

Assessment on the growth performance of planted *Dryobalanops beccarii* at reforestation sites after implementation of selective girdling

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Abstract. Wasli ME, Ambun DB, Kalu M, Sidi M, Nahrawi H, Elias H. 2020. Assessment on the growth performance of planted *Dryobalanops beccarii* at reforestation sites after implementation of selective girdling. *Biodiversitas* 21: 1880-1889. This study was conducted to evaluate the growth performance of planted *Dryobalanops beccarii* Dyer at reforestation sites after silvicultural practices in Gunung Apeng National Park (GANP), Sarawak. The assessed area was planted with *D. beccarii* in 2005 and undergo silvicultural treatment by understory clearing which implemented annually. Due to the suppressed growth rate of the planted trees, an additional silvicultural treatment, the selective girdling on selected pioneer species, was implemented once, in 2012. In this study, study plots with two treatments were established: T1: understory clearing only (control plot), and T2: additional selective girdling of existing pioneer species in addition to the understory clearing practice applied in T1. The growth performance of the planted *D. beccarii* in terms of DBH, height, survival and mean annual increments in diameter (MaiD) and height (MaiH) were assessed and monitored at the initial stage when the selective girdling treatment was applied and 4, 24, 36, 48, 60 and 72 months after girdling. Our findings showed that the survival rates of planted trees at 72 months under treatments T1 and T2 were 82.9% and 79.2%, respectively. The average tree DBH in T2 was significantly higher than that in T1, and the average tree DBH values for T1 and T2 were 7.5 cm and 9.4 cm, respectively. The average tree heights for T1 and T2 were 8.3 m and 9.2 m, respectively. In terms of the mean annual increments in height (MaiH) and diameter (MaiD), those in T2 were significantly higher than those in T1. Our findings indicated that T2 started to show better growth performance than T1 after a period of 36 months. In conclusion, the additional silvicultural treatment by selective girdling at the reforestation site had a long-term, progressive effect on the growth performance of the planted trees.

Keywords: *Dryobalanops beccarii*, growth performance, reforestation, selective girdling

INTRODUCTION

The loss of forests in Borneo has reached an alarming rate; an estimated 16.8 million ha of forest loss was reported from 1973-2010, and these losses were mainly due to extensive forest clearance to obtain forest products (Gaveau et al. 2014). This led to the destruction of habitat for flora and fauna and inevitably resulted in the loss of important medicinal plants and various climax tree species. Thus, reforesting the areas affected by these activities is essential for restoring the forest. Meanwhile, to ensure the success of the reforestation program, proper methods and techniques should be applied, such as the implementation of enrichment planting and suitable silvicultural practices. Enrichment planting is one of the methods used in attempts to supplement natural regeneration and improve the low tree growth performance observed in natural succession (Chai and Udarbe 1977; Appanah and Weinland 1993). Examples of enrichment planting, such as artificial gaps created by human intervention intended to reduce aboveground vegetation (Wyat-Smith 1963; Ådjers et al. 1995), reduce the competition between the planted tree and the adjacent bushes and shrubs. These practices can also be used to rehabilitate logged-over areas in tropical rainforests by using indigenous tree species; the process involves planting nursery-raised seedlings along a cleared line or in

gaps that have been created naturally or artificially (Wyat-Smith 1963). In addition, Kammesheidt et al. (2003) investigated the irregular growth pattern of dipterocarps in response to competition and silviculture treatment in the lowland Mixed Dipterocarp Forest in Sarawak.

Silvicultural treatments have been widely used in logged forests to restore forests to their original conditions, or as close to the original conditions as possible (Villages et al. 2009). Many treatments can be applied, such as thinning, pruning, fertilizers, girdling, felling and others. The main purpose of applying these silvicultural methods is to control and manage the forest in a desirable manner by controlling forest change, accelerating change and maintaining the condition of the tree stands (Nyland 1996). Hence, better results can be obtained from reforestation efforts when the silvicultural treatments enhance the tree growth performance so that it is faster than that in forests without silvicultural intervention (Oliver 1992). Colin et al. (2018) reported that silvicultural practices are preferred for forest restoration purposes because they allow the direct manipulation of stand composition and structure. Even though the use of enrichment practices in forest plantations and in forest reserves has been reported (Romell 2007), making conclusions about the effects of various silvicultural treatments and the optimal conditions for enrichment planting is difficult due to the variability in

natural forests and their dynamics. Moreover, there are knowledge gaps about enrichment planting and secondary forests as well as the performance of the planted tree species (Ramos and del Amo 1992; Ådjers et al. 1995; Kammesheidt 2002). In addition, numerous silviculture measures such as thinning, planting gaps and block planting have been proposed to improve forest management (Graaf 1986; Lamprecht 1989; Fredericksen and Mostacedo 2000; Fredericksen and Putz 2003), but such management practices aim to ensure future timber yields in the context of forest plantations (Jackson et al. 2002).

In this study, we introduced a silvicultural approach to maintain the forest structure and protect its ecological functions. Several studies have been performed on reforestation activities with indigenous tree species using various planting techniques to rehabilitate degraded land areas (McNamara et al. 2006; Hattori et al. 2013; Perumal et al. 2017; Jaffar et al. 2018). Thus, planting the original indigenous species to rejuvenate a specific forest area is essential, as these species can thrive better in the surrounding environment. *Dryobalanops beccarii* was planted to rejuvenate the forest ecosystem in Gunung Apeng National Park (GANP) after anthropogenic events (logging and forest clearance for agricultural purposes) in the area as this tree species indigenously grow on the hill (Ashton 2004). The implementation of selective girdling along with reforestation efforts is important. As Wasli et al. (2014) described in their preliminary assessment of the growth performance of planted trees under forest rehabilitation, proper silvicultural practices along a line planting system can potentially reduce competition between the dominant pioneer trees and the planted *D. beccarii*. Considering this finding, the specific objective of this study is to determine the effectiveness of additional silvicultural treatment, selective girdling, on the growth performance of planted *D. beccarii* in GANP.

MATERIALS AND METHODS

Study site

This study was conducted at the Gunung Apeng National Park (GANP), Serian Division, Sarawak, Malaysia (N00°55'24.7'', E110°38'32.2''). This region has a humid tropical climate with an average annual rainfall of 3500 mm and an annual temperature ranging from 23 to 33°C (Wasli et al. 2014). The size of the national park is estimated to be 1174 ha (Forest Department Sarawak 2009). GANP is located in an area of lowland hills with relatively steep slopes with elevation range from 60 m to 120 m above sea level with slope range 5 ° to 30°. The area was previously logged over and has a history of shifting cultivation by local farmers (Lee 2013). The establishment of and was initiated by cooperation among the Forest Department and Sarawak and Japanese NGOs with the support of the Japan-Malaysia Association. For reforestation purposes, various tree seedlings were planted using the line planting technique, with lines cut 5 m apart and trees planted at 5 m intervals along the lines. In addition, the width of the planting line was 3 m.

Experimental design and silvicultural treatments

In this study, the tree stand was planted in 2005 and accompanied by understory clearing practices. Silvicultural treatment, specifically selective girdling, was only applied in 2012 to improve the low survival rate and slow growth of the planted trees. The soil type at the study site from soil survey conducted was determined as grey-white podzolic soil, which has a prominent sandy texture with strong acidity, low nutrient contents, low moisture, and good aeration. Two study plots of 30 m × 50 m were established within the area planted with *D. beccarii* in 2005. Two types of silvicultural treatment were implemented: T1: understory clearing only, which acted as a control plot, and T2: understory clearing with additional selective girdling practices on the existing pioneer species between or on the planting lines.

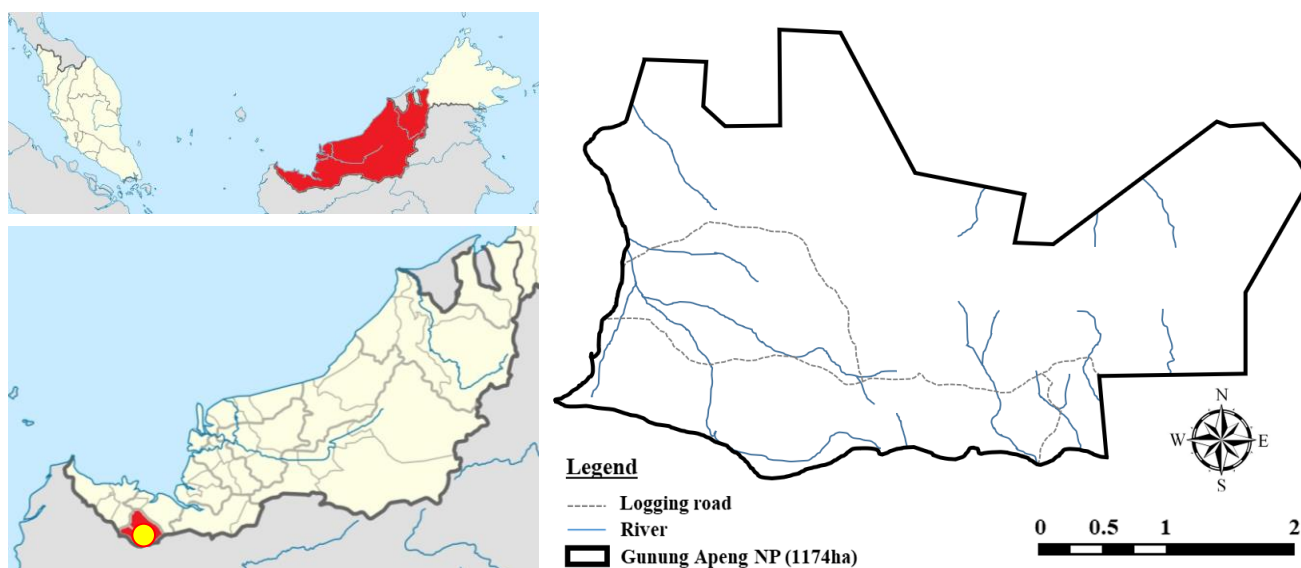


Figure 1. Location of Gunung Apeng National Park, Serian Division, Sarawak, Malaysia

Table 1. Silvicultural treatments applied in areas planted with *Dryobalanops beccarii* (DB05) starting in 2012

Treatment	Applications
Treatment I- Understory clearing only (T1)	The understory trees or unwanted trees were chosen to be cut. All herbaceous species and saplings of pioneer species were cleared along the planting line within a radius of 2 m from the planted trees by manual clearing using a bush knife. The understory clearing was done annually. The width of the cleared area is shown in Figure 2.
Treatment II- Understory clearing + selective girdling (T2)	Understory clearing practices were applied as in T1. Selective girdling was performed only once at the initial stage of the experiment. A single-blade knife was used to girdle the tree. A ring of the bark all the way around the trunk was removed. The girdling removed the bark of the encircled trunk to a depth of at least ½ inch on small trees and 1 to 1 ½ inch on larger trees. Girdling was only applied to the most dominant pioneer species with DBH more than 10 cm and large crown cover. Girdling was performed once at the initial stage of this study.

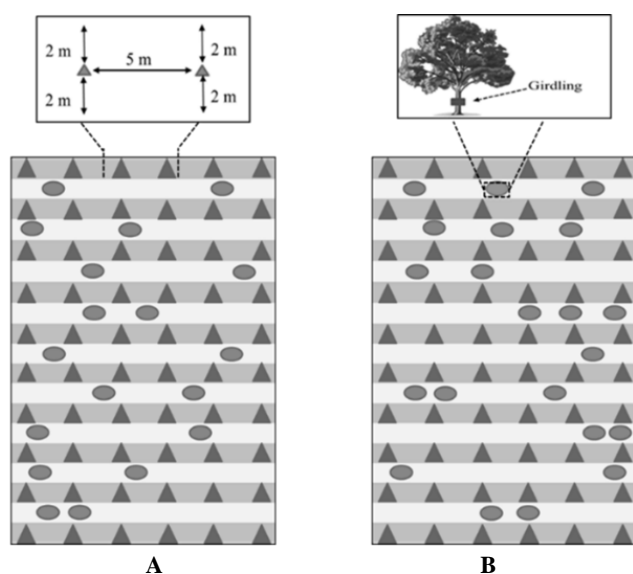


Figure 2. Experimental plots and planting layout. A. Treatment 1- Understory clearing only (T1), B. Understory clearing plus selective girdling (T2). Note: ▲: Planted *Dryobalanops beccarii*. ○: Pioneer species. □: Undisturbed planting zone. ■: Tree planting area maintained by understory clearing

Moreover, these two study site was purposely being selected due to almost mutual stand density characteristic in which both considered as mixed dipterocarp forest where predominantly covered by pioneer species mostly *Macaranga* species. The experimental layout is presented in Figure 2, and the description of the silvicultural practices is shown in Table 1.

Assessment of the growth performance of planted trees

The monitoring of the growth performance and survival of planted *D. beccarii* was carried out from 2012 until 2019. For the assessment of the growth performance in the study plots, measurements such as tree diameter at breast height (DBH) and total tree height were assessed annually. The DBH of the trees was measured at a constant height of 1.3 m above the ground. The height of the tree was measured using a clinometer, and trigonometry was used to determine the tree height. The mean annual increment in

diameter (MaiD) and mean annual increment in height (MaiH) were recorded. For all the mean annual increments were calculated using the following formula:

$$\text{Mean annual increment} = \frac{\text{Final measurement at time}}{\text{Years after planting}}$$

Relative light intensity in the studied sites was recorded, under standardized conditions as described by Jaffar et al. (2018) using an Extech 401025 Digital Light Meter [Lux/Foot-Candle (FC)] meters. Open space light intensity was measured outside the reforestation sites in order to compare the light intensity under every single tree at the planted area with the open space area. The unit of Foot-Candle was converted into Microeinstein to obtain light percentage according to the formula below (Hattori et al. 2009):

$$P = \frac{Q (FC \times 0.2)}{R} \times 100$$

P is percentage of light intensity under each tree

Q is light intensity in Foot-Candle (FC)

R is open space light intensity

FC x 0.2 is used to convert Foot-Candle unit to Microeinstein

Vegetation survey was carried out in each study plot to determine the number and size for pioneer tree species with the DBH of more than 10cm. All recorded species were identified with their scientific names at Universiti Malaysia Sarawak's Herbarium.

Statistical analyses

The planted tree growth performance in both treatments, including the DBH, height, MaiD, and MaiH, were analyzed using independent Student's t-tests at a 5% confidence interval. Next, as the independent variables were not distributed normally, nonparametric tests of significance were utilized. The Mann-Whitney U test was used to assess differences in the growth performance data between T1 and T2 for each assessment in terms of DBH and height. All data were analyzed using SPSS version 21.0, and descriptive statistics were generated using Minitab version 18.0.

RESULTS AND DISCUSSION

The effect of silvicultural treatments on neighboring pioneer species

Table 2 shows ten (10) of the most encountered non-planted or pioneer tree species found in both T1 and T2 plots initially and at the 72-month assessment in the experimental plots. As shown in Table 2, *Macaranga gigantea* was selected to be girdled, as it was the most dominant pioneer tree during the initial assessment of the trial plots. The dominance of *M. gigantea* may be due to the experimental plot being established in secondary forests, as Zakaria et al. (2008) reported that the genus *Macaranga* prefers to grow in non-forested areas or semi-forested areas (secondary forests). In addition, some researchers also reported that stands of *M. gigantea* were commonly found in open areas (Whitmore 1998). It is also generally known as one of the major species dominating secondary forests that are affected by logging activities (Tagawa 1988; Wermer 1997). In addition, most *Macaranga* species have large lobed leaves that form the main canopy where the characteristic structure and density may allow the development of a dense sub-canopy layer with opaque leaf foliage that will potentially inhibit the light availability for the lower understory and seedlings (Slik et al. 2000). In this trial plot, 36 *M. gigantea* were counted in the initial assessment, and 18 of those with the largest either diameter or canopy crown cover were selected. Later, girdling was performed on these trees. Seventy-two months after the girdling treatment, only 15 trees had fallen naturally, while another 3 trees were still standing but had no visible fresh leaves.

Figure 3 shows the trends in the occurrence of the neighboring pioneer tree species with DBH more than 10 cm for both treatments at the initial stage and at 72 months of experimental silviculture implementation. During the initial assessment, the number of pioneer species was higher in the T2 plot than in the T1 plot. This may be ascribed to the dominant occurrence of *M. gigantea* trees in the T2 plot, as shown in Table 2, which would contribute to the pattern of occurrences in the encountered pioneer trees. Meanwhile, after 72 months, the pattern of occurrences changed drastically. The trend shows an increase in the occurrences of larger pioneer species with DBHs greater than 20 cm in the T1 plot compared to the percentage occurrences at the initial assessment. Conversely, in the T2 plot, the percentage of pioneer species with DBHs greater than 20 cm decreased. Thus, the trend of occurrences, as shown in Figure 2, indicates that the number of larger pioneer species in the T1 plot increased after 72 months compared to that in the T2 plot. This may be due to the ungirdled pioneer species in T1 inducing the emergence of new saplings inside the study plot.

Survival rate of planted *D. beccarii* in T1 and T2

Figure 4 shows the survival trends of the planted *D. beccarii* for each subsequent month during the duration of this study. In both treatments, the survival rate for planted trees after 36 months was 100%. Later, the survival rate of planted trees in T2 decreased to 84.9%, while no changes

were observed in the survival rate in T1. At 48 and 60 months, the survival percentage in the T2 plot was sustained at 81.1%, with a slight decrease to 79.2% at 72 months. A slight decrease in survival is normal in secondary forests, as the mortality rate will keep increasing throughout the succession stage until only the fittest planted tree survives. In contrast to T2, the survival rate in T1 started to decrease gradually at 48 months, and a sudden decrease in the survival rate to 82.9% was observed at 72 months after silviculture implementation.

In our field observations (Figure 5) during the monitoring process, we noted that the girdled trees had started to die. Some of them may have fallen directly onto planted trees, based on stump observations (Figure 5.A), and damaged the planted trees. Moreover, some of the pioneer species, mainly the *Macaranga* species in the T1 plot, fell naturally, and their impact affected the overall survival rate of the planted trees (Figure 5.B).

Davies (2001) also reported *Macaranga* mortality rates in secondary forests of up to 21%, with particularly high mortality among common species such as *Macaranga triloba* (20.6%), *Macaranga beccariana* (17.9%) and *Macaranga winkleri* (16.7%). Despite the sudden increase in the mortality rates of both plots, the overall survival was still higher than those of some other planting experiments reported from line planting (Ådjers et al. 1995) and gap planting (Otsamo 2000) in Borneo. Otsamo (2000) reported only 71% survival among *Shorea parvifolia* after 19 months, while Ådjers et al. (1995) found survival rates between 40-85% for *Shorea johorensis*, *Shorea leprosula*, and *Shorea parvifolia* after 2 years of planting. Overall, the present study indicated that after 72 months of treatment implementation, both plots showed high survivability of more than 70%.

Table 2. Non-planted tree species encountered in plots planted with *Dryobalanops beccarii* at the initial assessment and 72 months after silvicultural treatment

Tree species	No. encountered initially	No. encountered at 72 months
T1: Understory clearing only		
T1		
<i>Macaranga gigantea</i>	16	30
<i>Ficus aurata</i>	3	9
<i>Euodia</i> sp.	-	5
<i>Dactylocladus stenostachys</i>	4	11
<i>Endospermum diadenum</i>	1	7
<i>Horsfieldia</i> sp.	-	4
<i>Calophyllum</i> sp.	4	6
<i>Litsea</i> sp.	5	5
<i>Lithocarpus</i> sp.	2	3
<i>Artocarpus elasticus</i>	-	3
T2: Selective girdling + understory clearing		
<i>Macaranga gigantea</i>	36	39
<i>Ficus aurata</i>	18	9
<i>Callicarpa</i> sp.	12	2
<i>Ficus auriculata</i>	4	2
<i>Euodia</i> sp.	4	3
<i>Sterculia</i> sp.	2	1
<i>Artocarpus kemando</i>	2	1
<i>Aglaia</i> sp.	2	1
<i>Horsfieldia</i> sp.	1	7
<i>Endospermum diadenum</i>	1	1

Growth performance of *D. beccarii* in T1 and T2

Figure 6 shows the box plot of the distribution of the DBH and height of *D. beccarii* from the initial period until 72 months after silvicultural treatment implementation. Overall, both treatments showed increments in terms of DBH and height. There was no significant difference between the treatments in DBH at the initial stage. However, the tree DBH began to show a significant difference between T1 and T2 at 48 months. Moreover, from the quartile division of the box plot, T2 showed better growth performance than T1 in terms of DBH, and most of the DBH was tabulated in quartile 3. In terms of tree height, the planted trees in both treatments showed no significant difference at the initial assessment. Then, from 24 months onward, there were significant differences in tree height between the treatments. However, both treatments showed variation in the quartile divisions for each assessment, resulting in difficulties in determining which treatments contributed more to tree height. However,

T2 showed greater growth performance in height than T1, even though there were no immediate effects on height.

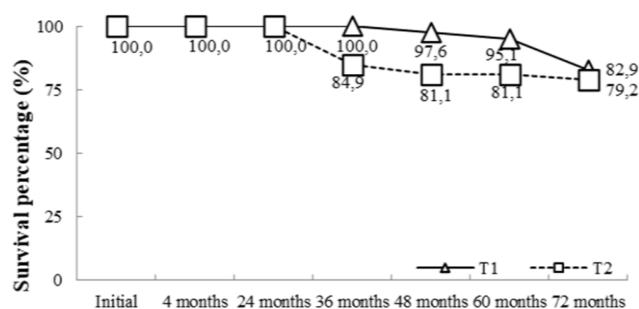


Figure 4. Survival of planted *Dryobalanops beccarii* for both treatments

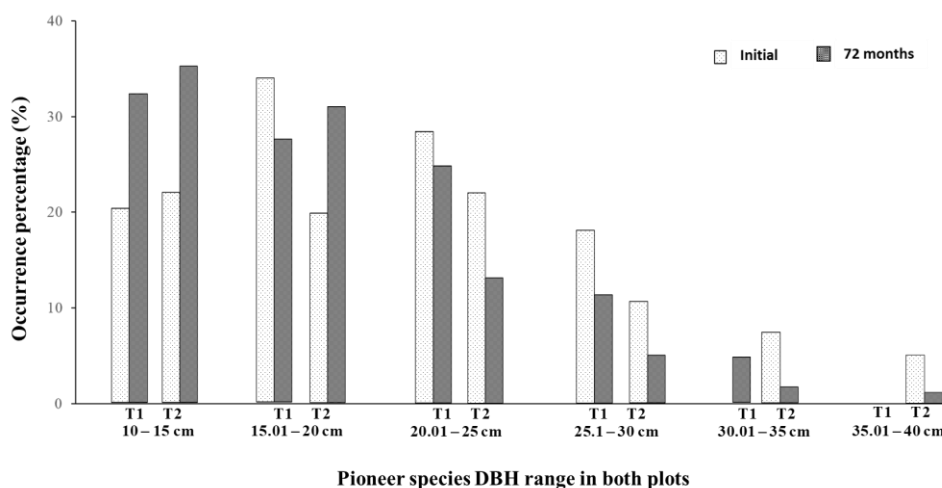


Figure 3. Occurrence percentage of pioneer species with DBH < 10 cm at initial silviculture implementation and after a period of 72 months



Figure 5. A. Fallen, fully rotten girdled tree in T2, B. Naturally fallen *Macaranga gigantea* that induced mortality in T1

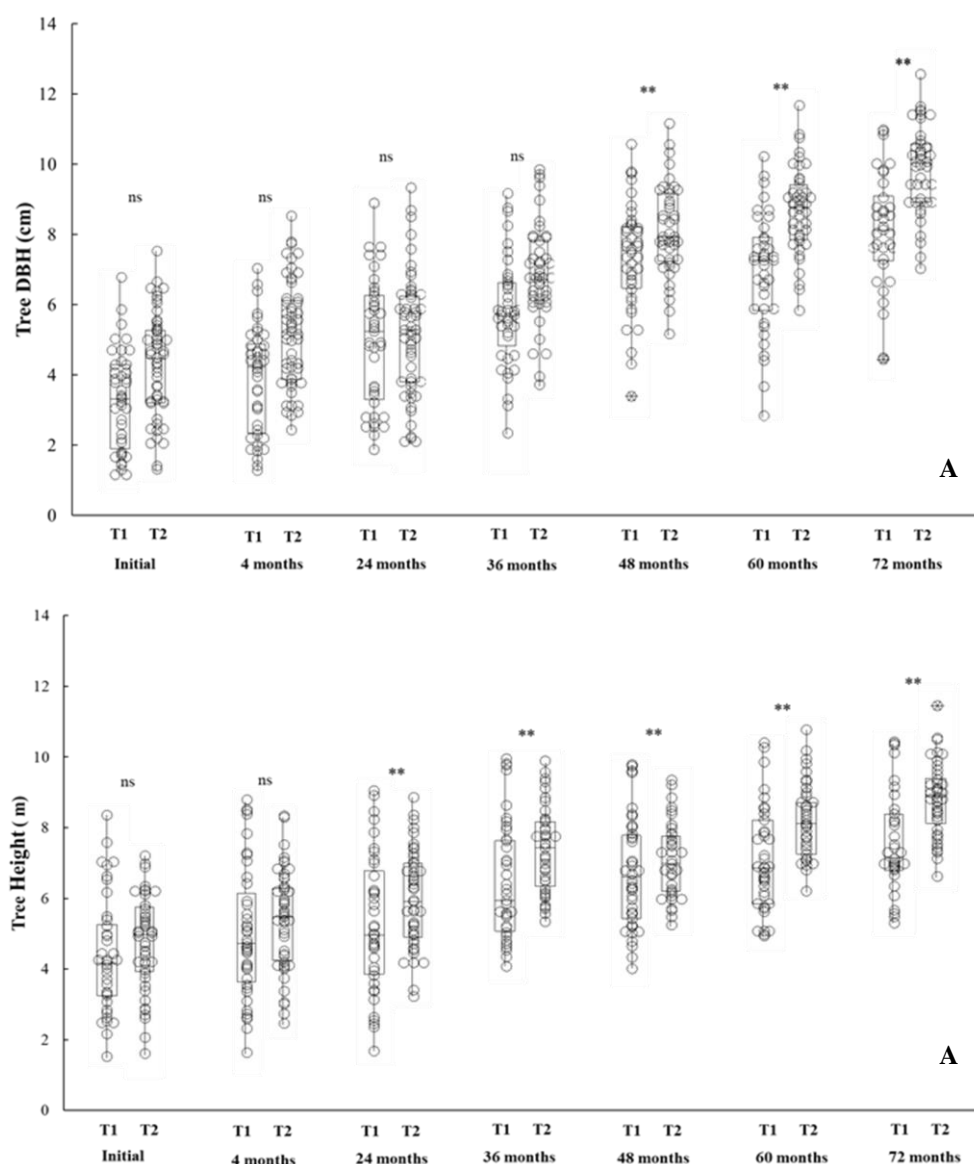


Figure 6. Boxplot distribution of the growth performance of planted *Dryobalanops beccarii* for both treatments. A. Mean annual increment in diameter, B. Mean annual increment in height. ** indicates a significant difference between both treatments using an independent Student's t-test at 5%. ns: not significant

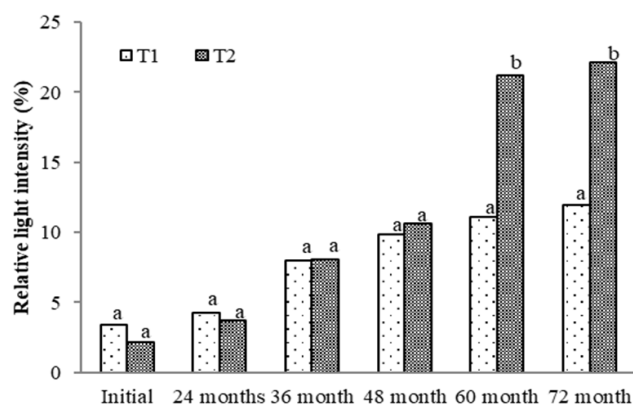
The mean annual increments in DBH and height of the planted *D. beccarii* under treatments T1 and T2 are shown in Table 3 and expressed in cm year^{-1} and m year^{-1} for DBH and height, respectively. Initially, the growth rates in DBH for T1 and T2 were 0.43 and $0.53 \text{ cm year}^{-1}$, respectively, and statistical analysis using the t-test showed no significant difference among the treatments initially. In addition, in terms of the growth rate in height, there was no significant difference between T1 and T2, and the rates were 0.55 and 0.64 m year^{-1} , respectively. Then, at 24 months, T2 started to show a higher growth rate in height compared to T1. Next, Table 3 also shows the comparative statistics between T1 and T2 using the Mann-Whitney U

test to further investigate which treatments contribute more to the growth performance of planted trees. The findings indicated that there are significant differences between treatments T1 and T2 for each particular assessment, i.e., growth in terms of height or diameter. From the P-value, T2 shows significantly higher growth performance in diameter than T1 ($P < 0.001$). Meanwhile, for the height parameter, the findings showed variation in the P-value, where $0.01 < P < 0.1$. This suggests that the T2 plot, where the implementation of selective girdling was accompanied by undergrown slashing, contributed more to the growth performance of the planted *D. beccarii* than T1, which did not have girdling practices.

Table 3. Results of the t-test and nonparametric test (Mann-Whitney U test) for the mean annual increment in diameter (MaiD) and height (MaiH) of planted *Dryobalanops beccarii* at T1 and T2

Parameter		Stand age (year)	Treatment		Mann-Whitney test P-value
			T1	T2	
Mean annual increment in diameter	Initial	8	0.43 ± 0.21ns	0.53 ± 0.22ns	0.026*
	4 months	9	0.44 ± 0.20ns	0.52 ± 0.20ns	0.096
	24 months	11	0.42 ± 0.20ns	0.52 ± 0.19ns	0.021*
	36 months	12	0.48 ± 0.15a	0.62 ± 0.14b	0.000***
	48 months	13	0.51 ± 0.14a	0.66 ± 0.11b	0.000***
	60 months	14	0.50 ± 0.14a	0.64 ± 0.11b	0.000***
	72 months	15	0.50 ± 0.13a	0.63 ± 0.10b	0.000***
Mean annual increment in height	Initial	8	0.55 ± 0.25ns	0.64 ± 0.20ns	0.034*
	4 months	9	0.59 ± 0.26ns	0.65 ± 0.19ns	0.095
	24 months	11	0.54 ± 0.22a	0.61 ± 0.15b	0.074
	36 months	12	0.55 ± 0.18a	0.63 ± 0.12b	0.024*
	48 months	13	0.56 ± 0.15a	0.63 ± 0.10b	0.014*
	60 months	14	0.55 ± 0.14a	0.62 ± 0.09b	0.004**
	72 months	15	0.55 ± 0.12a	0.61 ± 0.09b	0.009**

Notes: Different letters indicate significant differences at 5% using an independent Student's t-test between T1 and T2, ns= no significance, Mann-Whitney nonparametric test-*p<0.05, **p<0.01 and ***p<0.001

**Figure 7.** Relative light intensity trend over 72 months of silviculture implementation. Different letters indicate significant differences at 5% using an independent Student's t-test

Influence of selective girdling as an additional silviculture treatment on the RLI at the forest floor

Figure 7 shows the relative light intensity (RLI) for each particular assessment. At initial, the RLI at both plots showed no significant differences. The RLI gradually increase for both treatments throughout the monitoring period. At 60 months, RLI in T2 was significantly higher as compared to T1. Based on our field observation, the girdled *M. gigantea* in T2 has fallen onto the forest floor creating a significant forest gap. Romell (2007) explained that girdling practice was more persistent over time as compared to other canopy opening treatments. Besides, increasing the light intensity in the forest floor will lead to better growth performance of the target trees as Brown (1993) and Hattori et al. (2013) suggested that sunlight

exposure in a secondary forest can enhance the growth performance of Dipterocarp species.

Discussion

Girdling does not instantly fell or decompose unwanted trees, as this practice inhibits nutrient uptake by the targeted tree and results in the defoliation and slow death of the girdled tree. However, the application of selective girdling crucial in this study to reduce the dominance of *M. gigantea* in the study plot as this pioneer species can inhibit or suppressed the growth performance of the planted tree. Aoyagi et al. (2012) reported that the presence of *Macaranga* patches can affect the performance of dipterocarp seedlings through forest floor conditions because the nutrient accumulation rate beneath the litter layers is slow, resulting in the slow recovery of the nutrient availability of the forest floor. Hence, the immediate defoliation of the *Macaranga* tree by girdling reduces the possibility of slow nutrient recovery since the defoliated leaves degrade faster than naturally fallen fresh leaves. In the T1 plot, where no girdling was applied, the number of *M. gigantea* increased 72 months after the beginning of this study. Moreover, controlling the emergence of pioneers with a dense canopy layer is important for improving the light conditions on the forest floor, as light intensity was the main factor influencing seedling mortality and growth during the first 24 months of planting (Hattori et al. 2009).

Removing the pioneer species via girdling gradually increases the light intensity, as girdling practices do not provide a direct increase in light availability on the forest floor. Gradually increasing the light intensity provides optimum conditions for the planted *D. beccarii*. This species is considered a shade-tolerant tree at the seedling stage, and overexposure to sunlight causes scorching on the leaves. Incorporating the selective girdling of the dominant

Macaranga trees in the experimental plot allows the girdled trees to die slowly and reduces their impact when they fall, which provides a more favorable environment for the planted seedling. Furthermore, a decrease in stand density to an intermediate level can enhance the growth rate of seedlings planted under the trees (Paquette et al. 2006). There were some increases in the number of other pioneer trees (Table 2), such as *Ficus aurata*, *Dactylocladus stenostachys*, *Lithocarpus* sp. and *Horsfieldia* sp., in the study plot 72 months after silviculture implementation. This is considered a normal phenomenon in the secondary forest, where the number of plant species rises during the young secondary regrowth phase (Wermer 1997). Moreover, pioneer species proliferated shortly after silvicultural interventions but then diminished to primary forest levels by 20 to 30 years of post-treatment (Phillips et al. 2003; Van Gardingen et al. 2003).

In addition, girdling practices accompanied by slashing is also important to consider, since slashing frees the naturally growing or planted tree species from competition (Carandang et al. 2007). Overall, the growth rate was still higher than that of naturally grown seedlings; Widiyatno et al. (2013) reported that in natural tropical rainforests, the total growth rate for all species was approximately 0.22 cm year⁻¹, while for dipterocarp species, it was within the range of 0.34–0.40 cm year⁻¹. The girdling practices provide a competitive advantage for shade-tolerant species over pioneer forest floor vegetation, thus allowing the planted seedlings to gradually gain control of the growth resources liberated in the gap and prolonging the effect of the girdling (Romell et al. 2008). In addition, planting gaps created by girdling and slashing favored shade-tolerant dipterocarp species over light-demanding species (e.g., *Macaranga* sp.) due to the low level of irradiance in the sub-canopy layer (Sovu et al. 2010).

The results obtained from multiple assessments in the plots treated with different silvicultural treatments showed that girdling practices had a positive effect on the growth performance of the *D. beccarii* planted for reforestation purposes in GANP. The practice of girdling has a slow effect. The girdled pioneer tree does not die immediately, as it would in felling practices, because girdling practices do not lead to the immediate death and defoliation of the girdled tree. The effects of girdling are more difficult to assess than those of other practices, such as thinning and felling, in which the treated tree falls immediately. However, the effects of girdling are more persistent over time, and less damage is induced to the planted trees. This can be seen in Table 3; the girdling plot (T2) started to show better growth in diameter and height at 36 months and 24 months, respectively. Thus, the practice of selective girdling of pioneer species starts to take effect after 24 months, when the girdled tree starts to fall and provides favorable light conditions for the planted trees to grow. Romell (2007) reported that selective girdling needs at least 2 years after implementation to see its effects on canopy opening and the light environment on the forest floor. One possible explanation for the better height growth rate in the T2 plot was that the girdled trees had fallen, creating more

favorable light conditions for the planted trees to grow taller. The slower growth performance in T1 may be due to the low light conditions releasing shade-tolerant pioneer vegetation and obstructing the establishment of slow-growing tree seedlings (Romell et al. 2008). Next, the Mann-Whitney test showed that the trees planted in the T2 plot showed better growth performance than those in T1, and the mean annual increments in diameter and height were significantly higher than those in the T1 plot at 36 months onwards. The P-value in Table 3 shows that the MAI in diameter was strongly significant at $p < 0.001$ and was an important indicator, as the increment in diameter indicated that the planted tree started to increase greatly in size. Although this effect was only seen after 36 months, which is slower than 6–12 months, as reported by some researchers, there is great variability in the ecosystem, as various edaphic factors can obstruct the slow growth of the planted indigenous tree species.

For rehabilitation purposes, the speed of tree growth in planted indigenous trees is crucial, but tree survival after anthropogenic activities is another main consideration. In terms of survival rate, T2 showed a better growth pattern than T1. In T2, the survival rate was almost stable with no sudden increase in mortality rate. In T1, a sudden mortality increase was observed 60 months after the implementation of silvicultural treatment. Overall, both treatments T1 and T2 were practicable for managing the planted *D. beccarii* trees in GANP and could increase the probability for the tree to grow and adapt well to the ecosystem. However, the T2 practices were preferable because they tend to provide a better environment for planted indigenous trees to grow. In addition, T2 showed slightly faster growth in MaiD and MaiH than T1, with averages of 0.63 cm year⁻¹ and 0.61 m year⁻¹, respectively, compared to T1, with averages of 0.50 cm year⁻¹ and 0.55 m year⁻¹, respectively. The canopy openings created by girdling and the gaps created by slashing in T2 provided optimum growth conditions for *D. beccarii*. In addition, light availability plays an important role in regenerating tropical tree seedlings (Agyeman 1994). Creating gaps by slashing the understory seems to be an efficient treatment for forest floor shade reduction in secondary tropical forests (Romell et al. 2009). Mauricio (1987) also reported that dipterocarp seedlings or stands with DBH values ranging from 5–20 cm will triple their growth when competing for secondary growth is cleared. As in this study, girdling was only applied when the stands were eight (8) years old, since most dipterocarps seedlings demand shelter from sunlight during their establishment phase (Nicholson 1960; Weidelt and Banaag 1982; Mauricio 1987). Moreover, young trees (less than 30 cm in DBH) react better to liberation and a subsequent increase in light intensity (Weidelt and Banaag 1982). Aside from canopy treatments (girdling), weeding or slashing practices are also essential; at a young age, dipterocarp trees need intensive tending (Ådjers et al. 1995). The frequency of slashing also has to be adjusted considering the main climatic conditions in the area (Carandang et al. 2007). The study plot is located in a tropical rainforest, where weeds emerge rapidly due to the availability of rainfall throughout the year. Therefore, the frequency of slashing should be

high, and slashing should be conducted at a constant interval; if weeding is carried out inconsistently, the dipterocarps will be easily damaged (Priasukmana 1991). Although some forest plantation management systems primarily practice felling rather than frequent slashing due to the cost of maintenance, Weidelt (1976) pointed out the importance of maintenance, as insufficient tending is the most common reason for failure.

For the purposes of reforestation, and as recommended by Wasli et al. (2014) in their preliminary assessment, suitable silvicultural practices should be applied to ensure the success of reforestation programs. In the present study, our findings suggested that additional silvicultural treatment by means of selective girdling could be adopted to enhance the growth performance of planted trees in the reforestation program at GANP. As the forest continues to regenerate, given time and disturbance, the pioneer species in the forest will decline and be replaced by climax species, converting the secondary forest into a forest community that is similar to that of a mature primary forest (Osborne 2012). Hence, the implementation of selective girdling practices is crucial for enhancing the process of forest restoration, since natural primary forests take decades to reach maturity. To ensure successful enrichment planting, the necessary conditions must be met, including the provision of adequate light conditions, proper supervision and follow-up maintenance (especially for canopy opening treatments) (Akindale and Onyekwelu 2011).

Meanwhile, the location of the pioneer tree that will be girdled should be taken into consideration to fully utilize the gap created when the girdled tree falls. In addition, the intensity of the girdling should be taken into consideration to ensure its effective application. Slashing the undergrowth is still recommended, despite its cost, to keep the planting line accessible for future supervision and tending activities (Ådjers 1995). Further comprehensive studies in the future should broaden their focus to examine pioneer species competition with planted trees, soil-plant relationships, and canopy opening through the treatments applied. Meanwhile, the existing natural pioneer species inside the study plot that interact and compete with the planted trees for light, space, and nutrients should be identified clearly in future studies.

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