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Potential of carbon sequestration enhancement through intensive silvicultural techniques using *Shorea leprosula* plantation in Central Kalimantan, Indonesia

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Abstract. *Iskandar M, Siregar IZ, Krisnawati H. 2023. Potential of carbon sequestration enhancement through intensive silvicultural techniques using* Shorea leprosula *plantation in Central Kalimantan, Indonesia. Biodiversitas 24: 4699-4513.* Various sectors are involved in achieving Indonesia's Enhanced Nationally Determined Contribution (NDC), including Forestry and Other Land Uses (FOLU) sector. Sustainable Forest Management (SFM) implementation by forest concessionaires (PBPHs) enormously contributes to land-based mitigation activities, primarily at the local level. One of the SFM activities is forest enrichment with Intensive Silvicultural (SILIN) technique using *Shorea leprosula* Miq. to enhance carbon stock and sequestration. This study was conducted in PT Sarmiento Parakantja Timber (PT Sarpatim) in Central Kalimantan and used the measurement data from 32 purposive sampling plots. Each plot was 40 × 40 m in size, constructed under three different SILIN patterns (conventional strip, effective strip, and gap) as well as natural forest stands. This study found that SILIN gap pattern had higher carbon stock and sequestration potential, compared to the natural forest (reference) stands, and reached a net sink condition after 30 years. For the stands of SILIN conventional and effective strip patterns, the carbon stocks were lower than the reference stand, even when the vegetation aged 30 years. PBPHs applying SILIN technique as part of the SFM and the mitigation actions demonstrate an enhanced carbon stock and sequestration. This effort supports Indonesia's Enhanced NDC target and FOLU Net Sink 2030.

Keywords: Carbon, Dipterocarpaceae, intensive silvicultural techniques, mitigation, SILIN, sustainable forest management

INTRODUCTION

Climate change has emerged as a central concern in the international forums, prompting many countries to engage in concerted efforts aimed at mitigating global greenhouse gas (GHG) emissions. Among these nations, Indonesia stands as a committed participant, demonstrating a robust dedication to this cause through climate change mitigation and adaptation plans. This steadfast commitment was consolidated by Indonesia's submission of an Enhanced Nationally Determined Contribution (NDC) to the United Nations Framework Convention on Climate Change (UNFCCC) secretariat on September 23, 2022. Notably, Indonesia's Enhanced NDC reflects an augmented aspiration for emission reduction targets. Specifically, these targets have been revised from 29% to 31.89% in the unconditional scenario and from 41% to 43.20% in the conditional mitigation scenario (MoEF 2022a). The attainment of the NDC objective involves various sectors, with the forestry and Other Land Uses (FOLU) sector holding the most ambitious emission reduction targets compared to other sectors, amounting to 17.4% in the unconditional scenario and 25.4% for the conditional scenario).

The climate change mitigation action requires involvement from various stakeholders, including the Management Units operating under the forest concessionaires (PBPH). Indonesia's production forests cover a total area of 68.8 million ha, with 34.18 million ha allocated to different types of PBPH (MoEF 2022b). Recognizing the vital role of forests in storing and sequestering carbon, these ecosystems inherently contribute to substantial reduction of carbon emissions (Shi et al. 2022), thus helping in mitigating climate change (Mildrexler et al. 2020). The adoption of the Sustainable Forest Management (SFM) practices by the PBPHs contributes significantly to climate change mitigation, in terms of augmentation of carbon stocks and subsequent reduction of emissions (Hilwan et al. 2012).

One of the efforts in forest management that could enhance productivity and carbon stocks is enrichment planting (Sasaki et al. 2011) using native species of Indonesia's tropical forests (Widiyatno et al. 2013a; Widiyatno et al. 2020). The advantage of conducting enrichment planting in PBPH is to enhance sustainable timber production and conserve species of Dipterocarps (Widiyatno et al. 2013a). Dipterocarps are commercial and dominant, playing a crucial role in emission reduction, climate protection, and contributing significantly to tropical biodiversity (Naiem et al. 2016). This silvicultural system has been refined through various approaches, including enrichment techniques, environmental modifications, and integrated pest control, recognized as Intensive Silvicultural Technique (SILIN) (Lamis and Muhdin 2019). The SILIN technique is a novel approach derived from the previous Selective Logging and Strip Planting (TPTJ) system, aimed at increasing forest productivity. SILIN can enhance forest productivity by utilizing high-quality seeds, optimizing the environment, and managing pests and diseases (Naiem et al. 2016; Brancalion et al. 2019). The species commonly employed in enrichment planting using SILIN technique is *Shorea* spp.

Forests play a critical role in climate change mitigation, a global concern amplified with the introduction of the Clean Development Mechanism (CDM) and Reducing Emissions from Deforestation and Forest Degradation (REDD) within the carbon trading framework (Dharmawan and Ridwan 2022). The REDD scheme gained substantial traction during the COP-13 UNFCCC in Bali. Notably, there has been significant interest in participating in the carbon credit mechanism for emission reductions efforts through the prevention of deforestation, forest degradation, and enhancement of forest carbon stocks (Sasaki et al. 2011). PBPHs implementing SFM can reap economic benefits from carbon trading by accruing carbon emission reductions from forest management activities (Hilwan et al. 2012). The economic advantages linked to forest carbon offer financing incentive supporting the FOLU Net Sink action within PBPH. Effectively managing and utilizing the environmental services of forests as carbon stores and sinks is important to achieving emission reduction targets within the FOLU sector, aligning with Indonesia's Enhanced NDC and FOLU Net Sink 2030 objectives. Consequently, the assessment of total carbon stock and carbon sequestration resulting from planting *Shorea leprosula* using the SILIN technique becomes indispensable. This study aims to estimate the total carbon stock and carbon sequestration derived from implementing SILIN as an integral part of the SFM mechanism.

MATERIALS AND METHODS

Study area

This study was conducted in the forest concession area (PBPH) PT Sarmiento Parakantja Timber (PT Sarpatim), situated in the Central Kalimantan Province at the coordinates of 111°55' - 112°19' E and 1°12' - 1°56' S (Figure 1). PT Sarpatim is one of the PBPHs implementing SILIN, as stipulated by the Decision Letter of the Directorate General of Forestry Production Development 226/VI-BPHA/2005. The Ministry of Environment and Forestry has taken steps to enhance timber production by adopting the Indonesian Intensive Selective Cutting (TPTII) silvicultural system. This system includes felling techniques, land preparation, and tree planting (Dulsalam et al. 2018). The adoption of SILIN is primarily motivated by the aspiration to optimize forest productivity, efficiency, competitiveness, and sustainability (Lamis and Muhdin 2019). The SILIN approach, employing three planting systems - the conventional strip pattern (since 2006), the effective strip pattern (since 2014), and the gap pattern (since 2014) - has been incorporated. The main species featured in SILIN practices at PT Sarpatim is *Shorea leprosula*. A study by (Karlinasari et al. 2017) demonstrated that amongst the five studies *Shorea* spp., *Shorea leprosula* exhibited the highest growth rate. This outcome is consistent with its reputation as a fast growing *Shorea* species.

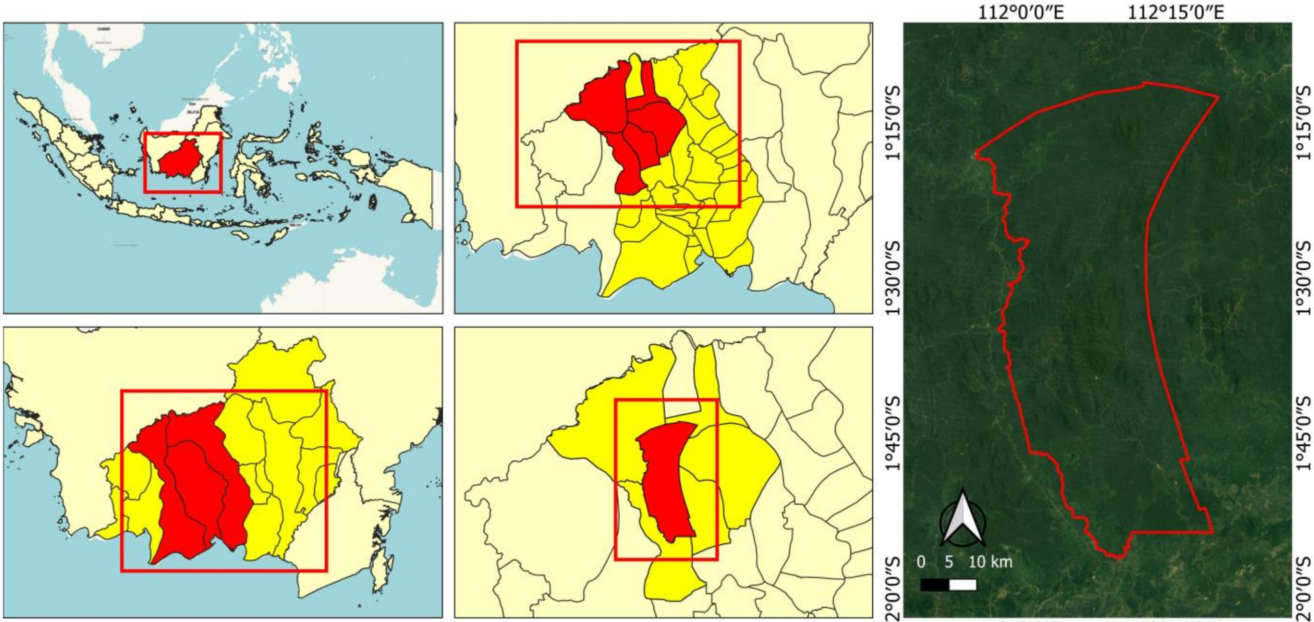


Figure 1. Research location in PT Sarpatim, Central Kalimantan, Indonesia

Data collection

Field data were collected in September 2022, which comprised the measurements of *S. leprosula* in SILIN plots and natural forests. Additionally, the data collection included the assessment of understory and litter biomass. The purposive sampling method was employed, entailing the establishment of 32 sample plots (Drescher et al. 2016). These plots comprised of 8 Permanent Measurement Plots (PUP) for the conventional strip pattern (planting period 2006-2013), 8 PUPs for the effective strip pattern (planting period 2014-2020), 8 PUP for the gap pattern (planting period 2014-2020), and 8 PUPs for natural forest (serving as reference stands). The dimensions of the sample collections plot were 40 × 40 m in size (Siregar and Dharmawan 2011). Within each plot, sub-plots were established, measuring 2 × 2 m to collect data of seedlings, understory, and litter; 5 × 5 m for sapling measurements (Adinugroho et al. 2022b); 10 × 10 m for pole measurements, and 40 × 40 m for tree measurements (Siregar and Dharmawan 2011; BSN 2019). For the *Shorea leprosula* trees situated within SILIN plots, measurements were conducted for diameter at breast height (DBH) and height (H). The non-destructive method was employed for the early-age of SILIN trees that had not undergone harvesting. Additional data were also compiled from the study area of PT Sarpatim and pertinent literature sources. The distribution of the SILIN plots across the study area and the design of the SILIN patterns are depicted in Figure 2.

The number of trees measured in the plots varied according to the age of the trees. The total number of trees measured in each SILIN plots is as follows: conventional strip pattern (218 trees), effective strip pattern (239 trees), and gap pattern (496 trees). Details on the measured *S. leprosula* trees, including average Diameter at Breast Height (DBH) and height (H) are outlined in Table 1.

Data analysis

Estimating standing biomass

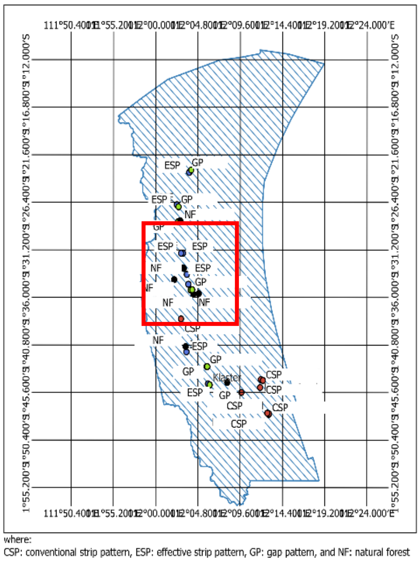
This study measured three carbon pools: aboveground biomass, litter, and belowground biomass following (Darmawan et al. 2022a). Aboveground biomass comprises the entire standing vegetation and understory (Krisnawati et al. 2014), providing a fundamental reference for evaluating forest conditions in relation to carbon and ecosystem services (Siddique et al. 2021). To estimate aboveground tree biomass, an allometric equation developed by (Siregar and Dharmawan 2011) for Dipterocarps in Central Kalimantan was used, considering the similar biophysical condition of the study area (Krisnawati et al. 2012). Allometric equations remain the most commonly utilized indirect method for estimating forest biomass (Akre et al. 2021). PBPH in Central and East Kalimantan constitute the primary habitats of species under Dipterocarpaceae. Much like the majority of allometric models developed in Indonesia (Krisnawati et al. 2012), these equations utilized tree diameter as the primary parameter for biomass estimation. The application of this model is deemed acceptable and reliable (Siddique et al. 2021). The range of tree diameters (DBH) used in developing the allometric model by Siregar and Dharmawan (2011) was 7-70 cm, involving 45 Dipterocarp tree samples; thus, making it suitable for the SILIN plots in this study. The allometric model developed by Siregar and Dharmawan (2011) is formulated as follows:

$$Y = 0.0112(DBH)^{2.6878}$$

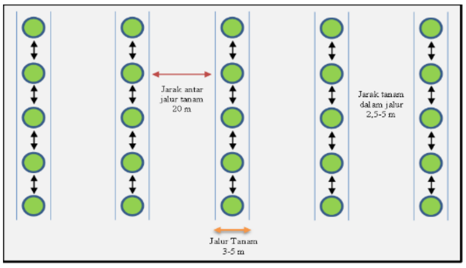
$R^2 = 0.91$

Where: Y = biomass (kg), DBH = diameter (cm)

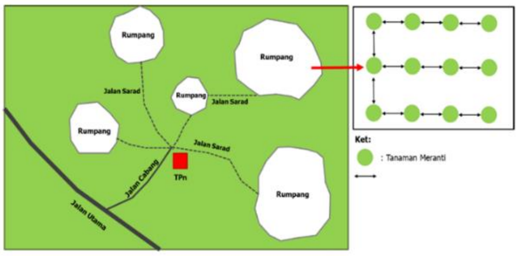
Biomass stock per hectare for SILIN plots and natural forest stands was estimated by multiplying the average biomass per tree with the average stand density, provided in Table 2.



where:
CSP: conventional strip pattern, ESP: effective strip pattern, GP: gap pattern, and NF: natural forest



A. SILIN strip pattern



B. SILIN gap pattern

Figure 2. Plots distribution in the study site and design of SILIN patterns

Understory biomass and litter were estimated from samples' wet weight and dry weight (BSN 2019), as provided in the equation as follows:

$$BTB = \frac{BKc}{BBc} \ x \ TBB$$

Where:
BTB = Understory biomass (g), BBc = Wet weight from samples (g), BKc = Dry weight from samples (g), and TBB = Total wet weight (g)

Belowground biomass was estimated using a root-to-shoot ratio (Krisnawati et al. 2014; BSN 2019), referring to the IPCC 2003 Good Practice Guidance for Land Use, Land Use Changes and Forestry. The standard formula used to calculate belowground biomass is as follows:

$$Bbp = NAP \times Bap$$

Where:
Bbp = belowground biomass (kg), NAP = root-to-shoot ratio (0.29) as referred to Krisnawati et al. (2014), and Bap = aboveground biomass (kg)

Carbon stock estimation

The potential of carbon stock was estimated from the total biomass obtained (aboveground biomass, litter, and belowground biomass), which was then converted into carbon. We used a formula from SNI 7724:2019 (BSN 2019) to derive carbon from each pool, as illustrated below:

$$Cb = B \times \% \text{ C Organic}$$

Where:
Cb = carbon from biomass (kg), B = total biomass (kg), and %C organic = percentage of carbon (47%).

After all carbon values from each pool were derived, the total carbon stock was estimated using the following equation:

$$Ctotal = \text{C aboveground} + \text{C litter} + \text{C belowground}$$

Estimating carbon sequestration

Carbon sequestration was estimated based on a conversion of carbon (C) to carbon dioxide (CO_2) equivalent. We used 3.67 as the conversion value from C to CO_2e (Siregar and Dharmawan 2011). The equation for estimating CO_2 sequestration is as follows:

$$CO_2\text{-eq} = 3.67 \times \text{C sequestration}$$

Where:
CO_2-eq = carbon dioxide sequestration value (ton/ha)

Table 1. *Shorea leprosula* trees measured in SILIN plots

No.	Plot number	Tree age (years)	Number of trees measured in the plot	Average DBH in the plot (cm)	Average H in the plot (m)
a	SILIN conventional strip pattern				
1.a	PUP 06-AD 77	16	19	24.5	25.6
2.a	PUP 09-AF 78	16	27	25.2	23.3
3.a	PUP 77-AB	16	29	19.1	9.8
4.a	PUP 79-AF a	15	21	17.7	11.7
5.a	PUP 79-AF b	15	22	18.7	15.8
6.a	PUP 41-AH 73	13	42	14.1	14.4
7.a	PUP 74-AF	12	24	10.6	11.5
8.a	PUP 44-O 91	9	34	5.9	6.9
b	SILIN effective strip pattern				
1.b	PUP 54-Q 97	8	26	10.8	10.5
2.b	PUP 55-Q 99	8	19	8.2	8.6
3.b	PUP 60-Q 85	7	17	10.2	10.6
4.b	PUP 66-V 79	6	38	7.1	8.0
5.b	PUP 76-O 103	4	39	4.4	5.2
6.b	PUP 77-P 103	4	30	3.5	4.1
7.b	PUP 81-O 112	3	47	2.9	4.1
8.b	PUP 119-R	2	23	2.0	2.5
c	SILIN gap pattern				
1.c	PUP 02-Q 96-P 05	8	64	23.1	15.9
2.c	PUP 02-R 96-P 03	8	68	22.0	14.9
3.c	PUP 01-U 82-P 01	7	58	17.8	14.5
4.c	PUP 03-U 82-P 06	7	50	17.7	13.8
5.c	PUP 02-U 78-P 02	6	56	13.9	13.3
6.c	PUP 110-N	4	62	9.1	7.1
7.c	PUP 112-O	3	77	6.3	4.0
8.c	PUP 119-R	2	61	3.7	2.5

Table 2. Trees density per hectare of SILIN and natural forests

Type	*Shorea* spp. planting		Natural forest		Total tree density per ha
	Tree density per ha	Increment DBH (cm/yr)	Tree density per ha	Increment DBH (cm/yr)	
SILIN conventional strip pattern	170	2.6	509	0.6	679
SILIN effective strip pattern	187	1.5	623	0.6	810
SILIN gap pattern	388	3.1	0	0	388
Natural forest	0	0	1335	0.6	1335

Note: SILIN conventional strip pattern and SILIN strip pattern can be effectively planted in all log over areas (LOA). SILIN gap pattern can be effectively planted in a maximum of 20% of log over areas (LOA). Average stand densities of natural forests in SILIN's conventional strip pattern and SILIN's effective strip pattern were derived from the company's harvest data under 1 ha of PUP. The average stand density of the natural forest (1335 trees/ha) was obtained from the study conducted by Siregar and Darmawan (2011), based on measurements from three plots. Increment in DBH of SILIN and natural forest stands was based on company's PUP data

Predicting carbon in one cycle of SILIN stands

Predicting carbon accumulation over a single cycle of SILIN stands (25 years) is essential for evaluating the potential of SILIN stands in enhancing carbon stock and sequestration. A higher carbon stock value of SILIN vegetation compared to natural forest indicates a net sink condition. Field measurements of SILIN vegetation encompassed vegetation ranging from 2 to 16 years. Subsequently, the DBH data of *S. leprosula* were used to derive a linear regression model for estimating SILIN tree diameter within the age range of 1 to 30 years. The linear regression models, representing depicting the relationships between age (y) and diameter (x) are presented in Table 3.

RESULTS AND DISCUSSION

Standing biomass estimation under SILIN system and natural forest

Since 1969, PT Sarpatim has been managing the natural production forest in Central Kalimantan. According to the company's data, 83.9% of the forest area is categorized into four potential production classes: high, moderate, low, and extremely low (Suryanto et al. 2018). The high and moderate potential areas are predominantly situated within the primary forest in the northern part, while the low potential areas are found in the southern region. The regions identified as having moderate potential have been recommended for implementing the SILIN strip pattern to support biodiversity conservation, whereas the low potential areas are designated for the SILIN gap pattern to enhance forest productivity, promote vegetation recovery, and improve environmental conditions. The implementation of SILIN is anticipated to amplify the productivity of the harvested wood. However, the practice of harvesting trees with large diameters specified for a single species could potentially lead to a 50% reduction in aboveground biomass within the ecosystem (Mildrexler et al. 2020).

The SILIN technique, implemented at PT Sarpatim integrates three harvesting systems: the conventional strip pattern, effective strip pattern, and gap pattern. This technique of applied in the natural production forest of the PBPH, particularly in logged-over forests with good accessibility. Intensive silviculture has the potential to mitigate forest-level risks associated with drought, fires, diseases, insects, and other disturbances, all of which could be exacerbated by climate change (Pinno et al. 2021). Both the SILIN conventional and effective strip patterns were introduced within the area of the TPTJ system, serving as post-harvest enhancement and natural regeneration strategies. The adoption of the SILIN approach within the TPTJ framework aims to rehabilitate and augment the productivity of logged-over areas (LOAs) in tropical rainforests by employing an enrichment planting pattern of commercially valuable forest plant species (Karmilasanti and Wahyuni 2018). Notably, the SILIN effective strip pattern was developed as an improvement over SILIN conventional pattern. Tree harvesting under these patterns leads to a reduction of 30-50 % in the forest vegetation stands, indicating a moderate level of forest disturbance (Girona et al. 2023). Additionally, the SILIN gap pattern was applied to secondary production forests that had experienced partial degradation, such as ex-timber collection areas, among others. The natural forest and SILIN stands at PT Sarpatim are represented in Figure 3.

SILIN planting distance for each planting pattern varies in PT Sarpatim. The SILIN strip pattern employs a planting distance of 2.5 m in rows, while the SILIN gap pattern utilizes a spacing of 5 × 5 m. In the strip pattern planting, a line gap of 3 m (constituting 15% of the total area) and a distance of 17 m between lines (comprising 85% of the total area) are implemented. This arrangement serves to maintain and support biodiversity through in-situ conservation efforts and to ensure optimal sunlight exposure (Widiyatno et al. 2013b; Naiem et al. 2016). Recognizing the interconnections of biodiversity and climate change, a coordinated approach focusing on landscapes can yield multiple benefits (Adinugroho et al. 2021). Regarding the ecological aspect of the production forest, the stand condition in the logged-over area remains suitable for productive forest activities in the subsequent rotations. For SILIN implementation, PT Sarpatim predominantly employs *Shorea leprosula*. The results obtained from data analysis for the three SILIN patterns show the relationships between diameter and stand age, and biomass (aboveground), as depicted in Figure 4.

A positive relationship is evident between the diameter and biomass of SILIN vegetation (Figure 4). A larger diameter of SILIN vegetation corresponds to a more pronounced positive correlation with biomass increment. As the SILIN vegetation progresses through its final cycle (25 years of age), is exhibits increase in biomass production. The age of the vegetation demonstrates a high correlation factor of 95.9% with biomass potential, indicating a strong correlation (Hardiansyah 2011). The alternation in vegetation carbon stock after one cycle (25 years) is linked to the incremental biomass of SILIN vegetation. The growth in vegetation age demonstrates a linear correlation with an augmented capacity of vegetation to sequester carbon, eventually reaching an equilibrium state (Li et al. 2022). Lamis and Muhdin (2019) have revealed that *Shorea leprosula*, in comparison to the other *Shorea* species, displays a diameter increment that is 1.6 cm higher and height increment that is 1.49 m greater, with a survival rate of 77.8%. The selection of *Shorea leprosula* for SILIN practice at PT Sarpatim is deemed suitable. Study by Widiyatno et al. (2013a) has shown that *Shorea leprosula* reaches *Shorea leprosula* achieves an annual diameter increment of around 2.2 cm/year and height increment of around 1.32 m/year, by the time it reaches 6.5 years of age.

Table 3. Linear regression models to estimate the relationship between SILIN tree age and diameter

SILIN tree	Linear regression model	R^2
SILIN conventional strip pattern	y = 2.6171 × - 18.873	0.82
SILIN effective strip pattern	y = 1.4744 × - 1.4196	0.89
SILIN gap pattern	y = 3.1063 × - 3.1448	0.95

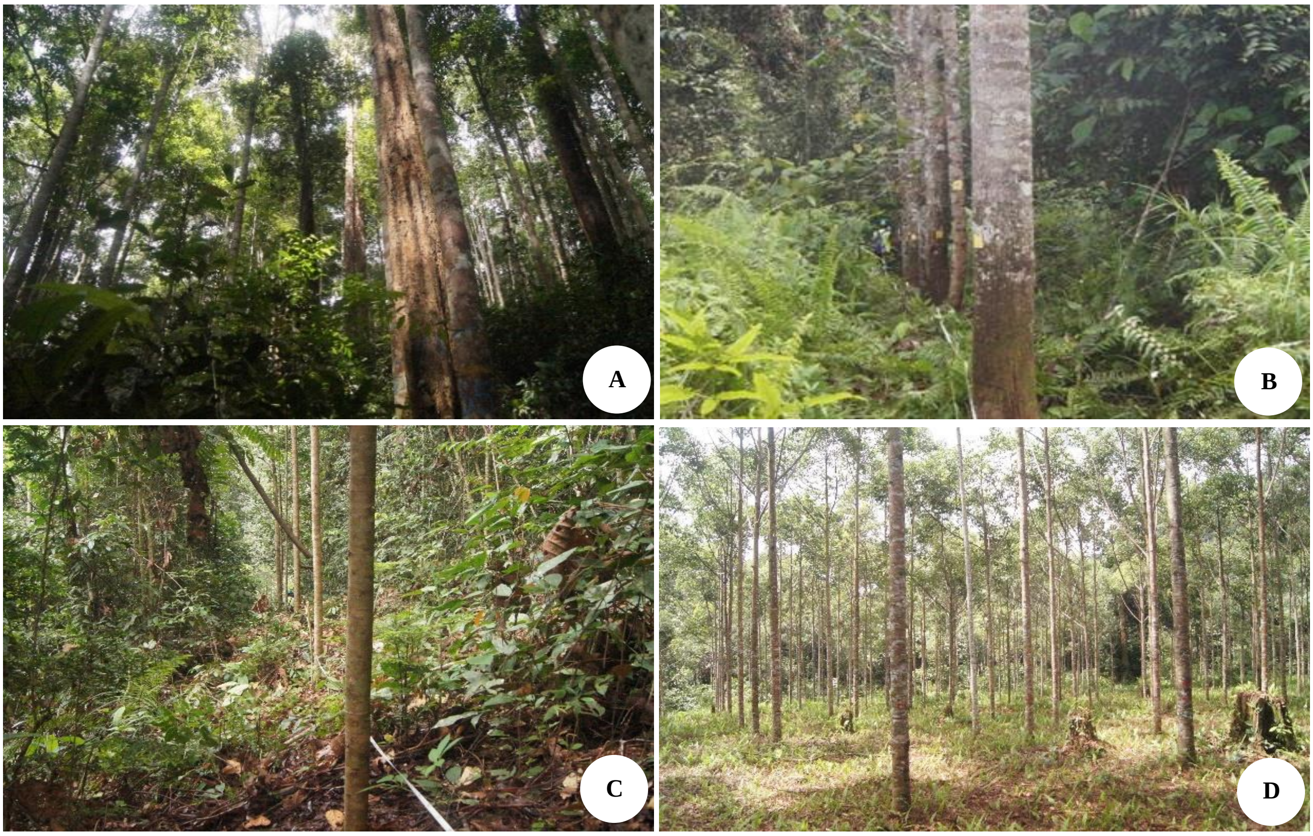


Figure 3. Natural Forest and SILIN stands in PT Sarpatim. A. Natural forests, B. SILIN stand with the conventional strip pattern (16 yrs.), C. SILIN stand with the effective strip pattern (8 yrs.), D. SILIN stand with the gap pattern (8 yrs.)

Forest biomass serves as a pivotal indicator for monitoring ecosystems and climate conditions (Schepaschenko et al. 2019). The accumulation of biomass in tropical forests resulting from reforestation and restoration activities is deemed crucial for climate change mitigation efforts (Brancalion et al. 2019). Study of Basuki et al. (2022) has revealed that the potential carbon uptake from reforestation activities during the period of 2019-2030 could reach as much as −2.7 GtCO2e. It is notable that tropical forests house around two-thirds of the total global biomass found in terrestrial ecosystems (Rozendaal et al. 2022). A linear correlation between forest biomass and effective forest area has been observed (Chen et al. 2022). The amount of carbon stored and the potential emissions released from various activities such as logging, clearing, degradation, and land conversion are determined by forest biomass (Krisnawati et al. 2014). The process of forest degradation may lead to recovery through natural or assisted regeneration, whereas deforestation entails changes in land use that result in the permanent loss of the forest (Adinugroho et al. 2019). On average, around 50% of living biomass in global forests is stored within the most significant 1% of living trees (Mildrexler et al. 2020). Total biomass of SILIN conventional strip pattern, effective strip pattern, and gap pattern from the early age to 30 years are presented in Figure 5.

The biomass of SILIN vegetation in the gap pattern exhibits a significant and positive trend of increase up to 30 years, surpassing that of conventional and effective strip patterns. A study by Widiyatno et al. (2013b) revealed that the survival rate for *Shorea leprosula* is the highest in open areas, making it the optimal choice for the SILIN gap pattern. Generally, fast-growing species require enhanced sunlight exposure and are characterized by low wood density (Yuan et al. 2018). *Shorea leprosula*, utilized in the SILIN gap pattern, displays a tendency to tolerate sunlight, thus promoting more optimal growth. In the span of one-year, a SILIN vegetation in the gap pattern can store approximately 6.08 ton/ha of biomass, which is projected to 784.53 ton/ha over 30 years. Meanwhile, a one-year SILIN vegetation in the conventional strip pattern stores around 75.75 ton/ha of biomass, projected to increase to 188.46 ton/ha over 30 years. For the effective strip pattern, biomass storage is estimated at approximately 140.33 tons/ha over 30 years. Despite logging activities, biomass storage has shown an increase due to the selectivity of timber harvesting within the forest concession (Ndjondo et al. 2014). Significant difference were observed between the SILIN vegetation in the gap pattern both the conventional and effective strip patterns. Dipterocarps enrichment planting with the strip pattern include *Shorea macrophylla*, *S. ovalis*, *S. parvifolia*, *S. leprosula*, and *S. johorensis*, all classified as shade-tolerant species (Widiyatno et al. 2020). The Forest tree enrichment can effectively enhance biodiversity within the ecosystem (Vinton et al. 2020). Native species exhibit a broad range of genetic variation linked to their natural environment, and their growth is often contingent on environmental conditions (Campos et al. 2017).

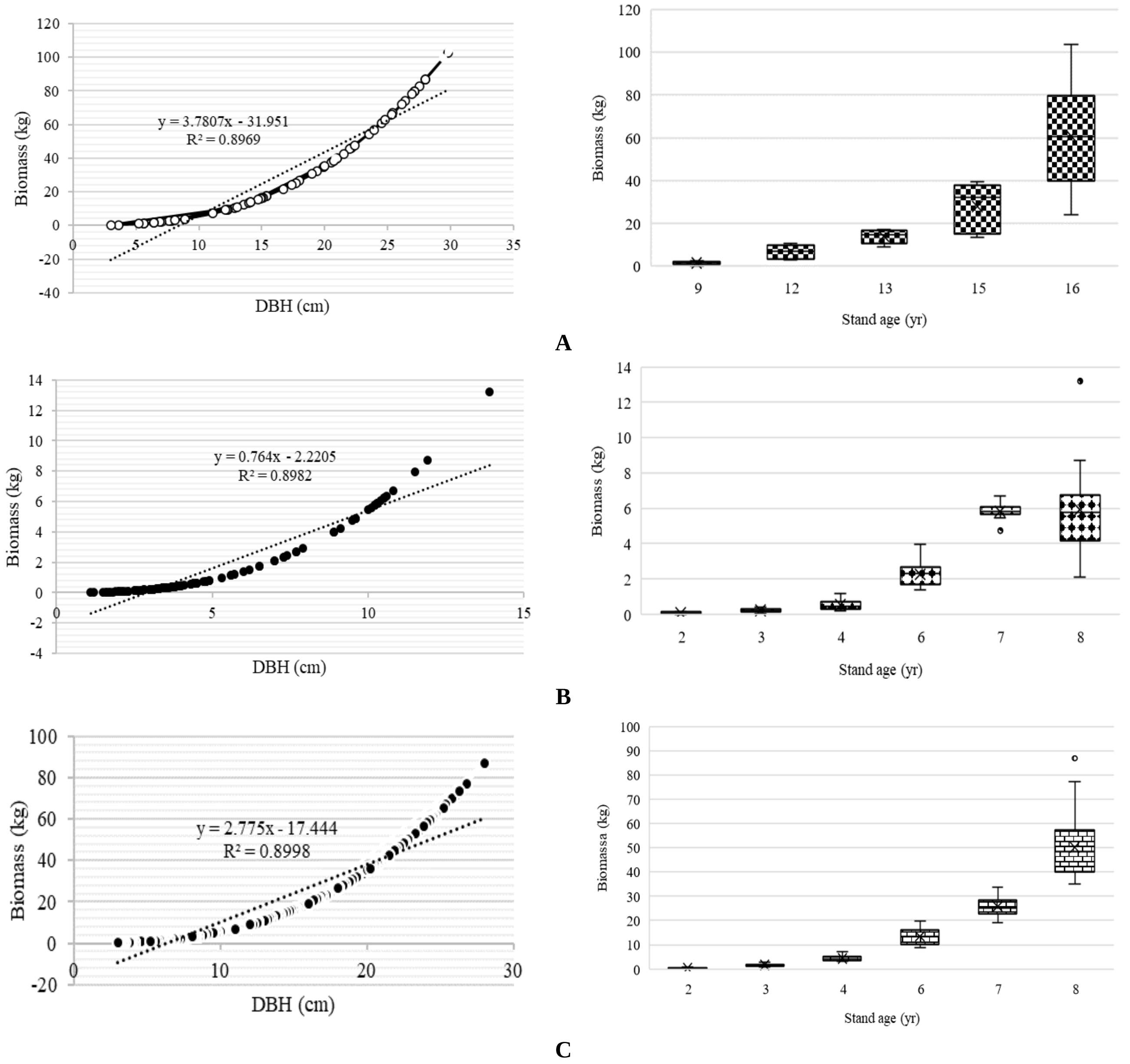


Figure 4. Relationship between diameter (cm) and stand age (yr) with biomass (kg) in each SILIN planting pattern. A. SILIN conventional strip pattern, B. SILIN effective strip pattern, C. SILIN gap pattern

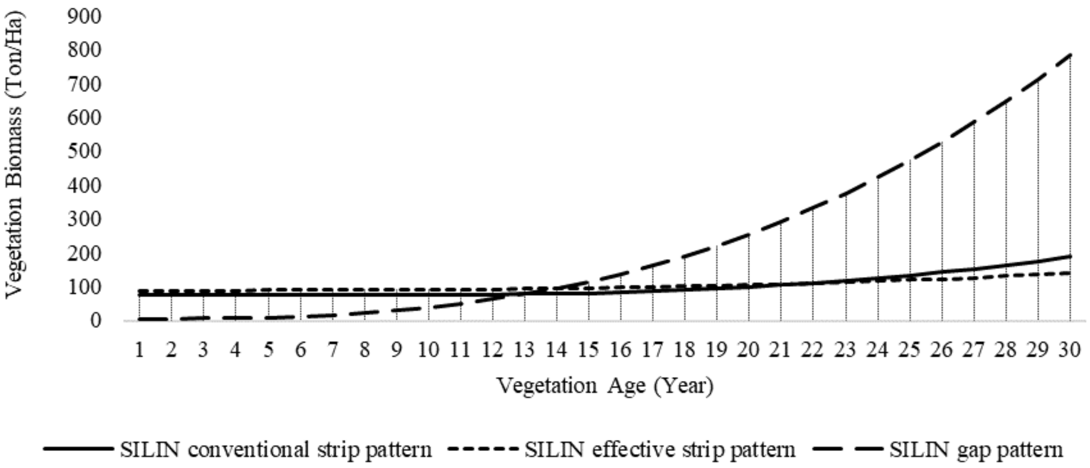


Figure 5. Trend of SILIN vegetation biomass

The quantity of biomass in trees, understory, and litter is highly influenced by age and species (Darmawan et al. 2022a). The study by (Bu et al. 2019) reveals that aboveground biomass exerts an impact on carbon storage and ecosystem services, illustrating the extent of sensitivity of ecosystem processes to changes in species richness. Referring to plot measurements, average aboveground biomass, belowground biomass, understory biomass, and litter biomass were obtained for SILIN conventional strip pattern, effective strip pattern, gap pattern, and reference natural forest. These biomass values were aggregated for each SILIN and natural vegetation plot to estimate total stand biomass. For the SILIN strip pattern, aboveground biomass is a cumulative measure encompassing SILIN vegetation, natural forest within-between the strip path, and understory. The natural forests in between the strip were categorized as secondary forests. While the aboveground biomass for the secondary forest was lower compared to the reference natural forest, it is anticipated to increase as young secondary forests mature into older secondary forests (Rozendaal et al. 2022).

Potential carbon benefits from *Shorea leprosula* SILIN vegetation stands

This study provides the estimates of carbon stock potential derived from SILIN implementation compared to the natural forest (baseline/reference stand) with goal of achieving a net sink condition. The primary natural forest has been selected as the comparative condition to the SILIN plots, following the approach of Hardiansyah (2011). Within this context, the study has calculated the average carbon stock from eight plots of primary natural forest, yielding an approximate value of 328.04 tC/ha. This estimation is in the range of carbon stock potentials for natural forests, as reported by Lasco (2002), provided estimated range of 254-390 tC/ha. Another study conducted by Siregar and Dharmawan (2011) revealed a total carbon stock potential of approximately 253.33 tC/ha within forest stands of Dipterocarp natural forest in PT Sarpatim. Further, the study conducted in a primary forest in PT Sari Bumi Kusuma (West Kalimantan) found a potential carbon stock of around 242.42 tC/ha (Hardiansyah 2011). In Bukit Tigapuluh National Park (Riau and Jambi), the aboveground carbon stock of the natural forest was approximately 269.25 tC/ha (Darmawan et al. 2022b). An investigation by (Lestari et al. 2019) demonstrated that secondary forests within Protection Forest Register 25 (Lampung) contribute a carbon value of 211.07 tC/ha. The composition of Natural forest stands is primarily dominated by big trees with large diameters. The presence of large-diameter trees plays a key role in determining a forest’s capacity to accumulate carbon stock, making it an integral element of climate change mitigation (Mildrexler et al. 2020). Variability within natural forest vegetation stands, including features like large DBH and height, significantly contributes to increased aboveground biomass, carbon stock, and overall forest productivity (Yuan et al. 2018).

Accurate measurement of Forest area and carbon stock is essential to comprehensively capture the emissions resulting from forest degradation and their subsequent release into the atmosphere (Goetz et al. 2015). The growth of trees contributes to the biomass accumulation, leading to increased diameter and growth rates, which in turn augments carbon sequestration process (Chen et al. 2022). With reference to the total biomass derived from the three carbon pools within SILIN vegetation stands and natural forest, we were able to estimate carbon potential associated with both the SILIN strip and gap pattern. The amount of carbon potential resulting from SILIN vegetation stands for these patterns, in comparison to the natural forest stand, is depicted in Figure 6.

The carbon stock potential of the SILIN gap pattern at age 29 years surpasses that of the reference stands (natural forest), which is estimated at 328.04 tC/ha (Figure 6). Specifically, the SILIN gap pattern at the age of 25 years stores approximately 222.80 tC/ha of carbon, and this value is projected to increase further to 335.78 tC/ha and 368.73 tC/ha at ages 29 and 30 years, respectively. It is noteworthy that during the initial 1-28 years, the SILIN gap pattern stored less carbon compared to the baseline/reference stand. In this context, it is argue that the SILIN gap pattern harvested in a single cycle of 25 years has not yet reached a net sink condition. However, extending the cycle to 30 years is anticipated to lead to a net sink condition being achieved in 29th year. As for the SILIN vegetation stands under the conventional strip pattern, at the age of 25 years, they store approximately 62.59 tC/ha of carbon, which is projected to increase to 88.34 tC/ha at the age of 30 years. Similarly, the SILIN vegetation stands following the effective strip pattern, at the age of 25 years, store around 55.72 tons of carbon per ha, and this value is anticipated to rise to 65.25 tC/ha at the age of 30 years.

Carbon sequestration plays a crucial role in assessing mitigation efforts, offering valuable insights into the trend of vegetation carbon accumulation over time. An alternative indicator for this purpose is the annual carbon sequestration rate, which allows us to gauge how vegetation carbon changes annually. While the growth of diameter and height in SILIN vegetation contributes to increased carbon sequestration, it’s important to note that such gains can be swiftly reversed due to factors like disease, pests, or mortality. The magnitude of carbon sequestration achieved through SILIN will determine its impact in comparison to the reference. In this study, we have employed the natural forest as the baseline (reference) with an average carbon stock of 328.04 tC/ha. The reference serves as a yardstick for assessing the net sink condition. An insight of annual carbon sequestration for SILIN vegetation is depicted in Figure 7.

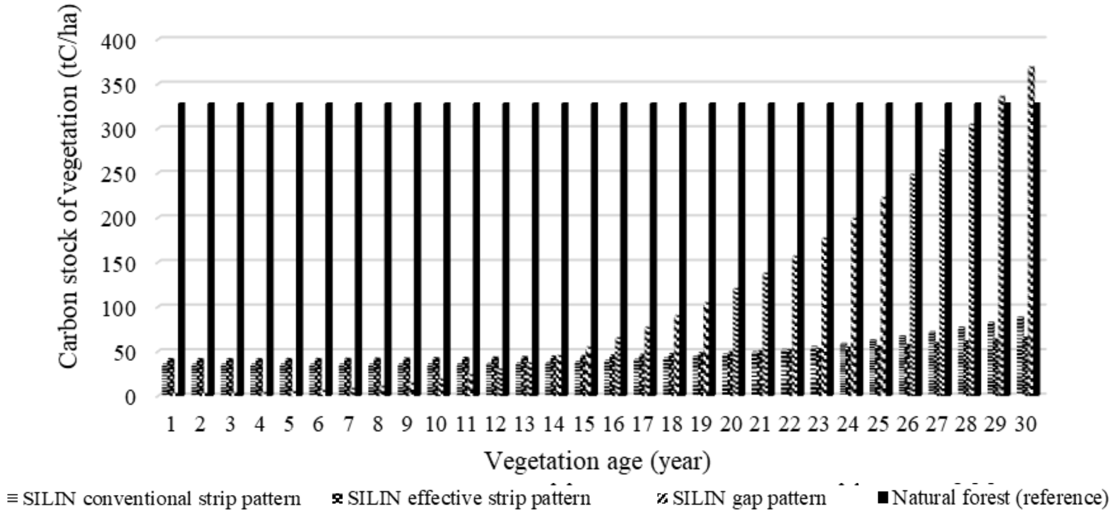


Figure 6. Comparison of SILIN and natural forest carbon from vegetation stands

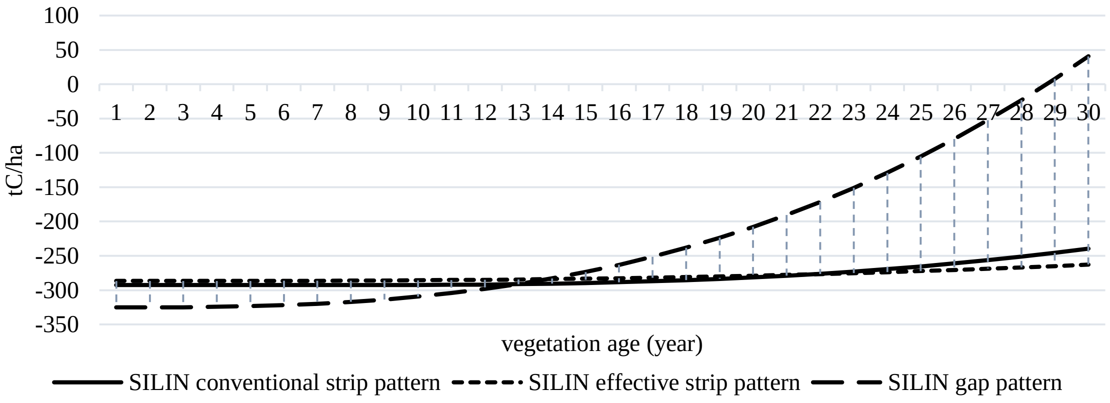


Figure 7. Potential of carbon sequestration of SILIN conventional strip pattern, effective strip pattern, and gap pattern, compared to the reference stands (natural forest). Note: the negative value indicates carbon sequestration lower than the baseline, which depicts carbon emission

Carbon sequestration from SILIN vegetation stands in this study equals the subtraction of SILIN carbon stands with baseline carbon stock. Carbon sequestration with a positive value indicates a higher carbon stock from SILIN stands compared to natural forest (reference) and vice versa. Notably, the SILIN gap pattern sequesters carbon more effectively compared to the baseline. At the age of 29 years, the SILIN gap pattern stands exhibit positive carbon sequestration of 7.74 tC/ha, which further increases to 40.69 tC/ha at 30-year mark. The relationship between carbon stored in vegetation and biomass is evident - larger biomass translates to higher carbon sequestration (Darmawan et al. 2022a). However, at the age of 30 years, the SILIN conventional strip pattern and effective strip pattern stands store stand store less carbon compared to the baseline, with values of -239.70 tC/ha and -262.76 tC/ha, respectively. These findings suggest that SILIN store less carbon than the baseline, and even less than post-forest logging with TPTJ. Over the past three decades, adopting enrichment planting in secondary forests has been shown to mitigate carbon loss in tropical forests (Besnard et al. 2021).

As an alternative indicator to monitor vegetation carbon trends over time, annual carbon sequestration provides valuable insights. Figure 8 presents the annual carbon sequestration for SILIN vegetation.

The SILIN gap pattern exhibits the highest potential for carbon sequestration, with a maximum of 32.95 tC/ha/yr achievable at the age of 30 years. Similarly, the SILIN conventional strip pattern can achieve a carbon sequestration rate of 6.02 tC/ha/yr at the age, while the SILIN effective strip pattern can achieve a rate of 2.15 tC/ha/yr. Hardiansyah (2011) previously reported that carbon sequestration from the SILIN strip pattern could reach 12.14 tC/ha/yr at the age of 25 years. Another study by Qie et al. (2017) conducted on forests across Borneo during the period of 1988-2010 found an aboveground carbon sink of 0.43 tC/ha/yr. Annual carbon sequestration is notably influenced by the trees' annual increments. Silvicultural treatments, such as those adopted in the SILIN technique, can accelerate regeneration and tree growth (Sasaki et al. 2011). The SILIN gap pattern proves particularly effective in restoring secondary forests that have experienced declining carbon stock. Consideration of both carbon and biodiversity is crucial while formulating silvicultural guidelines and forest policies (Brancalion et al. 2019). By implementing appropriate silvicultural techniques, the structure and composition of vegetation can be maintained, thereby enhancing ecosystem mitigation and adaptation to carbon sequestration (Girona et al. 2023).

Potential carbon dioxide sequestration for SILIN vegetation stands strip and gap pattern

Forests play a critical role in sequestering carbon dioxide from the atmosphere, a role that is indispensable for mitigating climate change (Shi et al. 2022). Forest ecosystems serve as essential tool in climate change mitigation by absorbing atmospheric CO_2 and storing it within tree biomass (Raihan et al. 2021b). Besides improving the ecological condition post-forest logging, implementation of SILIN technique contributes to enhanced forest productivity and increased carbon dioxide sequestration within natural forests under the PBPH area. The potential of carbon dioxide sequestration was estimated from the carbon sequestration of each SILIN vegetation stand type. The carbon sequestration potential of SILIN conventional strip pattern, SILIN effective strip pattern, and SILIN gap pattern are depicted in Figure 9.

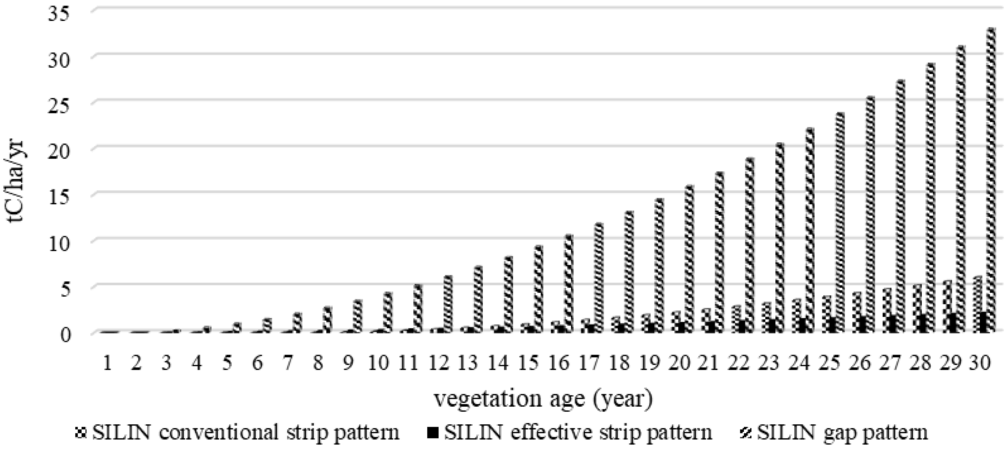


Figure 8. Annual carbon sequestration potential for SILIN strips and gap pattern (tC/ha/yr)

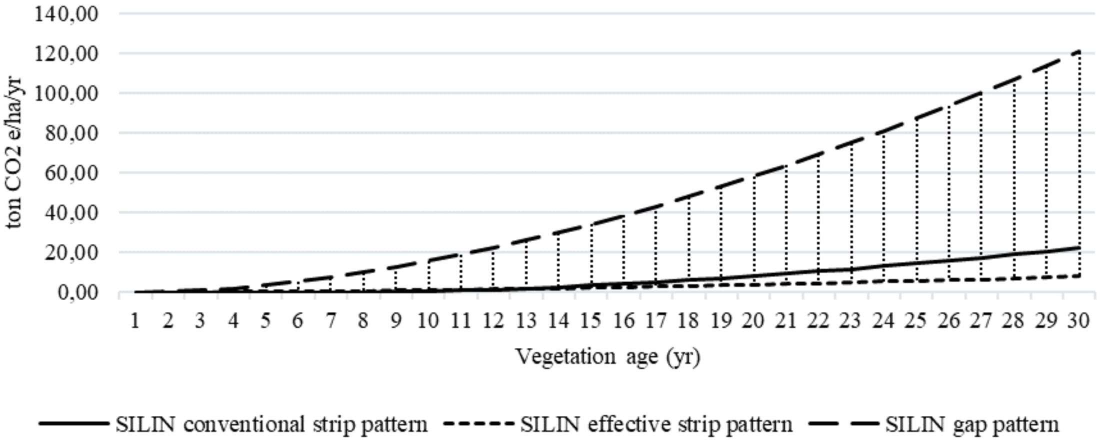


Figure 9. Comparison of potential CO_2 sequestration from SILIN strip and gap pattern

The SILIN gap pattern emerges as the most favourable approach for CO_2 sequestration. The quantity of carbon dioxide sequestration positively correlates with the carbon sequestration process itself. CO_2 sequestration exhibits an upward trend as SILIN implementation using *S. leprosula* progresses from early planting stages to the 30-year mark. Specifically, at the age of 25 years, the SILIN gap pattern demonstrates as capacity to sequester 87.30 tCO_2e/ha/yr, a value that escalates to 120.91 tCO_2e/ha/yr by the 30-year mark. The SILIN conventional strip pattern, at 25 years of age, exhibits a CO_2 sequestration potential of 14.39 tCO_2e/ha/yr, which is projected to increase to 22.09 tCO_2e/ha/yr at 30 years. Similarly, the SILIN effective strip pattern at 25 years of age, sequesters 5.70 tCO_2e/ha/yr, rising to 7.89 tCO_2e/ha/yr at 30 years. SILIN gap pattern proves to be instrumental in the enhancement of secondary production forests while simultaneously increasing forest productivity. Notably, study of Brancalion et al. (2019) has demonstrated how intensive silviculture can elevate carbon accumulation through restoration to levels upto three times that of aboveground biomass. Furthermore, a positive correlation exists between carbon stock and tree species regeneration, emphasizing the significance of large trees for climate stability and the management of forest ecosystems as integral socio-ecological system (Mildrexler et al. 2020).

Discussion

The implementation of Sustainable Forest Management (SFM) strategies at PBPH plays a pivotal role in mitigating the impacts of climate change at the site level. PBPH holds a crucial role in reducing greenhouse gas (GHG) emissions. By empbacing ecosystem-based forest management, PBPH charts a course towards achieving SFM, a holistic endeavor that strives to harmonize ecological, economic, and societal goals (Girona et al. 2023). On a local scale, PBPH is tasked with implementing measures that can optimally capture and sequester carbon, thereby making a substantial to the Indonesia's NDC and FOLU Net Sink 2030 targets. Indonesia's production forest, located within PBPH, have contributed significantly to the national economy. However, the potential of forest trees has faced continuous decline dut to timber logging, consequently impacting both the quantity and quality of the products as well as biodiversity (Naiem et al. 2016; Suryanto et al. 2018; Girona et al. 2023). The Indonesia's natural forests are grappling with productivity challenges, currently yielding only 0.5-1.5 m^3/ha/yr, a stark contrast to 60-70 m^3/ha/yr output observed in the 1970s (Naiem et al. 2016). This decline stands in contrast to temperate plantation forests which can attain prodictivity levels of 4-10 m^3/ha/yr (Naiem et al. 2016). Among the numerous species harvested in production forests under the selective logging system, Dipterocarp trees remain primary targets (Widiyatno et al. 2020; Widiyatno et al. 2013a, b). Given their primary utilization as sawn wood, diameter growth emerges as an essential parameter in generating timber of high quality (Widiyatno et al. 2020).

The implementation of the SILIN technique with *Shorea leprosula* has resulted in a notable increase in carbon stock and sequestration. Three distinct SILIN techniques have been implemented at PT Sarpatim, combining conventional strip patterns, effective strip patterns, and gap patterns. Economically viable SILIN demonstrates feasibility at PBPH, particularly in logged-over areas, exhibiting a net present value (NPV) and benefit-cost ratio (BCR) greater than 1, along with an internal rate of return (IRR) surpassing the discount rate (Lamis and Muhdin 2019). By the sixth year post-planting, survival rates can reach an impressive 84.4% (Widiyatno et al. 2013a). Employing the SILIN technique with *S. leprosula* aligns well, given the species's heightened tolerance to water deficit and its need for adequate sunlight during initial growth stages (Naiem et al. 2016). Notably, study by (Widiyatno et al. 2014) suggest that *Shorea* spp. display divergent growth rates and hold potential for supporting future breeding programs. For the restoration of lowland degraded dipterocarp forest, it is advisable to opt for species such as *Shorea leprosula*, *S. macrophylla*, and *S. ovalis*, planted using the SILIN gap pattern. This approach factors in a survival rate exceeding 67% and an annual diameter increment of 1.7 cm. Conversely, in denser secondary forests suitable for strip pattern, *Shorea platyclados* is a recommended choice, as it exhibits shade tolerance and achieves an impressive diameter of 2.2 cm/yr (Widiyatno et al. 2020).

Standing biomass estimation under SILIN system and natural forest

The implementation of the SILIN technique reveals notable differences in vegetation biomass among its various patterns. Notably, the gap pattern demonstrates a significant increase in biomass compared to conventional and effective strip patterns. Through SILIN planting in the gap pattern, a substantial enhancement in biomass vegetation stand has been confirmed, offering effective land restoration and increased timber productivity. In monocultural systems, the aboveground biomass (comprising of 47.6% of the total stock) accumulates within tree stands (45.5%), necromass (1.1%), and litter and herbaceous plants (<1%) (Miharza et al. 2023). In the context of natural forests, *Shorea leprosula* emerged as the most suitable SILIN vegetation species. With a mean annual diameter increment of 1.67 cm/year, this species is projected to yield approximately 400 m^3/ha in 30 years as standing stock, or approximately 280 m^3/ha per 30 years in the form of timber production (Naiem et al. 2016). This value is higher than production of natural forests, which typically ranges from 20-30 m^3/ha per 30 years (Naiem et al. 2016).

A trade-off between planting distance and vegetation biomass is evident, alongside planting distance's influence on vegetation growth across various age classes (Gabira et al. 2023). A higher vegetation density tends to hinder diameter growth while height increases with a rising density (Gabira et al. 2023). Tree density plays a pivotal role in carbon accumulation, with the majority of carbon stock stored in trees (56.47%) and root components (56.93%) of the total C stocks (Miharza et al. 2023). SILIN's strip pattern tends to yield higher vegetation height and a lower diameter compared to the gap pattern. Competition with adjacent natural forest stands contributes to the increased height of SILIN strip pattern vegetation. Notably, the 2.5 × 2.5 m planting distance in the strip pattern necessitates competition between SILIN vegetation and nearby natural forest stands. The significance of spacing is evident in its impact on DBH, tree height, carbon sequestration, and tree volume, as observed in the study by (Rahmawati et al. 2022). Furthermore, the maintenance of plant alignment in line planting enhances tree productivity, prompting the need to widen line planting to facilitate optimal penetration of light to support plant growth (Pamoengkas et al. 2014). Variability in DBH notably influences aboveground carbon content (Yuan et al. 2018). Gap pattern SILIN demonstrates increment in height and species survival, largely due to its planting distance (5 × 5 m), enabling optimal growth conditions.

Dipterocarp species could be classified into three distinct groups according to their sunlight requirements: those that need sunlight and exhibit rapid growth, those tolerant to shade and grows fast, and those tolerant to shade but grows as a slower pace (Widiyatno et al. 2020). Among these, *Shorea leprosula* displays susceptibility to sunlight compared to other species (Widiyatno et al. 2013b). Species of *Shorea* spp. that demonstrate more tolerance to sunlight are considered more adaptable and thus suitable for both strip and gap patterns (Widiyatno et al. 2020). It is notable that the SILIN strip pattern intensifies light exposure, decreases humidity, and elevates water stress, potentially leading to increased mortality among dipterocarp species, specifically those that are more tolerant to shade during early growth stages (Widiyatno et al. 2020). Contrarily, planting strips in SILIN facilitate more gaps for sunlight penetration, enhancing the survival rate and growth of *Shorea* spp. (Widiyatno et al. 2013).

A study by Krisnawati et al. (2012) within lowland dipterocarp forests reported that the aboveground carbon pool comprises the highest proportion of total carbon stock, ranging from 53.6% to 70.6%. Within the total carbon, 44-65% was stored within vegetation stand; with 4% in the understory, 1-2% in litter, and 5-20% in belowground biomass. Notably, degraded forest retained only 20% of aboveground carbon. The contribution of large trees (DBH ≥ 60 cm) to biomass and natural forest carbon stock is substantial, while smaller trees (DBH < 10 cm) generally contribute less than 15% on an average (Piponiot et al. 2022). This variability in biomass and volume primarily stems from diverse environmental and anthropogenic conditions. Furthermore, discrepancies in estimated biomass and volume were also influenced by sampling and measurement methodologies in the field (Krisnawati et al. 2014). The implementing of SILIN by PBPH could generate multiple benefits, including (1) a more controlled planting process through company resources and independent auditors, (2) the incorporation of three main key aspects of intensive silviculture (high-quality seedlings, good environment modification, and integrated pest control) to foster productive and sustainable forests, (3) increased employment opportunities and enhanced company profits (Naiem et al. 2016), and (4) environmental service benefits (Lamis and Muhdin 2019).

Potential carbon benefits from *Shorea leprosula* SILIN vegetation stands

The concept of carbon sinks presents a powerful avenue for controlling carbon concentrations, with the implement of carbon sink programs offering a robust solution (Siregar and Dharmawan 2011). These programs encompass a range of activities, actions, or mechanisms designed to capture and absorb CO_2 from the atmosphere (Wei and Shen 2022). By enabling the storage of organic carbon from photosynthesis within woody vegetation, these programs have a particularly important role to play in forest ecosystems, which function as natural carbon sinks that maintain the overall carbon balance of ecosystems (Zhang et al. 2022). The relationship between forest type and aboveground carbon content has been firmly established, further emphasizing the significance of these carbon sinks in various forest ecosystems (Darmawan et al. 2022b). Within Indonesia's FOLU sector, there lies substantial potential to sequester carbon, thereby aligning with nation's NDC and 2030 FOLU Net Sink goals. The quantification of forest biomass is a fondational step in understanding the global carbon cycle and its relationship with climate (Adinugroho et al. 2022a). Our study shows the substantial potential of the SILIN gap pattern to store carbon, surpassing that of the reference stand (natural forest). To optimize the carbon stock and sequestration, it is suggested to implement the SILIN gap pattern until it reaches 30 years of age within a single cycle. SILIN gap pattern which stores at one-year age 2.85 tons of carbon per ha, hypothetically could grow to 368.73 tC/ha at the age of 30 years. While the SILIN gap pattern demonstrates lower carbon stock in early years than the baseline, it is important to note that it does not yet reach a net sink state after one cycle (25 years). However, it is projected to achieve a net sink condition at the age of 29 years within a 30-year cycle. The superiority of the SILIN gap pattern in terms of carbon stock can be attributed to several factors: (1) its planting under open areas that facilitate abundant sunlight for optimal growth, (2) a planting distance of 5 × 5 m that minimizes competition between trees, (3) a higher tree density compared to strip patterns, and (4) reduced competition with natural forest vegetation. This aligns with findings that tree density, canopy cover, and soil organic carbon positively correlate with carbon stock levels (Miharza et al. 2023). Further, the study of Ingram (2022) in the SILIN gap pattern (PT. Sarpatim) has reported lower erosion levels in SILIN gap pattern areas compared degraded natural forest areas (12.047 ton/ha <38.732 ton/ha).

At the age of 30 years, the SILIN conventional strip pattern potentially stores 88.34 tons of carbon per ha, while the SILIN effective pattern only 65.25 tC/ha. This indicates a lower carbon stock in the SILIN strip pattern compared to the SILIN gap pattern. With a lower carbon stock compared to baseline, both the SILIN conventional and effective strip patterns will not achieve a net sink condition, even at age 30 years. The reasons for this are as follows:

(1) a planting distance of 2.5 × 2.5 m leading to competition between trees, (2) shade from the natural forest that hinders sunlight availability, and (3) a predetermined number of trees has been decided for each 20 m strip. While the SILIN strip pattern may not store as much carbon as natural forests, the vegetation growth still facilitates a carbon-storing mechanism during the TPTJ post-logging phase. Secondary forests store less biomass compared to primary forests (Krisnawati et al. 2014).

The implementation of Sustainable Forest Management (SFM) in PBPH can expedite the ecological restoration of degraded forests, due to its 27-year production cycle compared to the 30-year of logging rotation (Hilwan et al. 2012). A study by Inada et al. (2015) has shown an increase in the number of trees in the ex-logging areas after 11 years of *Shorea* spp. plantation. Although planting *Shorea* spp. contributes to restoring dipterocarp density, these contributions remain relatively low even after 11 years of planting, compared to the pre-condition of a natural forest. The growth rate of carbon sequestration in plantation forests is higher than in natural forests (Shi et al. 2022). The lower sequestration rate of primary forests is attributed to their equilibrium state. Primary natural forests are commonly dominated by vegetation with a large DBH. Despite accounting for only 1.2% of the relative abundance, trees with DBH > 60 cm contributes to approximately 20% of aboveground biomass (Yuan et al. 2018). Primary natural forests were used as the baseline/reference to compare the carbon stock after reaching an equilibrium state. High carbon stock in primary forests often corresponds to a low carbon sequestration rate (Besnard et al. 2021). Natural forests store an enormous amount of carbon, making them susceptible to potential losses from illegal logging (Mildrexler et al. 2020). This emphasizes the stable condition of primary forests, which have limited capacity for additional biomass generation, having reached their final development stage. Forest logging after 30 years cycle will reduce the total carbon stock. It is important to note that the loss of carbon stock in secondary forests is unrelated to forest logging activity; secondary forest carbon will be decrease after logging (Krisnawati et al. 2012b). The increasing carbon stock from SILIN implementation using *S. leprosula* will offset emissions from logging activity, while concurrently enhancing forest carbon sequestration.

The SILIN gap pattern sequesters more carbon compared to the SILIN strip pattern. The highest carbon sequestration potential for the SILIN gap pattern can reach 32.95 tC/ha/yr (30 years), while for the SILIN conventional strip pattern, it is 6.02 tC/ha/yr (30 years), and for SILIN effective strip pattern, it is 2.15 tC/ha/yr (30 years). The annual increment of DBH in the SILIN gap pattern, based on the age-biomass model, potentially reaches 3.11 cm/yr. In contrast, the annual increment of DBH in the SILIN conventional strip pattern potentially reaches 2.62 cm/year, and for SILIN effective strip pattern, it is 1.47 cm/year. A higher annual increment of DBH correlates with increased carbon sequestration in SILIN vegetation. Carbon sequestration in vegetation signifies its capacity to capture carbon dioxide from the atmosphere and store it in vegetation and soils, thus reducing GHG concentration (Chen et al. 2021). Forests play a crucial role in sequestering and storing carbon from the atmosphere, contributing to the reduction of GHG emissions (Verma and Ghosh 2022). Tropical forests are pivotal in climate change mitigation due to their capacity for increased carbon sequestration (Sasaki et al. 2011; Raihan et al. 2021a). Carbon sequestration in the forestry sector involves measures such as reducing deforestation, afforestation, rehabilitation, and sustainable forest management (Shi et al. 2022; Raihan et al. 2021a).

The modification of a forest ecosystem toward an improved state accelerates the growth of healthy trees for carbon sequestration. A positive correlation exists between tree biomass, forest carbon sequestration, and carbon stock (Chen et al. 2021). The economic value of carbon corresponds to the capacity of carbon-storing mechanisms absorbed from the atmosphere (Raihan et al. 2021a). Carbon sequestration from the SILIN gap pattern could serve as an alternative financing scheme for PBPH to implement mitigation activities under the carbon project scheme. PBPH's participation in adopting the SILIN technique as part of SFM, has contributed to an increase in productivity of production forests. SILIN implementation in concession areas can also be considered as local mitigation action to reduce emissions, enhance carbon storage, and optimize carbon sequestration. Our study recommended the SILIN gap pattern to augment carbon sequestration, enhance stand productivity, and improve environmental conditions. The application of the SILIN technique using *Shorea leprosula* will contribute to achieving Indonesia's Enhanced NDC and FOLU Net Sink 2030.

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