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Does Gap Opening and Planting to Rehabilitate the Degraded Tropical Natural Forests Affect the Forest Composition and Structure?

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Abstract

By 2020, there were 33.4 million ha of degraded forests in Indonesia. If it is not rehabilitated, there will be land-use changes that significantly affect its biodiversity and environment. Gap opening and planting is an important silvicultural regeneration method to rehabilitate degraded tropical natural forests. We studied the subject in a 10 ha degraded lowland tropical natural forest in Central Borneo, Indonesia. The study aims to compare the composition and structure of degraded tropical natural forests before and after gap opening and planting. The methods used consist of 1) gap opening and planting with a proportion of the total gap area to the total degraded natural forest area of 40%; 2) vegetation analysis to assess the composition and structure of forest. The results showed that the gap opening and planting activities led to a decrease in the density of seedlings, saplings, poles, and trees, and cause loss of two species at seedling level and one species at sapling level. The analysis results of the stand structure and species composition, index of species diversity, species evenness index, and community similarity index before and after gap opening and planting of the degraded forest in the study area of 10 ha showed that there is no changes of these variables. These results showed that the use of the gap opening and planting method in the rehabilitation of degraded forests is able to maintain the stability of species composition and stand structure, species diversity, species evenness, and forest communities. In conclusion, the study provided significant empirical results on the composition and structure of degraded tropical natural forests before and after gap opening and planting, which would be instrumental for the development of rehabilitation strategies. It is recommended that the rehabilitation of degraded tropical natural forests in Indonesia can be carried out using the gap opening and planting method.

Keywords: *artificial gap, productivity, degraded forest, biodiversity, environmental performance*

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Introduction

In 2020 degraded forest in Indonesia reached 33.4 million ha (MoEF, 2020). Rehabilitation of these degraded natural tropical forests using the silviculture system of clear cutting and artificial regeneration or clear cutting and natural regeneration is very dangerous since it would damage forest ecosystem and reduce forest biodiversity. Therefore, these sylvicultural systems are not legally permitted to be applied in Indonesia's natural production forest areas (MoF, 2014). Meanwhile, the use of the Indonesian selective cutting and planting or the selective cutting and line planting silvicultural system to manage the degraded natural forest is not profitable, because the potential of commercial timber is low (≤ 40 m^3 ha^{-1}), and the cultivation of dipterocarp species using enrichment planting requires a long investment period of 25 years (Elias, 2015).

To maintain the quality and quantity of forest cover, degraded forests should then be rehabilitated immediately in an appropriate manner. Lamprecht (1986) stated that there are two methods to rehabilitate the degraded tropical natural forests, namely: 1) the method of volume or biomass stock improvement through improvement felling and enrichment planting and 2) the method of regeneration improvement through the regeneration of certain species that will become new generation trees replacing the previous generation. Elias (2015) mentioned that gap opening and planting is one of the regeneration improvement methods. This method is based on the succession theory of tropical natural forests. In line with this theory, the research results of Long et al. (2018) showed that the management of Engelmann spruce in Intermountain West used a small group selection cutting system, which is preferred because it mimics the dynamics of the gap phase. Furthermore, some research on gap opening and planting for rehabilitation of degraded natural forests in Indonesia dan Brazil showed that the cultivation of local superior intolerant tree species using gap opening and planting is more cost-effective and needs shorter-term investment (Grogan et al., 2013; Schwartz et al., 2017; Elias & Suwarna, 2019). Elias

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and Suwarna (2019) mentioned, that the application of gap opening and planting did not harm the environment in terms of open areas, soil erosion, soil compaction, and forest fire risk aspects. On the contrary, it showed positive impacts such as cost-effectiveness, job creation for local communities, and a productivity increase in rehabilitated forests. Therefore, the application of the gap opening and planting method is expected to be a solution in the effort to rehabilitate degraded tropical natural forests in Indonesia.

Study on species composition and stand structure has been frequently used in assessing restoration (Gunawan et al., 2011), monitoring (Palace et al., 2016; Feldmann et al., 2020; Ramli et al., 2022), and evaluation of degraded natural forest conditions (Gunawan et al., 2011; Marvin et al., 2014; Kituyi, et al., 2018; Segura et al., 2021), and in obtaining information on changes in a forest area due to natural and human-related disturbances (Mawazin & Subiakto, 2013; Nopiansyah et al., 2016; Fischer et al., 2016; Gebeyahu et al., 2019; Pamoengkas et al., 2019; Feldmann et al., 2020; Siti Nurfaeiza et al., 2022; Larocque, 2022; Liang et al., 2022; Zhang et al., 2022), species diversity (Gunawan et al. 2011; Soendjoto et al., 2014; Gebeyahu et al., 2019; Segura et al., 2021; Ahmad Fitri et al., 2022; Rohaiza et al., 2022), protected threatened and economic species (Murdjoko et al., 2016; Niningsih et al., 2017; Gebeyahu et al., 2019), and plant communities (Gebeyahu et al., 2019). However, studies of the effects of gap planting implementation to rehabilitate degraded tropical natural forest on its species composition and stand structure remain scarce. The objective of this study is then to determine the composition and structure of degraded tropical natural forests before and after rehabilitation by applying of gap planting method through creating artificial gaps.

Methods

Study location This study was conducted in a 10 ha degraded lowland tropical natural forest area of the Sarmiento Parakantja Timber Company in Central Borneo, Indonesia. The study area is located at S1°47'10"–S1°47'26" and E112°13'0"–E112°13'6.5". The soil type was Dystropepts and Tropodults. The topography consist of 50% flat to gentle slope, 35% moderate slope, and 15% steep slope. The altitude ranges from 70 m to 140 m above sea level (Sarpatim, 2021). The study was conducted from January to December 2021.

Research design The design of the study was begun by selecting an area of 10 ha in the field, which meets the following criteria: good access; degraded tropical natural forest; and the topography consists mostly of flat to the medium slope (0–25%). Data on contour lines, tree species, tree diameter, and location of the tree with diameter at breath height (dbh) ≥ 10 cm were then collected using the transect survey method. The survey design used the systematic sampling with random start. The size of the transect was 20 m × 500 m, with a total of 10 parallel transects that strectch from north to south. The resulted survey data was used for mapping contour lines and tree locations on a scale of 1:500.

Artificial gap areas were planned on the contour lines and tree locations map using the following criteria: maximum total gap areas are 40% of the total research area; gap location is chosen an open and less productive forest area, and the artificial gap area size is 40 m × 50 m or 2,000 m^2. The sample gap area in this study consist of 16 units. It's locations are distributed in the study area of 10 ha (Figure 1). Artificial gap areas were constructed by cutting off all trees inside the gap area boundary, except commercial tree species with dbh ≥ 20 cm and proteced tree species. Crop stripes were constructed inside these areas in the east-west direction. After which the seedlings of jabon putih (*Anthocephalus cadamba* Miq.) were planted in the crop stripes area. The research location and artificial gap area design were shown in Figure 1.

Data collection The study area of 10 ha was divided into 10 parallel survey stripes that stretch from north to south with a width of 20 m and a length of 500 m. Along the survey stripes measuring plots for vegetation analysis is made as follows: 20 m × 20 m for tree measuring plots, 10 m × 10 m for pole measuring plots, 5 m × 5 m for sapling measuring plots, and 1 m × 1 m for seedling measuring plots. The total number of measuring plots was 1,000 plots. The data collected from the seedling measuring plots and the sapling measuring plots are the tree species and their respective numbers. The data collected from the pole measuring plots are the tree species, the size of the dbh, and the number of poles of each tree species. The data collected from the tree measuring plots are tree species, dbh size, and the number of each tree species. Data collection in the study area of 10 ha was conducted two times, consisted of first survey conducted before gap opening and planting, and second survey conducted immediately after gap opening and planting.

Data analysis The tested variables consisted of species composition, stand structure, species diversity index (H'), species evenness index (E), and community similarity index (IS). The composition of species is determined by the number of species at each growth level and the total number of species in the stand. The stand structure was analyzed by comparing the distribution of trees diameter size using the negative exponential function (Meyer et al., 1961) as shown in Equation *[1]*.

$$N = N_0 e^{-kd} \qquad [1]$$

note: N = number of trees diameter d cm per hectare; *No* = coefficient of equation elevation; k = a constant that indicates the decline rate in the number of trees at each increase in the diameter of the tree; d = diameter of the tree (cm); and e = Napier number (2.7183). The species diversity index is calculated by the formula (Odum, 1971) as shown in Equation *[2]*.

$$H' = -\sum_{i=1}^{n} \left(\frac{n_i}{N_t}\right) ln \left(\frac{n_i}{N_t}\right) \qquad [2]$$

note: H' = Shannon-Wiener diversity index; n = number of species; ni = number of individuals of a species; and Nt = the total number of individuals of the entire species. The H' value < 2.0 indicates low species diversity; H' at 2.0-3.0 indicates moderate diversity; the H' value > 3.0 indicates high diversity of species. The species evenness index is calculated by the formula (Ludwig & Reynold, 1988) as shown in Equation *[3]*.

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$$E = \frac{H'}{\ln S} \qquad [3]$$

note: E = species evenness index; H' = Shannon-Wiener diversity index; and S = number of species found. Index of community similarity is calculated using the formula (Odum, 1971) as shown in Equation *[4]*.

$$IS = \frac{2w}{a+b} \times 100\% \qquad [4]$$

note: *IS* = index of community similarity; *a* = number of species in the stand community of study area before gap opening and planting; *b* = number of species in stand community of study area after gap opening and planting; and *w* = number of species found in stand before and after gap opening and planting.

Results and Discussion

Species composition The effect of gap planting on the composition of species was studied through the presence or absence of changes in species composition due to gap opening and planting activities. Based on field observations, gap opening activities that cause loss of individuals in the growth levels consist of 1) forest road construction; 2) the cleaning of all undergrowth and sapling, and tree felling in gap areas; 3) path construction to the gap area; 4) path construction to connect among gap areas; 5) excess area of gap; 6) gap opening error; and 7) sewerage construction. Open areas due to gap opening activities are mapped and calculated using the QGIS 3.14 application. The results of mapping and calculation of open areas are presented in Figure 2 and Table 1.

The data presented in Table 1 shows that gap opening activities of 16 units of gaps area cause an open area of 41,968.88 m^2 or 41.97% of the total rehabilitated area (10 ha). The proportion of gap openings is the largest at 32%, followed by forest road construction at 5.52%.

Table 2 showed the results of the vegetation analysis on the species composition before and after gap opening and planting.

The average number of trees ($\geq$ 20 cm) cut per ha in the gap was about 18.2 trees per ha. As shown in Table 2, the number of trees ($\geq$ 20 cm) before gap opening and planting

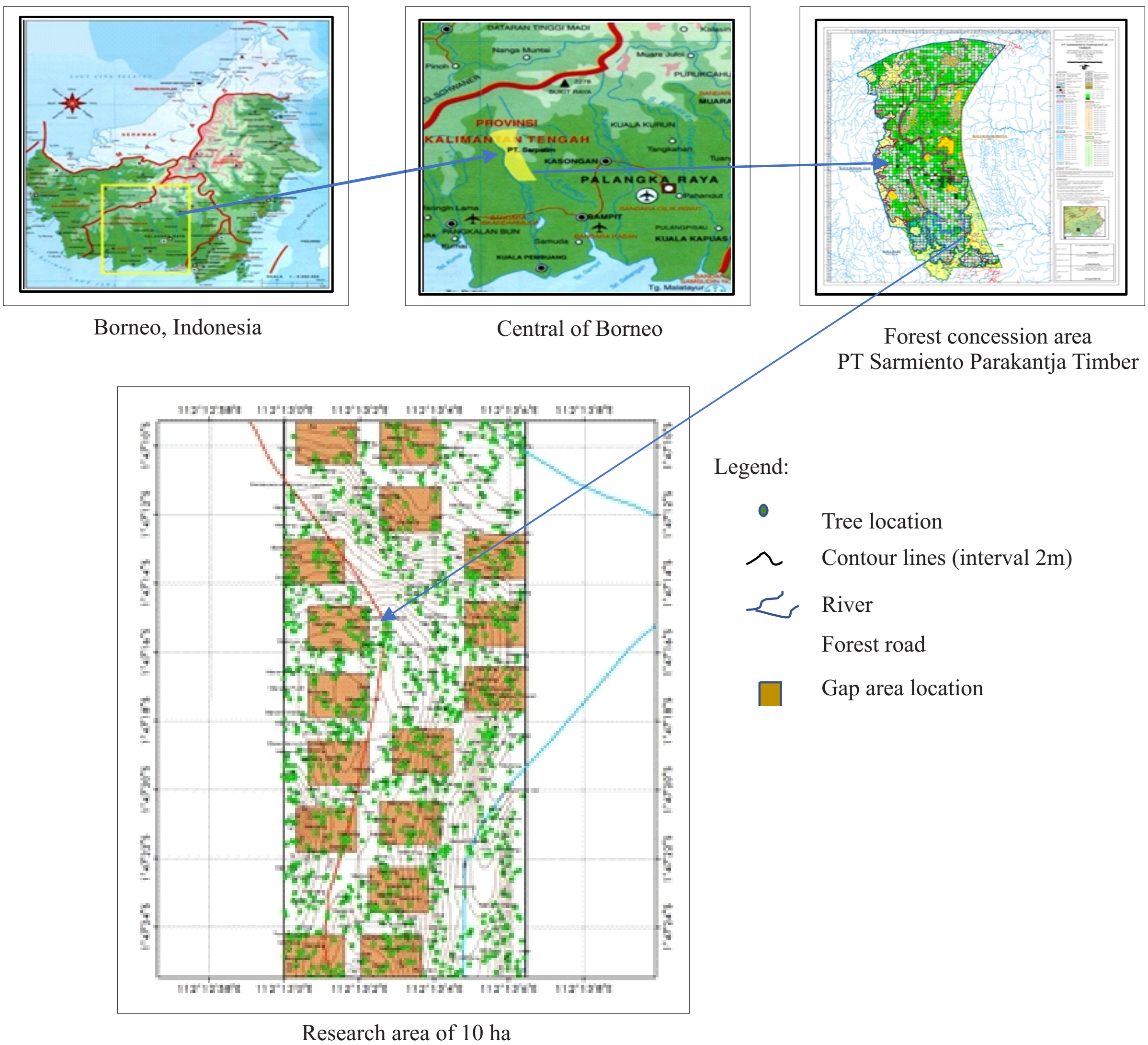

Figure 1 Research location and artificial gap area design.

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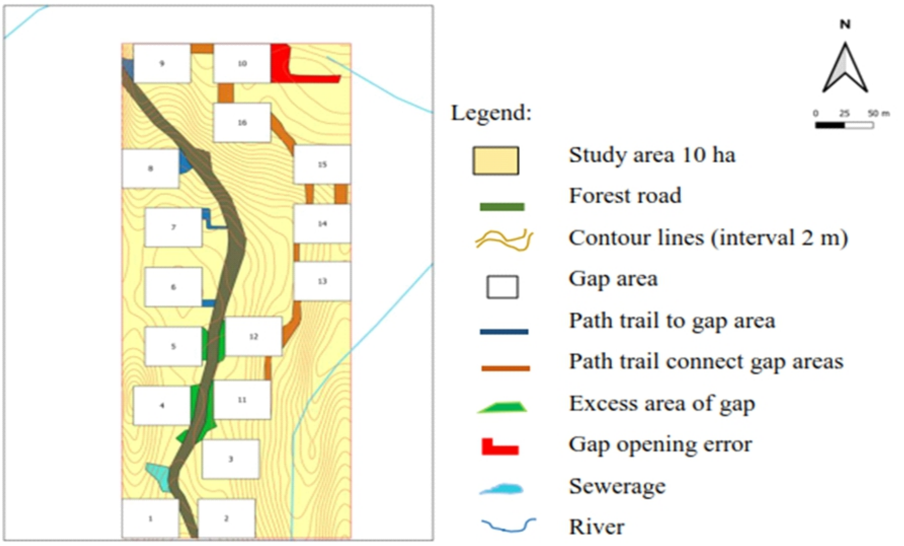

Figure 2 Opened area caused by gap opening activities in the study area (10 ha).

Table 1 Opened area caused by gap opening activities in the study area of 10 ha

Gap opening activities	Opened area	
	Size (m^2)	Proportion (%)
Felling trees and clearing of gap area	32,000	32.00
Forest road construction	5, 519.70	5.52
Opening path to gap area	543.16	0.54
Opening paths connecting gap areas	1,677.72	1.68
Excess area of gap	923.73	0.92
Gap opening error	958.92	0.96
Sewerage construction	345.65	0.35
Total opened area	41,968.88	41.97

Table 2 Species composition before and after gap opening and planting in the study area of 10 ha

Growth levels	Species composition							
	Before gap opening and planting				After gap opening and planting			
	∑ ind.	∑ spe.	∑ gen.	∑ fam.	∑ ind.	∑ spe.	∑ gen.	∑ fam.
Seedling	153,200	24	19	17	104,800	22	17	15
Sapling	18,192	22	17	15	10,144	21	16	14
Pole	2,372	24	19	15	1,388	24	19	15
Tree	1,124	36	28	21	942	36	28	21

was 1,124 trees per 10 ha or 112.4 trees ha^{-1}, while after gap opening and planting was 942 trees per 10 ha or 94.2 trees ha^{-1}. Based on data of the individual number at each growth level before and after gap opening and planting in Table 2, it can be calculated that gap opening activities of 16 units of gap area in study area of 10 ha cause the damage of seedlings is 31.59% [(153,200 – 104,800)/153,200 × 100%], the damage of saplings is 44.24% [(18,192 – 10,144)/18,192 × 100%], the damage of poles is 41.48% [(2,372 – 1,388)/ 2,372 × 100%], and the damage of trees is 16.19% [(1,124 – 942)/1,124 × 100%]. This figure is in line with the total opened area due to gap opening activities of 16 units of gap area, which is about 41.97% of the total study area (Table 1). Data on composition species presented in Table 2 shows that the highest number of species found at the tree level, followed by the pole level, then the seedling level, and finally the sapling level. Gap opening and planting activities do not cause species loss at tree and pole levels in the study

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area. It causes the loss of 2 species at the seedling level, which are *Dillenia* sp. of Dilleniaceae and *Mallotus paniculatus* of Euphorbiaceae; and 1 species at the sapling level, which is *Nephelium costatum* of Sapindaceae. The loss of species at the seedling and sapling level in the research area was due to the cleaning of all undergrowth and all tree species with dbh < 20 cm when the gap opening activities.

The total number of species recorded at the tree, pole, sapling, and seedling level were respectively, 36, 24, 22, and 24 species. These figures indicate a relatively lower number of species compared with the total number of species found in primary tropical natural forests in East Borneo, and in logged-over tropical natural forests in Papua. Indrawan (2000) reported the number of species found in primary tropical natural forests of PT Ratah Timber in East Borneo, Indonesia, consisted of 79 species at tree level, 80 species at pole level, 80 species at sapling level, and 98 species at the seedling level. Kuswandi et al. (2015) mentioned that the number of species found in logged-over tropical natural forests in Papua for the tree, pole, sapling, and seedling level were respectively ranged from 71–131, 113–168, 99–119, and 74–86 species. However, these study results are in line with the results of the previous study by Sularso (1996) and Amir (1996) in the logged-over forest of PT Sumalindo Lestari Jaya IV in East Borneo, Indonesia. Sularso (1996) reported that the number of species in the logged-over forest by selective cutting at age 0 year after logging for the tree and pole (a tree with dbh ≥ 10 cm), sapling, and seedling level were respectively ranged from 22–36, 16–25, and 14–19 species, while Amir (1996) mentioned that the number of species in the logged-over forest by stripe cutting at aged 0 year after logging for the tree and pole, sapling, and seedling level were respectively ranged from 23–42, 11–25, and 8–25 species.

Stand structure The effect of gap opening and planting on the forest structure was studied through the presence or absence of change in forest structure. In this study, we compared between the forest structure before and after gap opening and planting based on the distribution of the tree density and tree growth level. The study resulted in a negative exponential equation of stand structure of trees with dbh ≥ 20 cm before gap opening and planting $N = 243.915\ e^{-0.072D}$, with adjusted $R^2 = 0.9904$; and stand structure after gap opening and planting $N = 198.545\ e^{-0.070D}$, with adjusted $R^2 = 0.9925$. These equations have high adjusted R^2 values, which indicate a very close relationship between the diameter and the density of the trees. The coefficient value of equation elevation (No) obtained from the negative exponential equation before gap opening and planting is 243.915, and after gap opening and planting is 198.545. These values were high which indicates a good regeneration in the stand structure before and after gap opening and planting.

The stand density of various diameter size before and after gap opening and planting showed a decrease in the number of individuals along with the increase in diameter size. The same pattern was observed in many studies in Indonesia such as reported by Indrawan (2000), Nurfatma et al. (2017), and Pamoengkas et al. (2019), in Malaysia reported by Siti Nurfaeiza et al. (2022), Ahmad Fitri et al. (2022), and Rohaiza et al. (2022), and in Ethiopia reported by Gebeyehu et al. (2019).

Figure 3 showed the equation of the stand structure before and after gap opening and planting forms an inverted "J" curve with *p*-value < 0.05. The trendlines of the curves almost coincide showing that the stand structure after gap opening and planting is close to the stand structure before gap planting.

Figure 4 showed the changes in the growth levels of the stand before and after gap opening and planting. The gap opening and planting activities led to a decrease in the density of seedlings from 15,320 to 10,480 seedlings ha^{-1}, saplings from 1,819 to 1,014 saplings ha^{-1}, poles from 237 to 139 poles ha^{-1}, and trees from 112 to 94 trees ha^{-1}. This figure showed that although there is a decrease in density of each growth level after gap opening and planting but the stand structure is still relativly same.

Based on figures presented in Figure 3 and Figure 4 and the analysis results, it is concluded that the application of gap opening and planting to rehabilitate degraded tropical natural forests did not affect the stand structure. This finding is in line

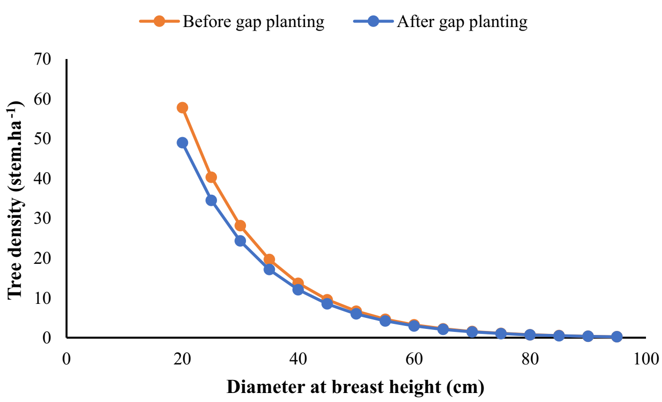

Figure 3 Stand structure before and after gap opening and planting in study area of 10 ha.

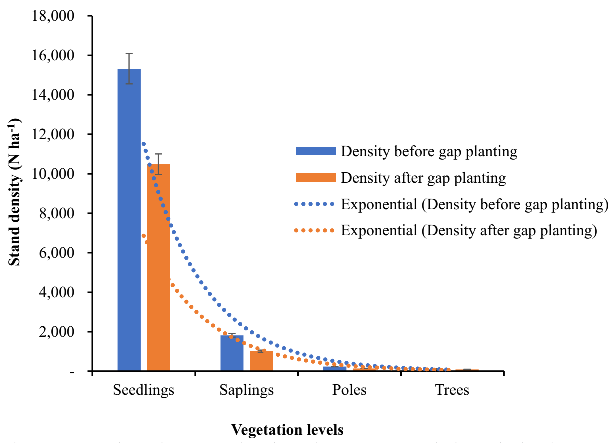

Figure 4 The changes in density at growth levels before and after gap opening and planting in the study area of 10 ha.

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with the concept of gap opening and gap planting to rehabilitate the degraded tropical natural forests in this study. The gap opening and gap planting uses only an area of ca. 40% of the total area of rehabilitated forest so that there is still ca. 60% of the total area which is natural forest. In addition, the location of the gap opening and planting area was deliberately chosen from an opened area and shrubs.

The density at the tree level of the study area indicates a low tree density compared to the density at the tree level in general lowland tropical natural forest. Lamrecht (1986) mentioned, that the density at the tree growth level in lowland tropical forests is 182 individuals ha^{-1} (Foerster, 1973, as cited in Lamprecht, 1986) and 154 individuals ha^{-1} (Lizano, 1966, as cited in Lamprecht, 1986). This condition is understandable because the study area is a degraded tropical natural forest area.

Species diversity, species evenness, and community similarity The analysis results of the species diversity index (H), species evenness index (E), and community similarity index (IS) of this study is shown in Table 3.

Data in Table 3 showed the index value of species diversity at all growth levels before and after gap opening and planting ranged between 2.307 and 2.758. The species diversity index before and after gap opening and planting for seedlings is 2.700 and 2.706; for saplings is 2.721 and 2.632; for poles is 2.307 and 2.314; for trees is 2.743 and 2.758, respectively. The index values before and afer gap opening and planting are almost the same and considered as moderate, which indicate there are no changes in species diversity at all growth levels. The value of species diversity in this study area is smaller than that value of species diversity in logged over tropical natural forests in the same concession area, and in logged over tropical natural forests in Papua. Study of Pamoengkas et al. (2019) indicated that species diversity values in logged-over areas in this concession area ranged from 3.1 to 3.7 at the seedling level, 3.3 to 4.1 at the sapling level, 3.0 to 3.5 at the pole level, and 3.3 to 3.7 at the tree level. Meanwhile, Kuswandi et al. (2015) mentioned that the value of species diversity in logged-over tropical natural forests in Papua is more than 3.79. Conversely, the value of species diversity in this study area is larger than that value of species diversity in secondary natural forest at Muara Enim District, South Sumatera Province, and in forest stands in Mount Gede Pangrango National Park, West Java. According to Al-Reza et al. (2016), the index value of species diversity at all growth levels in secondary natural forest at Muara Enim District, South Sumatera Province ranged between 1.33 and 2.44. Meanwhile, according to Dendang and Handayani (2015), the species diversity value at all growth levels of forest stands in Mount Gede Pangrango National Park, West Java, ranged between 0.765 and 0.901.

Species evenness index (E) values of all growth levels before and after gap opening and planting range between 0.717 and 0.835. According to Magurran (1988), if the species evenness index is above 0.6, it indicates the species evenness is high. This means that the species evenness of all growth levels before and aftar gap opening and planting in the study area is included high category. The species evenness index before and after gap opening and planting at each growth level is almost the same. Hence, it can be concluded that there was no difference between the species evenness of all growth levels before and after gap opening and planting, where the species evenness of all growth levels included a high category.

The results of the community similarity index analysis before and after gap opening and planting of the study area showed the value of IS $\geq$ 75% so the forest stand communities before and after gap opening and planting can be considered similar.

Based on data presented in Table 3 and the analysis results, it is concluded that the application of gap opening and planting to rehabilitate the degraded tropical natural forest does not affect the species diversity, species evenness, and forest community. These findings are possible because 1) the area of gap opening and gap planting uses only ca. 40% of the total rehabilitated forest area; 2) the location of the gap opening and gap planting is placed in an opened area and a shrubs area; and 3) the tree species planted in the gap area are locally superior intolerant tree species.

The results of this study showed that the gap opening and gap planting that uses only ca. 40% of the total rehabilitated forest area is able to maintain the stand composition and structure, biodiversity, and environment.

Table 3 Species diversity index, species evenness index, and community similarity index before and after gap opening and planting in the study area of 10 ha

Study area condition	Vegetation levels	H'	E	IS
Before gap opening and planting	Seedling	2.700	0.802	98.24
After gap opening and planting		2.706	0.812	
Before gap opening and planting	Sapling	2.721	0.835	98.03
After gap opening and planting		2.632	0.818	
Before gap opening and planting	Pole	2.307	0.717	95.83
After gap opening and planting		2.314	0.738	
Before gap opening and planting	Tree	2.743	0.754	100.00
After gap opening and planting		2.758	0.758	

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Conclusion

The present study showed that the use gap opening and planting to rehabilitate degraded tropical natural forests did not affect the forest composition and stand structure. It is able to maintain the stability of species diversity, species evenness, and forest communities. Based on these results, it was concluded that the gap opening and planting method is an environmentally friendly method.

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