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Economics of Gap Planting Technology to Rehabilitate Degraded Natural Forests in Indonesia

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ABSTRACT

The economics of gap planting technology matter because they determine whether restoring degraded natural forests can be done at scale in a way that's economically and financially viable for governments, communities, and investors, while also recovering biodiversity and ecosystem services. This study assessed the economic benefits of using gap planting technology—planting commercial, shade-intolerant tree species in artificial gaps—to rehabilitate degraded natural forests. A purposive sampling technique was used to establish 16 artificial gaps, each covering 2,000 m², which were inventoried on four occasions. Based on the data, the mortality rate, diameter and height increments were determined. Net present value (NPV), internal rate of return (IRR), benefit-cost ratio (BCR), and land expectation value (LEV) were also determined in the economic analysis of three scenarios differentiated by rotation age of 6, 7, and 8 years. The results showed the average mortality, diameter and height increments were, respectively, 30%, 3.80 cm year^{-1} and 326.45 cm year^{-1}. Assuming a real discount rate of 8% year^{-1} and a real stumpage price of IDR 0.75 million m^{-3}, all scenarios showed NPV $\geq$ 0, BCR $\geq$ 1, IRR $\geq$ minimum acceptable rate of return (MAR), LEV > IDR 115 million ha^{-1}, and job creation of 106 man-days ha^{-1}. Moreover, NPV and LEV are more sensitive to changes in the real stumpage price than to changes in the real discount rate. It is concluded that gap planting technology with white jabon is financially and economically viable under these assumptions and is recommended for the rehabilitation of degraded natural tropical forests in Indonesia.

1. Introduction

Indonesia has the third-largest tropical natural forest in the world, covering around 125.8 million ha; however, about 36.47 million ha of it were in degraded condition in 2022 (MoEF 2024). Coupled with forest land conflicts, low productivity of natural forests, and the low contribution of the forestry sector to income (< 1% of total government revenue), this has resulted in the real economic value of forest land being lower than that of other commodity lands. These problems serve as triggers for changes in the use of natural forest land (BPS-Statistics Indonesia 2026; Nurrochmat et al. 2021). On the other hand, forest entrepreneurs are not interested in pursuing forest rehabilitation because it is not economically profitable when silvicultural systems such as

Indonesian selective cutting and planting or selective cutting and line planting are used, due to low commercial timber potential (≤ 40 m^3 ha^{-1}). Meranti, a dipterocarp species, has a natural diameter increment of 0.5 cm $year^{-1}$ (Dulsalam et al. 2018) and a long investment period of 15–25 years for cultivating dipterocarp species through enrichment planting (Elias and Simangunsong 2023). Other silvicultural systems, such as clear-cutting with artificial or natural regeneration, are even more dangerous when used to rehabilitate degraded tropical forests, as they can damage the ecosystem and reduce biodiversity. Hence, these silvicultural systems are not legally permitted in Indonesia's natural production forests, except in Industrial Forest Plantations (*Hutan Tanaman Industri*, HTI) management (Elias and Simangunsong 2023).

According to MoEF (2024), as of December 2023, the Ministry of Environment and Forestry of Indonesia had granted access to Social Forestry (*Perhutanan Sosial,* PS) permits covering 6,400,000 ha of forest area. In 2023, through Presidential Regulation of the Republic of Indonesia Number 28 of 2023 concerning Integrated Planning for the Acceleration of Social Forestry Management, the government has decided to provide legal access to 1,100,000 ha of PS per year from 2026–2030 (Minister of State Secretary of the Republic of Indonesia 2023). This PS program needs to be closely monitored to prevent extensive logging in the PS area, which can lead to the opening of forest areas, loss of biodiversity in natural forests, increased soil erosion, and more frequent natural disasters such as floods and droughts. On the other hand, the communities around the forest are also in desperate need of employment. Therefore, to address deforestation and degradation of natural forests, reforestation and forest rehabilitation alone are not enough. It must be accompanied by efforts to increase forest productivity, the real economic value of forests, and the welfare of communities around forests (Nurrochmat et al. 2021). To meet these requirements, it is necessary to develop innovative methods for rehabilitating degraded natural forests.

Theoretically, there are two methods for rehabilitating degraded tropical natural forests. They are the volume- or biomass-stock improvement method through felling and enrichment planting, and the regeneration improvement method through the regeneration of certain species that replace the previous generation. The gap-opening and planting method is one of the latter methods (Elias and Simangunsong 2023). This method is based on the succession theory of tropical natural forests, as demonstrated by the management of Engelmann spruce in the Intermountain West using a small-group selection cutting system that mimics the dynamics of the gap phase (Long et al. 2018). Several studies conducted in Indonesia and Brazil showed that cultivating local superior intolerant tree species through gap opening and planting was more cost-effective and required shorter-term investment (Elias and Suwarna 2019; Schwartz et al. 2017).

During 2017–2022, the authors studied gap planting technology in degraded tropical natural forest areas in the provinces of Central Kalimantan and North Kalimantan, Indonesia (Elias and Simangunsong 2023). Some commercially valuable, locally intolerant tree species that can grow rapidly in marginal soils were identified as superior. These tree species are recommended for rehabilitating degraded natural forests under the gap-opening and planting silvicultural system. They are: non-Dipterocarpaceae trees species with a rotation of 6–8 years such as jabon putih (*Anthocephalus cadamba* Miq.), jabon merah (*Anthocephalus macrophylla*), jelutung (*Dyera polyphylla*), kayu afrika (*Maesopsis eminii*), gmelina (*Gmelina arborea*), kenanga (*Canangium odoratum*), suren (*Toona sureni*), pinus (*Pinus merkusii*), mindi (*Melia azedarach*), binuang laki (*Duabanga moluccana* Blume), binuang bini (*Octameles sumatrana* Miq.), bira-bira (*Fagraea crenulata*), pulai (*Alstonia scholaris* (L.) R. Br), nyawai (*Ficus variegata*), and sengon (*Paraserianthes falcata* (F) Nielsen); and Dipterocarpaceae trees species with a rotation of 15–25 years such as *Shorea leprosula, S. johorensis, S. platyclados, S. macrophylla, S. parvifolia, S. selanica,* and *S. smithiana* (Elias and Simangunsong 2023).

Elias and Suwarna (2019) and Raharja et al. (2021) indicated that the application of gap opening and planting did not harm the environment, including open areas, soil erosion, soil compaction, and forest fire risk. Moreover, the gap-opening and planting method maintained the stability of species composition and stand structure, as well as species diversity, species evenness, and forest communities (Elias and Simangunsong 2023). These previous studies focused on ecology, but economic feasibility remains underdeveloped.

Since degraded forests should be rehabilitated immediately in an appropriate manner to maintain the quality and quantity of forest cover, the economic benefits of the gap-opening and planting method should also be studied to address its economic aspects, especially the impacts of the gap-opening and planting application on job creation for local communities, productivity increase in rehabilitated forests, and forest value. The objective of this research was to assess the potential economic benefits of gap planting technology for rehabilitating degraded natural forests. When positive economic benefits are confirmed, the gap-opening and planting method is expected to be one of the solutions for rehabilitating degraded tropical natural forests in Indonesia.

2. Materials and Methods

2.1. Research Location

This study was conducted in a forest concession managed by PT Sarmiento Parakantja Timber in Central Kalimantan, Indonesia, from January 2021 to December 2022. A 10-ha degraded lowland tropical natural forest area was selected as the study site and is located between 1°47′10″–1°47′26″ S and 112°13′00″–112°13′06.5″ E (**Fig. 1**).

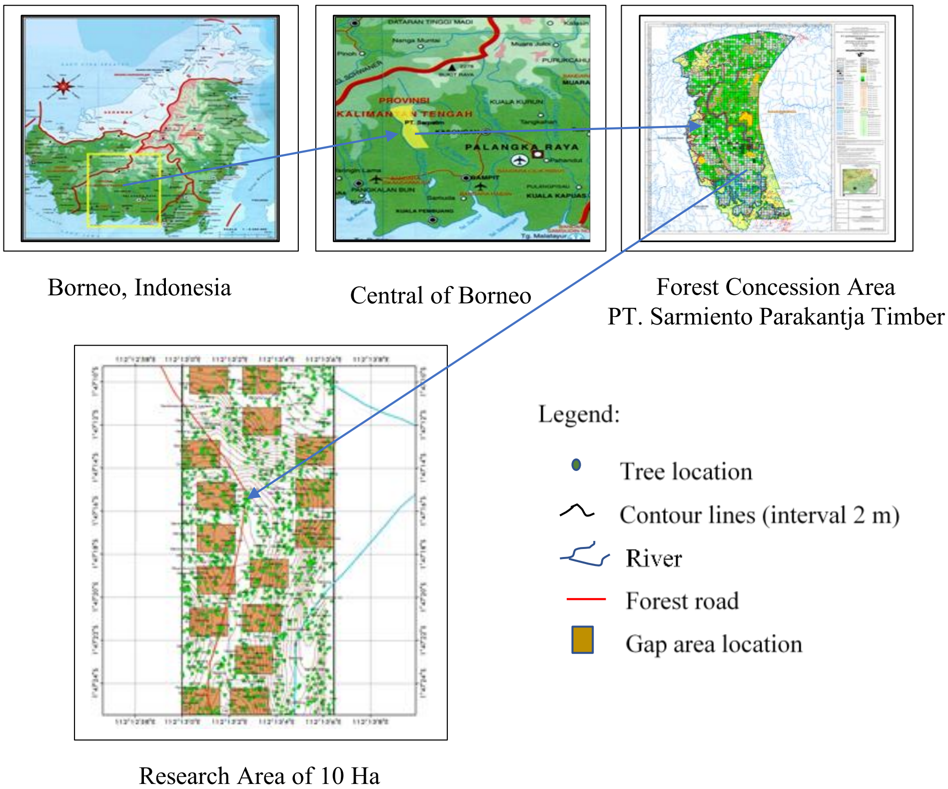

Fig. 1. Research location and design of the artificial gap area.

The soil types are Dystropepts and Tropodults. About 50% of the research area is flat to gently sloping, 35% is moderately sloping, and 15% is steeply sloping. Climate types include climate type A (Schmidt & Ferguson). Average rainfall is 3,804 mm year$^{-1,}$ and forest days average 182 days year^{-1}. The highest rainfall is from October to January, and the lowest from May to September. The altitude ranges from 70 m to 140 m above sea level (PT Sarmiento Parakantja Timber 2021).

2.2. Research Design

The 10-ha research area was selected based on the following criteria: has good access; is a degraded tropical natural forest; has a wood volume of commercial tree species of less than or equal to 20 m^3 ha^{-1} for trees with diameter at breast height (DBH) ≥ 40 cm; and its topography consists mostly of flat to medium slope (0–25%). The transect survey method, with a transect size of 20 m × 500 m and 10 transects, was then used to collect data on contour lines, tree species, tree diameter, and the locations of trees with a DBH ≥ 10 cm. Hence, contour lines and tree locations in research areas were mapped with a scale of 1:500 (Elias and Simangunsong 2023).

Artificial gap areas were designed on the contour lines and tree locations map according to criteria: maximum total gap areas are 40% of the total research area (Elias and Simangunsong 2023); a gap is located in an open and less productive forest area with a maximum area of 2,000 m^2; the shape of the gap is rectangular with a length of 50 m and a width of 40 m. There are 16 artificial gap areas, distributed across the 10-ha study area (**Fig 1**). As a comparison, the size of artificial gaps for enrichment planting in tropical natural forests in Quintana Roo, Mexico, ranges from 400–1,800 m^2 (Navarro-Martínez et al. 2017), and the management of the lowland dipterocarp forests with a gap felling silvicultural system ranges from 250–2,500 m^2 (Raharja et al. 2021).

Artificial gap areas were constructed by cutting off all trees inside the gap area boundary, except for a commercial tree species with a DBH ≥ 20cm and a protected tree species. Clearing the gap speeds up the rehabilitation process and increases forest productivity. The trick is to mimic the succession process by increasing the intensity of light entering the stand, thereby creating a suitable microclimate during the succession phase. The small trees that are felled are not transported out; instead, they are used to conserve soil and water by creating erosion-prevention pathways. Soil erosion prevention bulkhead lines and crop strips were then constructed inside these areas in the east-west direction. Soil erosion prevention bulkhead lines are lines of logs and branches from the waste of the gap opening, and are located among crop strips. Crop strips were designated for tree planting at a spacing of 4 m × 5 m. After which, seedlings of white jabon (*Anthocephalus cadamba* Miq.) were planted in the crop strips area (Elias and Simangunsong 2023).

White jabon was chosen because it is a local tree species widely found in research areas and natural forests in Indonesia, is fast-growing, and is a commercial tree species that sells well in the market (Sari and Hamzari 2021). It can be used as a raw material for plywood, furniture, pulp and paper, and other wood-processing industries (Purwoko et al. 2023). Moreover, white jabon has advantages, including adaptability to various growth sites, relatively easy silvicultural treatment and relative resistance to pests and diseases (Martias et al. 2021; Sari and Hamzari 2021; Sarjono et al. 2017b).

2.3. Data Collection

To monitor the evolution of the forest over time, 16 artificial gap units were inventoried four times: May 2021 (I1), October 2021 (I2), May 2022 (I3), and November 2022 (I4). Data on the number of live and dead trees, tree diameter, and tree height were then collected. Other data, such as the cost of gap planting per ha, were obtained from the cost analysis based on total working time and total cost per hour incurred during the work stages. This total cost consists of mechanical equipment (an excavator), manual tools (machetes, hoes, and others), material costs (fertilizer and seedlings), and workers' wages.

2.4. Data Analysis

Based on collected data, the mortality rate, number, diameter and height increment of live trees and the potential wood-harvest volume per tree and per hectare were determined. Formulas to determine the mortality rate (MR), diameter increment (MAI_d) and height increment (MAI_h) of live trees, and harvest volume per hectare are presented in Equations 1–4.

$$MR = \frac{\sum_{i=1}^{g} m_i/M_i}{g} \tag{1}$$

$$MAI_d = d_{i2} - d_{i1} \tag{2}$$

$$MAI_h = h_{i2} - h_{i1} \tag{3}$$

$$V = \frac{1}{4}\pi D^2 HN \tag{4}$$

where M_i and m_i are the number of planted and dead trees in the i^{-th} gap area, respectively; g is the number of gap areas; d_{i1} and d_{i2} are, respectively, the tree diameter at the initial and the final measurements in the i-th gap area, whereas h_{i1} and h_{i2} are, respectively, the tree height at the initial and the final measurements in the i^{-th} gap area; and *D, H* and *N* are diameter, height, and number of trees per hectare, respectively.

Further, investment and economic analyses, as described in Buongiorno and Gilles (2003), Klemperer (1996), and Zhang and Pearse (2025), were conducted. These analyses would determine the net present value (NPV), internal rate of return (IRR), benefit-cost ratio (BCR), and land expectation value (LEV), or willingness to pay for land (WPL), as well as the social and economic impacts of the application of gap planting. Formulas to determine NPV, IRR, BCR, and LEV are presented in Equations 5–8.

$$NPV = \sum_{t=0}^{n}\left[\frac{B_t - C_t}{(1+r)^t}\right] \tag{5}$$

$$IRR = \sum_{t=0}^{n}\left[\frac{B_t - C_t}{(1+IRR)^t}\right] \tag{6}$$

$$BCR = \frac{\sum_{t=0}^{n} B_t/(1+r)^t}{\sum_{t=0}^{n} C_t/(1+r)^t} \tag{7}$$

$$LEV = -c + \frac{wv_R - c}{(1+r)^R - 1} \tag{8}$$

where B_t is the economic benefit in year *t* and C_t is the corresponding cost; *r* is the real interest rate, expressed as a fraction per year; *n* is the duration of the project, in years; *R* is a rotation age in years; V_R is the harvest volume per hectare at rotation age; w is the price of timber, per unit of volume, net of harvesting cost; and c is the initial cost of establishing the forest or the cost of reforestation per hectare. The IRR is the particular value of r that solves the second equation above.

3. Results and Discussion

3.1. Mortality, Growth, and Harvest Volume

Based on the four inventories conducted, the initial and cumulative numbers of trees and dead trees in 16-unit artificial gaps are shown in **Table 1**. The initial number of trees ranged from 84 to 117 per gap, with an average of 96, and the cumulative number of dead trees at the fourth inventory (I4) ranged from 6 to 47 per gap, with an average of 29. This implies a medium mortality rate of 6–43%, with an average of 30%. The causes of tree mortality include insect attacks (such as grasshoppers and caterpillars), fungal infections, and tree failure caused by soil saturation or strong winds.

Table 1. Initial number of trees, cumulative number of dead trees, and mortality rate, by gap number and forest inventory

Gap number	Initial number of trees	Cumulative dead trees at:				Mortality rate (%)
		I1	I2	I3	I4	
1	84	0	12	27	36	43
2	93	0	10	16	18	19
3	94	0	12	30	38	40
4	94	0	16	28	37	39
5	94	0	9	16	31	33
6	96	0	9	15	23	24
7	94	0	13	17	21	22
8	98	0	3	6	6	6
9	96	0	5	14	14	15
10	94	0	13	13	22	23
11	97	0	3	19	22	23
12	97	0	19	31	39	40
13	117	0	20	42	47	40
14	96	0	20	31	41	43
15	96	0	22	25	33	34
16	96	0	10	26	36	38
Average	96.0	0.0	12.3	22.3	29.0	30

Notes: I1, I2, I3, and I4 represent the first, second, third, and fourth inventories, respectively.

Based on observed live trees after four inventories, average diameter and diameter increment in 16-unit artificial gaps were calculated (**Table 2**). The average diameter of trees ranged from 0.05 to 0.53 cm with a grand average of 0.44 cm in the first inventory (I1) and ranged from 3.45 to 9.19 cm with a grand average of 6.14 cm in the fourth inventory (I4). This implies that the diameter increment ranged from 2.00 to 5.82 cm year^{-1}, with an average of 3.80 cm year^{-1}.

Further, the average tree height and tree height increment in 16-unit artificial gaps are shown in **Table 3**. The average height of the trees ranged from 28.00 to 51.72 cm with a grand average of 34.09 cm in the first inventory (I1) and ranged from 353.48 to 759.33 cm with a grand average of 523.77 cm in the fourth inventory (I4). This implies that height increment ranged from 209.67 to 485.73 cm year^{-1} with an average of 326.45 cm year^{-1}.

Table 2. Average diameter and diameter increment of live trees after four inventories, by gap number

Gap number	Average diameter (cm) at:				Increment (cm year^{-1})
	I1	I2	I3	I4	
1	0.49	1.79	4.55	6.54	4.03
2	0.53	1.93	5.00	7.54	4.67
3	0.05	2.04	4.91	6.87	4.54
4	0.50	2.00	3.63	5.99	3.66
5	0.43	2.47	4.62	6.55	4.08
6	0.47	1.86	4.15	5.06	3.06
7	0.49	2.17	3.91	5.45	3.31
8	0.29	2.21	5.55	6.75	4.31
9	0.44	2.38	5.68	7.29	4.57
10	0.48	1.87	4.51	6.23	3.84
11	0.46	2.15	6.23	9.19	5.82
12	0.52	2.43	3.19	4.39	2.58
13	0.46	2.38	3.74	5.64	3.45
14	0.45	1.74	2.90	3.45	2.00
15	0.46	2.29	3.47	4.90	2.96
16	0.52	1.99	4.02	6.43	3.94
Standard deviation	0.12	0.24	0.93	1.36	0.92

Notes: I1, I2, I3, and I4 represent the first, second, third, and fourth inventories, respectively.

Table 3. Average height and height increment of live trees after four inventories, by gap number

Gap number	Average height (cm) at:				Increment (cm year^{-1})
	I1	I2	I3	I4	
1	28.00	116.43	222.50	544.17	344.11
2	51.72	106.51	265.87	714.93	442.14
3	29.29	130.48	289.34	598.57	379.52
4	34.40	125.96	222.37	480.35	297.30
5	31.67	142.30	263.66	417.30	257.09
6	33.53	135.85	238.59	518.08	323.03
7	33.78	120.24	239.33	510.96	318.12
8	29.45	136.54	322.91	607.12	385.11
9	28.42	103.14	281.89	504.02	317.07
10	35.60	76.58	261.14	515.38	319.85
11	30.73	125.27	345.71	759.33	485.73
12	51.40	114.20	208.31	365.91	209.67
13	28.55	84.43	221.87	387.57	239.35
14	32.49	76.94	183.33	404.73	248.16
15	30.26	98.05	214.67	353.48	215.48
16	36.10	104.10	248.73	698.33	441.49
Standard deviation	7.29	20.82	42.84	125.43	83.31

Notes: I1, I2, I3, and I4 represent the first, second, third, and fourth inventories, respectively.

The average diameter and height of the white jabon tree in this study are smaller than those reported by Sarjono et al. (2017a, 2017b) for the PT Intraca Hutani Lestari area in East Kalimantan. Sarjono et al. (2017a, 2017b) found that the diameter and height of a 1-year-old white jabon tree were, respectively, 5 cm and 300 cm; and the diameter and height of a 3-year-old white jabon tree were, respectively, 13 cm and 440 cm.

With regard to diameter and height increments of jabon tree, this study's results are larger than those found by Purwoko et al. (2023), which were 2–3 cm year^{-1} and 2–3 m year^{-1}, respectively. The diameter increment of white jabon in this study is almost the same as the diameter increment of white jabon in Rokan Hulu Regency, Riau, which was 3.30 cm $year^{-1}$ (Rahmayanti 2016). According to Junaedi (2018), some research results showed that the growth of white jabon height and diameter in the age range of 2–4 years ranged from 1.62–4.21 m $year^{-1}$ and 2.03–5.25 cm $year^{-1}$, respectively. In addition, Sari and Hamzari (2021) reported that measurements of 4- and 5-year-old white jabon trees planted in Wulai Village, West Sulawesi Province, and Rerang Village, Central Sulawesi Province, showed average diameters of 16.08 and 21.43 cm, average heights of 10.64 and 15.65 m, and stand volumes of 92.71 and 209.45 m^3 ha^{-1}, respectively.

Conservative estimates of height, diameter, volume per tree, and harvest per hectare of gap white jabon plantation at the ages of 6.7 and 8 years are presented in **Table 4**. The estimated height of the white jabon tree at ages 6.7 and 8, based on the average height growth, was, respectively, 19.59 m, 22.85 m, and 26.12 m. In contrast, the estimated diameters based on average diameter growth were 23 cm, 27 cm, and 30 cm. Hence, estimates of volume per tree were 0.50 m^3, 0.80 m^3, and 1.20 m^3, respectively, and harvest volume per hectare at a rotation age was, respectively, 176.56 m^3, 280.36 m^3, and 418.50 m^3. The estimated average diameter for 6–8-year-old white jabon trees in this study was similar to that simulated by Sarjono et al. (2017a), ranging from 23.5 to 31.0 cm. Meanwhile, harvest volume per hectare for 6-8-year-old white jabon trees in this study was higher than that simulated by Sarjono et al. (2017a), ranging from 150.64 to 199.60 m^3.

Table 4. Conservative estimates of height, diameter, volume per tree, and harvest per hectare of gap plantation at PT Sarmiento Parakantja Timber by rotation age

Rotation (year)	Height (m)	Diameter (cm)	Volume per tree (m^3)	Volume per hectare (m^3/ha)
6	19.59	23	0.50	176.56
7	22.85	27	0.80	280.36
8	26.12	30	1.20	418.50

Notes: It is assumed that only 90% of the tree height is used to calculate volume per tree with white jabon's artificial form factor of 0.70.

3.2. Investment and Economic Analysis of Gap Planting

The economic feasibility of the gap planting business with white jabon trees is based on 1 ha of white jabon trees, with a cutting rotation of 6, 7, or 8 years. The cost of gap planting per ha was obtained from the cost analysis based on total working time and total cost per hour incurred in completing the stages of work, which consists of the cost of using mechanical equipment (excavator) and manual tools (machetes, hoes, and others), material costs (fertilizer and seedlings), and workers' wages. The business expenses include planting costs and maintenance costs for years 1, 2, and 3, totaling IDR 11.83 million ha^{-1}, IDR 9.55 million ha^{-1}, IDR 9.55 million ha^{-1}, and IDR 6.37 million ha^{-1}, respectively. After that, the plants are left until they reach a cutting rotation. Assuming a management cost of 20%, the total cost of gap planting in one rotation was IDR 44.76 million ha^{-1}.

Meanwhile, revenue was generated from the sale of jabon logs at a stumpage price of IDR 0.75 million per m^3. This chosen stumpage price was plausible, as the local price of jabon wood in 2020 ranged from IDR 0.70–1.20 million per m^3 for logs, depending on diameter. The overall cost of harvesting jabon wood (logging, loading, and local transportation) in 2020 ranged from IDR 0.15–0.25 million per m^3, depending on the distance from the forest to the wood collection point. In this economic analysis, the year 2020 is chosen as the base year (Year-0). Minimum acceptable rate of return (MAR) is assumed to be 8% year^{-1}. In Indonesia, the social discount rate (SDR) is used for public policy and is typically inflation-free, making it a real discount rate. This SDR ranges from 6–12% (i.e., 6–7% by the Indonesian government, 9% by the Asian Development Bank, and 10–12% by the World Bank). It is reasonable to select 8% as the real MAR. The results of the investment and economic analyses were presented in **Table 5**.

Table 5. Economic analysis results of the gap planting business with white jabon trees

Item	Unit	Scenario		
		A	B	C
Rotation	year	6	7	8
Harvest volume	m^3 ha^{-1}	176.56	280.36	418.50
Real discount rate	% year^{-1}	8%	8%	8%
Real stumpage price	IDR million m^{-3}	0.75	0.75	0.75
Costs (including management costs)				
Year-0: Planting	IDR million ha^{-1}	14.19	14.19	14.19
Year-1: Maintenance (every 3 months)	IDR million ha^{-1}	11.46	11.46	11.46
Year-2: Maintenance (every 4 months)	IDR million ha^{-1}	11.46	11.46	11.46
Year-3: Maintenance (every 6 months)	IDR million ha^{-1}	7.64	7.64	7.64
Revenue				
Year-6: Harvesting	IDR million ha^{-1}	132.42	–	–
Year-7: Harvesting	IDR million ha^{-1}	–	210.27	–
Year-8: Harvesting	IDR million ha^{-1}	–	–	313.88
Investment criteria				
Net present value (NPV)	IDR million ha^{-1}	42.75	81.99	128.88
Benefit-cost ratio (BCR)	–	2.05	3.01	4.17
Irate of return (IRR)	% year^{-1}	25.08%	30.16%	32.72%
Land expectation value (LEV)	IDR million ha^{-1}	115.59	196.86	280.34
Labor creation	man-day ha^{-1}	106	106	106

Table 5 shows that the gap planting business with white jabon is financially and economically very feasible across all scenarios: NPVs are ≥ 0, B/C is ≥ 1, and IRR is ≥ MAR. The cost of planting 1 ha of white jabon trees, with a rotation of 6, 7, or 8 years, totaled IDR 44.76 million. A sensitivity analysis was also conducted to examine the effects of changes in stumpage price and the discount rate on NPV and LEV. For the white jabon planting business with a 6-year cutting rotation, the results are shown in **Tables 6** and **7**. **Table 6** indicates that the NPV is more sensitive to changes in the stumpage price than to changes in the discount rate. Given the stumpage price and other things being the same, the NPV would decrease from IDR 42.75 million ha^{-1} to IDR 21.89 million ha^{-1} if the stumpage price were decreased by 25%. In contrast, the stumpage price held constant, a 25% increase in the discount rate from 8% to 10% year^{-1} changes the NPV from IDR 42.75 million ha^{-1} to IDR 34.92 million ha^{-1}. **Table 7** shows that the LEV is also more sensitive to changes in the stumpage price than to changes in the discount rate. Given the stumpage price and other things being the same, the LEV would decrease from IDR 115.59 million ha^{-1} to IDR 59.18 million ha^{-1} if the stumpage price were decreased by 25%. In contrast, the stumpage price held constant, a 25% increase in the discount rate from 8% to 10% year^{-1} changes the LEV from IDR 115.59 million ha^{-1} to IDR 80.18 million ha^{-1}. Based on investment criteria (NPV, BCR,

and IRR) and economic value (LEV), planting 1 ha of white jabon trees with an 8-year rotation was the most profitable and had the highest economic value.

Table 6. Impacts of stumpage prices and discount rate changes on NPV

Stumpage price changes	Discount rate changes				
	-50%	-25%	0%	25%	50%
-50%	9.72	5.05	1.03	-2.45	-5.46
-25%	35.89	28.39	21.89	16.24	11.31
0%	62.05	51.73	42.75	34.92	28.09
25%	88.21	75.07	63.61	53.61	44.86
50%	114.38	98.40	84.47	72.30	61.63

Table 7. Impacts of stumpage prices and discount rate changes on LEV

Stumpage price changes	Discount rate changes				
	-50%	-25%	0%	25%	50%
-50%	46.37	17.13	2.78	-5.63	-11.06
-25%	171.15	96.23	59.18	37.28	22.93
0%	295.92	175.33	115.59	80.18	56.93
25%	420.70	254.43	172.00	123.09	90.92
50%	545.47	333.53	228.41	166.00	124.92

Regarding the white jabon planting business with a 6-year cutting rotation, the results of this study are consistent with those of the feasibility study on multi-business gap planting with jabon conducted by Elias et al. (2020). They found that planting 1 ha of jabon trees with a 6-year cutting rotation produced around 134.6 m^3 ha^{-1}, incurred a total cost of IDR 40.7 million $ha^{-1,}$ and generated revenue of IDR 80.8 million ha^{-1}. Further, they found that the white jabon planting business was financially feasible, with an NPV of IDR 16.2 million ha^{-1}, BCR of 1.65, and IRR of 34.7% $year^{-1}$.

3.3. Social and Economic Impacts

The gap planting business requires at least 106 man-days ha^{-1} of labor. This labor is required for gap-making activities, planting, maintenance, pest and disease control and harvesting jabon trees. Indirect employment will also be available in activities that support the inputs and outputs of the gap planting business and the wood-processing industry. In addition to increasing community and government incomes, the gap planting business plays an important role in the equitable distribution of people's income. People who previously lived at a subsistence level may increase their income by working in this business. People who previously had no opportunity to do business now have an incentive to try to make a profit. These results were in line with the study by Elias and Simangunsong (2023) at PT Intraca Manufacturing, in North Kalimantan Province, Indonesia, which state completed gap planting to rehabilitate degraded natural tropical forests, required 24 man-days per ha and generated a wage of IDR 2,842,608. This could provide employment and income, thereby supporting the livelihoods and well-being of communities surrounding the rehabilitation forest area in Indonesia. Moreover, infrastructure development by the gap planting business is a very important means of income distribution. With the infrastructure in place, the population’s mobility will be high. Hence, business opportunities will become more accessible to many community members.

The gap planting business with jabon is expected to contribute to regional economic development. The cost of jabon plantation of IDR 44.76 million ha^{-1} can be considered net value added because almost all of this cost is used to pay for domestic production factors and there are no-leakages, especially for the import of capital goods and foreign experts; thus, cost of jabon plantation multiplied by the area being cultivated is a contribution of the gap planting business to the regional gross domestic product (RGDP). Since the government has decided to provide legal access to 1.1 million ha of the social forestry program annually from 2026–2030 and there is a need to accelerate the rehabilitation of degraded forests, the gap planting business activity would be large enough, whether applied within an agroforestry system or not (Roslinda et al. 2023; Samrin et al. 2024), making its role in regional economic growth important.

In general, the socio-economic impacts of the community from the implementation of gap planting with white jabon tree in degraded natural forest areas include: increasing wood production and production of the wood processing industry; providing employment; increasing community income; increasing government revenue from business taxes, business licenses, income taxes, forest resources royalty provision, and exports that can generate foreign exchange. In contrast, degraded lands in the production forests must be immediately rehabilitated so that forest productivity increases and the area of forest cover will also increase; otherwise, they can become a source of conflict, threatening social, economic, and environmental stability (Nurrochmat et al. 2020; Purwawangsa et al. 2021; Silalahi et al. 2025; Suryanto et al. 2024). This implies that potential benefits of implementing gap planting include: reducing land conflicts in forest areas; improving the livelihoods and socio-cultural activities of forest communities; improving environmental conditions; and reducing disasters resulting from forest destruction.

4. Conclusions

The application of gap planting technology to rehabilitate tropical natural forests did not harm the environment. On the contrary, it could create jobs for local communities and increase the productivity and economic value of degraded natural forests. Based on these results, it is concluded that gap planting technology using the white jabon tree in the forest concession area of PT Sarmiento Parakantja Timber in Central Kalimantan is financially, socio-culturally, and economically feasible under the assumptions used. The application of gap planting technology can also accelerate the rehabilitation of degraded forests. Since 2023, the Government of the Republic of Indonesia has provided access to PS permits in a fairly large area of natural forest. In implementing this PS program, it is recommended to develop and apply gap planting technology to ensure the program has environmentally friendly impacts.

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B.C.H.S.: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft Preparation, Writing – Review and Editing, Supervision; E.: Conceptualization, Methodology, Software, Validation, Writing – Review and Editing, Visualization, Project

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Conflict of Interest

The authors declare no conflict of interest.

Declaration of Generative AI And AI-Assisted Technologies in the Manuscript Preparation

Not applicable.

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