarii* with faster radial growth, although this species is not a fast-growing tree species. Thus, xylem maturation in *D. beccarii* might depend on diameter growth as well as the fast-growing tree species (Fig. 1A). It could also be related to the specific positive relationships between radial growth rate and wood properties for *D. beccarii* within the Dipterocarpaceae family. The finding might be associated with the fact that, in *D. beccarii*, girdling treatment of pioneer trees promoted radial growth, but did not affect the wood properties. However, xylem maturation manner in *D. beccarii* could be determined by assessing the radial variation of anatomical characteristics and physical and mechanical properties of wood. In addition, since the sample trees were derived from seedlings of unknown origin, there is another possibility that *D. beccarii* trees with genetically faster radial growth rates tend to produce wood with higher density and strength. Therefore, further research is needed to clarify how xylem matures and the genetic background of *D. beccarii*, and to determine how these factors relate to the neighborhood effects on the wood properties of *D. beccarii* planted in Malaysia.

### *Future perspectives*

This study was conducted at Gunung Apeng National Park, Sarawak, Malaysia, the only known long-term reforestation site with planted *D. beccarii* in Sarawak. Because the sample size was limited, further studies with increased numbers of sampled trees and plots are needed to generalize the results. However, this study provides a rare opportunity to evaluate the long-term effects of silvicultural treatments on both growth and wood properties of this species. Thus, the findings in this study might serve as a valuable baseline for future comparative studies across sites and regions in Southeast Asia, as well as for developing species-specific guidelines for reforestation and timber utilization.

In addition to the silvicultural implications, the dataset generated in this study could also support future biomass and carbon research. Stem diameter, tree height, and wood density are core variables in allometric models (Chave et al. 2014), and the present data might facilitate the development of species-specific approaches for estimating biomass and carbon stocks of *D. beccarii*. This is particularly relevant in reforestation contexts, where few studies have examined dipterocarp species in relation to both growth and wood properties. Considering that naturally grown *D. beccarii* might differ from planted trees, these findings highlight the potential of plantation-based research to improve the accuracy of biomass estimation and carbon stock assessment in tropical forest restoration.

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### *Conflict of Interest Statement*

The authors declare no competing interests.

### *Data Availability Statement*

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

### *Author Contribution Statement*

Conceptualization: IN, MEW, FI.
Funding acquisition: MEW, SY, FI.
Investigation: IN, HY, MEW.
Supervision: IN, MEW, FI.
Visualization: IN.
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Not applicable

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