

RESEARCH ARTICLE



Inter-species Competition Analysis Between Native Lowland Forest Trees to Optimize Land Rehabilitation Management in Bedegung Biodiversity Park, South Sumatra, Indonesia

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ABSTRACT

Effective CO₂ sequestration (S_C) in rehabilitated tropical forest depends heavily on species performance and competition dynamics. This study evaluates S_C potential and interspecific competition of native lowland forest tree species in Bedegung Biodiversity Park, South Sumatra, Indonesia—an area rehabilitated since 2014 through collaboration between the South Sumatra Provincial Environmental Service, National Gas Company, and IPB University. Despite the rehabilitation efforts, early planting did not consider the planting distances (L_{ij}), impacting tree density (D_x) and individual competition index (CI_i)—factors directly influencing S_C . From 2020 to 2023, monitoring of tree diameter, height, and L_{ij} data collected within a 60 × 20 m permanent plot revealed a decline in D_x from 900 ind ha⁻¹ in 2020 to 725 ind ha⁻¹ in 2023, primarily due increased competition. The site's average S_C reached 69.91 tCO₂ ha⁻¹ y⁻¹, lower than mature tropical forests due to stand age. Among all species, *Bayur* (*Pterospermum javanicum*) exhibited superior S_C performance, sequestering 10.02 ± 6.98 tCO₂ ind⁻¹ y⁻¹—well above the mean—and showing increased resilience, indicated by $1/CI_i$ from 0.62 to 4.38. These results highlight *Bayur*'s exceptional role in S_C under competitive pressure. For enhanced S_C outcomes, management interventions such as thinning, fertilization, remove the weeds, and removing dead trees are urgently recommended. Prioritizing species with high S_C potential and adaptive performance, like *Bayur*, is essential for optimizing carbon gains in forest rehabilitation programs.

Introduction

The world faces a critical need to mitigate climate change by reducing greenhouse gas (GHG) emissions, particularly atmospheric carbon dioxide (CO₂). Forest rehabilitation, restoration, and reforestation can increase climate resilience, promote biodiversity, and provide essential ecosystem services. Additionally, these activities serve as long-term carbon storage solutions [1]. Bedegung Biodiversity Park (hereafter referred to as “Bedegung”) is a conservation area for local biological resources outside the state forest in Muara Enim Regency, South Sumatra, Indonesia. According to KSDAE [2], Biodiversity Park serves a dual conservation role, preserving the genetic diversity of rare plant species (in situ conservation) and providing seeds for forest restoration efforts elsewhere (ex situ conservation). The South Sumatra Environmental Service (hereafter referred to as “DLH”) has been rehabilitating this area in collaboration with the National Gas Company (hereafter referred to as “PGN”) and IPB University [3].

In 2014, Bedegung was a barren land dominated by weeds and bushes. To revitalize the area, DLH partnered with PGN through a corporate social responsibility (CSR) initiative as part of the company's commitment to

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supporting both the government and local communities. The PGN also invited IPB University to provide technical assistance for the planting activities. Biodiversity potential survey, activity planning, and rehabilitation training were conducted between 2014 and 2015. In 2016, forest rehabilitation efforts introduced 32 native lowland tropical tree species from Sumatra, planted at traditional intervals of 2 to 3 m, with initial heights ranging from 60 to 125 cm. The success of these plantings was assessed in 2020 by measuring diameter at breast height (DBH) and tree height (H).

Forest rehabilitation in Bedegung aims to conserve critically endangered native tree species while simultaneously enhancing local biodiversity in South Sumatra [4]. Forest planting and maintenance efforts contribute significantly to CO₂ sequestration. As the trees matured, Bedegung transformed into a dense lowland forest, fostering an increase in fauna diversity, and indicating a recovery of the forest ecosystem [5]. By 2020, the trees planted in Bedegung had entered the forest development stage, where competition among individuals had become evident. This can be seen from the thickening of tree canopies and the increasing tendency of trees to touch each other [6]. As DBH and tree height (H) continued to increase, annual monitoring became essential to assess tree growth and evaluate the contribution of Bedegung to CO₂ sequestration. Numerous forestry studies have highlighted tree density as a critical factor influencing the success of forest and land rehabilitation, as it directly affects competition among trees [7–10]. However, the competition dynamics in Sumatra's lowland forest rehabilitation areas, including Bedegung, remain largely unexplored. Therefore, it is necessary to introduce new methods to measure competition in these ecosystems.

The success of forest rehabilitation depends on proper maintenance, particularly by reducing competition among individuals to optimize growth [10]. Effective tree care involves various practices, including weed removal, soil loosening, replacing dead trees, thinning, pruning branches, and fertilization [11]. An appropriate planting distance is crucial for successful rehabilitation. However, planting in Bedegung in 2016 did not account for optimal spacing, leading to intense competition that disrupted tree growth and caused unexpected tree mortality [8]. A proper planting distance is essential in forest and land rehabilitation to ensure sufficient growing space and enhance CO₂ absorption [8]. Therefore, recommendations are needed to optimize forest management by considering competition factors that influence tree growth. This study aimed to improve forest management by analyzing tree density, competition, and their impact on CO₂ sequestration. The findings are expected to provide insights into the ideal planting distance for forest and land rehabilitation in Bedegung.

Materials and Methods

Research Site

This study was conducted in the Bedegung Biodiversity Park, Muara Enim Regency, South Sumatra, Indonesia (4°03'13"–4°03'29"S and 103°45'53"–103°45'46"E). The area is part of a lowland ecosystem [5], with an altitude ranging from 240 to 390 meters above sea level (masl). Bedegung is situated within the Bukit Barisan Mountain range, featuring topographic slopes ranging from 4° to 55°. The predominant soil types in this region are red-yellow podzolic and alluvial soils [12]. Established by DLH in 2013, Bedegung covers an area of 6.58 hectares, with a designated display area of 1.61 hectares [13]. The display area serves as the central site for trial plantings of native South Sumatran tree species, representing the broader Bedegung landscape [13]. The experimental plot was strategically selected to reflect the diversity, density, and growth conditions of trees within the display area, ensuring its representativeness for Bedegung's overall management [14]. Figure 1 shows the placement and layout of the experimental plots.

This study aimed to determine the optimal timing for initiating the forest-thinning phase to prevent the loss of species that significantly contribute to the rehabilitation of lowland forests. Thinning is a critical component of forest rehabilitation management [15,16], as selecting the right trees for removal enhances the forest's capacity to absorb CO₂. In natural forests, a similar process occurs during the canopy transition phase, where trees compete for growing space and essential resources [17]. In 2016, 32 native tree species were planted in this area, as described in the introduction.

Data Collection

Location mapping was conducted using QGIS 3.34 Prizren Program for Windows, with data sourced from the Bedegung Biodiversity Park database, as specified in Decree of the Regent of Muara Enim Number 711/KPTS/BLH/2013 concerning the Designation of Regional Government-Owned Land for Biodiversity

Conservation in Bedegung Village, Tanjung Agung District, dated October 16, 2013. In 2014, field delineation was performed using a geodetic GPS to establish area boundaries. Mapping utilized Basemap by ESRI Imagery (Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aeogrid, IGN, IGP, Swisstopo, and the GIS User Community) to provide a general illustration of the research location. The experimental plot design consisted of three repetitions of the minimum lowland forest survey plot size (20 x 20 meters), resulting in a total plot area of 60 x 20 meters [18]. A minimum of three repetitions was used to ensure data reliability. The sampling location was selected within the display area to represent the diversity of the Bedegung site. The layout of the experimental plot is shown in Figure 1.

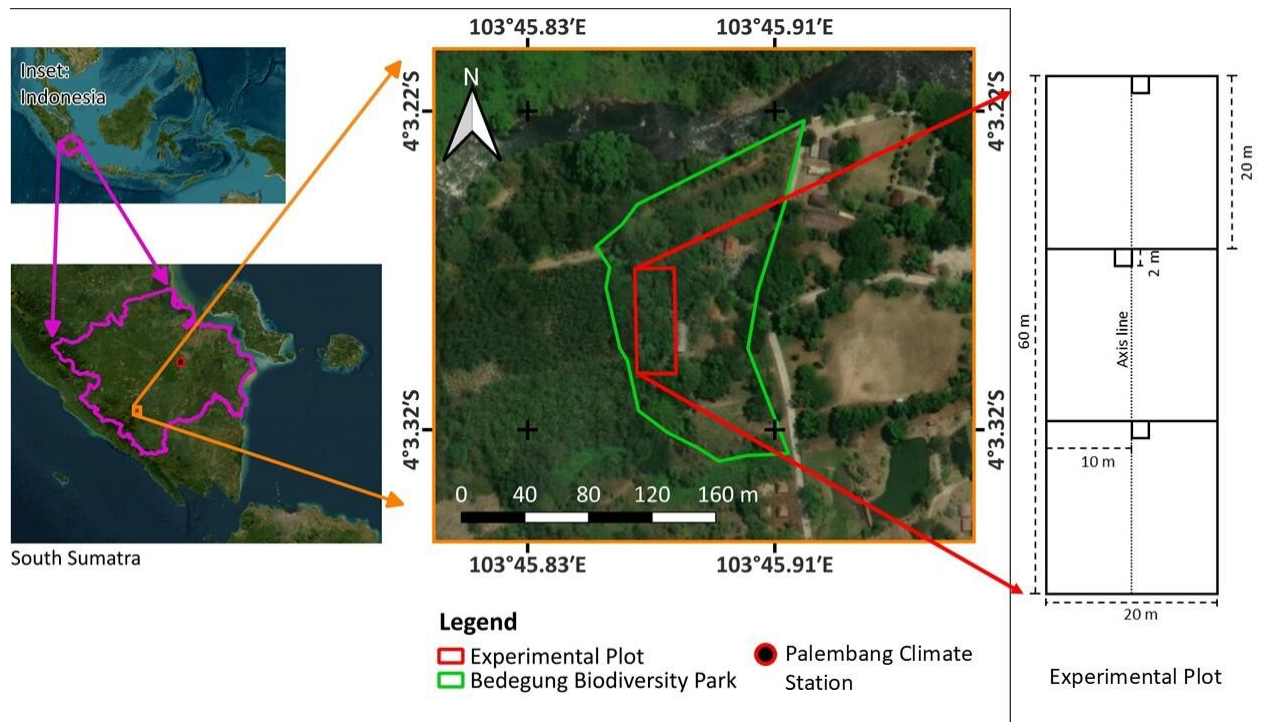


Figure 1. Research site and experimental plot design in the Bedegung Biodiversity Park, South Sumatra, Indonesia.

As shown in Figure 1, the 60 × 20 m experimental plot was divided into three 20 × 20 m sections. Within each section, 2 × 2 m subplots were arranged at the beginning of the plot in an alternating pattern: the first and third sections were positioned on the right side of the axis line, whereas the second section was on the left. This design facilitated the identification of the trees to be measured. Data collected in each section included DBH, tree H, and the distance between trees spaced less than five meters apart. Tree seedlings were identified and counted for each species in each subplot.

Time, Tools, and Objects

Tree dimensions, including diameter at DBH and H, were measured annually from 2020 to 2023 in the experimental plots. Measurements were conducted on the following dates: July 20–24, 2020; July 13–17, 2021; July 24–28, 2022; and July 29–August 2, 2023. Data were collected via direct field observations using various tools. General plant growth and leaf morphology of each species were recorded using a digital camera. Tree coordinates were recorded using a GPS navigator (GPSMAP 64s GARMIN, United Kingdom) and extracted using the DNRGarmin Software [19]. The experimental plot size and DBH were measured using a measuring tape, while tree H was measured with a sHaga-Altimeter (Hagametallwarenfabrik, Germany). Weather data were obtained from the nearest climate station, Palembang Climate Station, South Sumatra, located 155 km from the research site, at an altitude of 10 masl. Climate data included monthly rainfall (R), air temperature (T_a), relative humidity (RH), wind speed (u), and total sunshine (SS) duration from 2016 to 2023. These climate data (R, T_a , RH, u , SS) were downloaded from the official Meteorology, Climatology, and Geophysics Agency online database in December 2023 and January 2024 [20]. Tree species identification was initially conducted using local names provided by local tree identification services. The leaf, stem, flower, and fruit samples were then compared with herbarium specimens from the Forest Ecology Laboratory, Faculty of Forestry and Environment, IPB University, to determine and validate the scientific names of each species.

Data Analysis

This study analyzed species data and categorized tree guilds based on their growth type, growth speed, and shade tolerance. These classifications were determined by comparing ecological information from global plant species databases, including the Royal Botanic Gardens and the International Union for Conservation of Nature (IUCN) [21,22]. The categorized species were grouped into three guilds according to their specific resource utilization. Additionally, the analysis examined forest regeneration processes and succession patterns to determine the phases of forest development. Tree density was calculated annually using equation (1) [23]. Seedling density and frequency were calculated using the following equations (2) and (3) [24]. The competition index of each tree was calculated using the Hegyi Index formula [8], as described in equations (4) and (5), respectively.

$$D_x = \frac{N_x}{a} 10,000 \quad (1)$$

$$D_{sx} = \frac{N_{sx}}{b} 10,000 \quad (2)$$

$$f_{sx} = \frac{p_{sx}}{T} \quad (3)$$

$$CI_i = \sum_{j=1}^n \frac{d_j}{d_i L_{ij}} \quad (4)$$

$$CI = \sum_{i=1}^{N_i} CI_i \quad (5)$$

where D_x is tree density in year x (ind ha^{-1}), N_x is number of tree individuals in a year x (ind), a is an experimental plot measurement area ($= 1,200 \text{ m}^2$), D_{sx} is seedling density for each species in year x (ind ha^{-1}), N_{sx} is number of seedling individuals for each species in year x (ind), b is an experimental subplots measurement area ($= 12 \text{ m}^2$), f_{sx} is the frequency of encounters for each species in year x (ind), p_{sx} is the number of subplots encountered for each species in year x , T is the total number of subplots ($= 3$), i is a competing tree, j is a tree that competes with tree i , CI_i is the competition index of the tree i , CI is the competition index of the whole experimental plot, n is the number of competing trees against the target tree i (ind), d_i is the DBH of the target tree i (cm), d_j is the DBH of the competing tree j against the target tree i (cm), and L_{ij} is the distance between the target tree and the competing tree (m). Edge effects within stands were ignored, as measurements focused solely on competition among individuals within the permanent plots. Sun et al. [8] demonstrated that the Hegyi competition index effectively quantifies competition levels among trees in a forest by incorporating their spatial distributions. This index is particularly useful for identifying trees that should be removed during forest thinning to enhance growth conditions.

The study of plant population dynamics involved comparing biotic and abiotic factors within and around forests. Allometric model equations have been applied to estimate above-ground tree carbon [25,26]. These equations are widely used to assess tree biomass based on variables such as diameter, height, and volume. This study employed a non-destructive method, following the tree biomass estimation guidelines [27] in equations (6) and (7). To convert biomass into carbon storage and CO_2 sequestration at the individual tree level, equations (8) and (9) from the Intergovernmental Panel on Climate Change (IPCC) in 2006 [28] were applied.

$$V = 0.25\pi \left(\frac{\text{DBH}}{100} \right)^2 \times H \times F \quad (6)$$

$$B = V \times \text{WD} \times \text{BEF} \quad (7)$$

$$\text{CB} = B \times \text{CF}_B \quad (8)$$

$$S_C = \text{CB} \times \text{CF}_C \quad (9)$$

where V is tree volume (m^3), DBH is the diameter at breast height (cm), and H is the tree height (m). F represents the form factor, a correction coefficient calculated as the ratio between the actual stem volume and the cylinder volume at the same DBH and H . When species-specific form factors were unavailable, a general value of $F = 0.6$ was applied [27]. B denotes biomass (kg), while wood density (WD , kg m^{-3}) accounts for species-specific variations in wood mass. The biomass expansion factor (BEF) values were sourced from the ICRAF (The International Council for Research in Agroforestry) database [29]. Whenever species-specific BEF values were available, they were applied; otherwise, the genus-level (the biological taxonomy between species and families) BEF value was used. CB represents carbon content (kg) derived from biomass, B is total biomass (kg), and CF_B is 0.47, which is the constant for converting biomass value to carbon value. S_C is CO_2 sequestration value (kg) and CF_C is 3.67, which is the constant for converting the weight of CO_2 molecules (44.01 g mol^{-1}) to C atoms (12.01 g mol^{-1}).

Results and Discussion

Result

General Conditions of The Research Location

Trees planted in Bedegung gradually transformed the landscape from open land to forested areas. Figure 2 shows the visual progression of tree growth from the initial planting in 2016 to that in 2023. At the time of planting, the trees measured approximately 60 to 125 cm in height, as indicated by the red arrow in Figure 2 (a). Over time, significant growth was observed, which was reflected in the increase in plant height and canopy expansion (Figure 2 (b)–2 (h)).



Figure 2. Physical conditions of tree growth from July 2016 to July 2023. Trees at the initial planting stage are indicated by red arrows in Figure 2 (a).

The research site was located 155 km from the nearest climate station, the Palembang Climate Station, South Sumatra. Although Bedegung and Palembang differ in altitude by ± 200 m, they share a similar climate [20]. For instance, the dry season typically occurs between August and October [20]. Figure 3 shows the monthly variations in Figure 3 (a) rainfall (R), Figure 3 (b) average air temperature (T_a), Figure 3 (c) relative humidity (RH), Figure 3 (d) wind speed (u), and Figure 3 (e) total monthly SS duration from 2016 to 2023 [20].

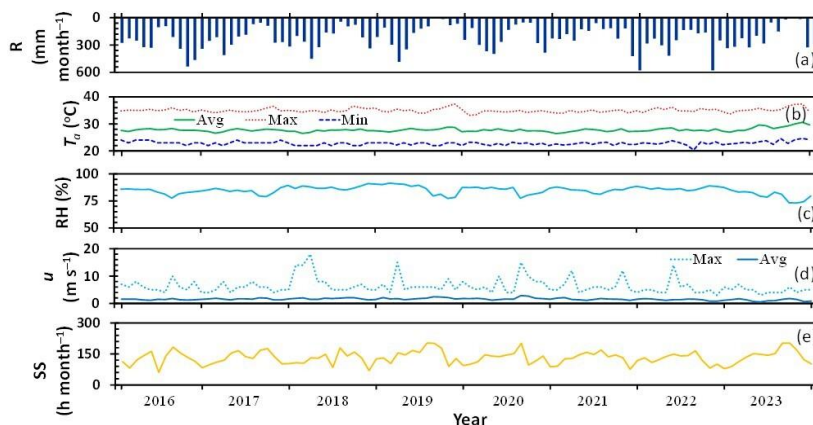


Figure 3. Variations in general climatic conditions from 2016 to 2023. Monthly (a) rainfall (R), (b) average air temperature (T_a), (c) relative humidity (RH), (d) wind speed (u), and (e) total sunshine (SS) duration.

Diversity of Species and Succession Type

A total of 32 species were initially planted in the study area, and this number remained unchanged by 2023. Table 1 shows the species found in the experimental plots along with their respective succession types. Seedling observations revealed that the three species originated from the fallen fruits and seeds within the

experimental plot. These seedlings were first recorded in 2023, whereas no seedlings were found in the experimental subplots in the previous years. The results of the observations and analysis of seedling density in the 2023 experimental subplots are shown in Table 2.

Table 1. List of species, their respective families, and succession types in experimental plots.

No.	Family	Local name	Species	Type
1	Anacardiaceae	Rengas Burung	<i>Buchanania arborescens</i>	Climax
2	Apocynaceae	Pulai	<i>Alstonia scholaris</i>	Pioneer
3	Bignoniaceae	Jakaranda	<i>Jacaranda mimosifolia</i>	Climax
4	Bignoniaceae	Kunto Bimo	<i>Kigelia africana</i>	Pioneer
5	Calophyllaceae	Nyamplung	<i>Calophyllum inophyllum</i>	Climax
6	Dipterocarpaceae	Meranti Tembaga	<i>Shorea leprosula</i>	Climax
7	Dipterocarpaceae	Resak	<i>Vatica pauciflora</i>	Climax
8	Ebenaceae	Eboni	<i>Diospyros celebica</i>	Climax
9	Elaocarpaceae	Janitri/Ganitri	<i>Elaeocarpus angustifolius</i>	Climax
10	Lamiaceae	Jati	<i>Tectona grandis</i>	Pioneer
11	Lythraceae	Bungur	<i>Lagerstroemia speciosa</i>	Climax
12	Malvaceae	Bayur	<i>Pterospermum javanicum</i>	Pioneer
13	Malvaceae	Durian	<i>Durio zibethinus</i>	Climax
14	Malvaceae	Kepuh	<i>Sterculia foetida</i>	Pioneer
15	Moraceae	Biola cantik	<i>Ficus lyrata</i>	Climax
16	Moraceae	Terep/Benda	<i>Artocarpus elasticus</i>	Pioneer
17	Myrtaceae	Ekaliptus	<i>Eucalyptus deglupta</i>	Pioneer
18	Myrtaceae	Jamblang	<i>Syzygium cumminii</i>	Climax
19	Phyllanthaceae	Buni	<i>Antidesma bunius</i>	Pioneer
20	Salicaceae	Lobi-lobi	<i>Flacourtia inermis</i>	Climax
21	Salicaceae	Rukam	<i>Flacourtia rukam</i>	Pioneer
22	Sapotaceae	Tanjung	<i>Mimusops elengi</i>	Climax
23	Fabaceae	Petai	<i>Parkia speciosa</i>	Pioneer
24	Fabaceae	Angsana	<i>Pterocarpus indicus</i>	Pioneer
25	Fabaceae	Merbau	<i>Intsia bijuga</i>	Pioneer
26	Fabaceae	Asam Jawa	<i>Tamarindus indica</i>	Climax
27	Gentianaceae	Tembesu	<i>Cyrtophyllum fragrans</i>	Climax
28	Meliaceae	Mindi	<i>Melia azedarach</i>	Climax
29	Meliaceae	Kecapi	<i>Sandoricum koetjape</i>	Pioneer
30	Sapindaceae	Matoa	<i>Pometia pinnata</i>	Pioneer
31	Sapindaceae	Rambutan	<i>Nephelium lappaceum</i>	Climax
32	Thymelaeaceae	Gaharu	<i>Aquilaria malaccensis</i>	Climax

Table 2. Seedling observations from the 2023 experimental plot.

No.	Family	Local name	Species	D_{s2023} (ind ha ⁻¹)	f_{s2023}
1	Fabaceae	Merbau	<i>Intsia bijuga</i>	9,166.67	0.67
2	Sapindaceae	Matoa	<i>Pometia pinnata</i>	5,000.00	0.33
3	Anacardiaceae	Rengas Burung	<i>Buchanania arborescens</i>	1,666.67	0.33
4	Myrtaceae	Pucuk Merah	<i>Syzygium myrtifolium</i>	1,666.67	0.33
5	Euphorbiaceae	Mahang	<i>Macaranga bancana</i>	833.33	0.33
6	Rubiaceae	Kopi Robusta	<i>Coffea canephora</i>	833.33	0.33

Tree Guilds Composition

Tree guilds are groups of tree species classified based on their resource use for growth during different development phases [30]. Species were categorized by growth type (pioneer/climax), growth speed (slow/fast), and shade tolerance (tolerance/intolerance) [21,22]. These variables were used to classify species into guilds based on their natural behavior and niche characteristics [31]. Field observations and species classification in Bedegung identified seven tree guilds: climax-fast-intolerant (CFI), climax-fast-tolerant (CFT), climax-slow-intolerant (CSI), climax-slow-tolerant (CST), pioneer-fast-intolerant (PFI), pioneer-fast-tolerant (PFT), and pioneer-slow-intolerant (PSI). Tree guild composition varied in species count, with CST (Climax-Slow-Tolerant) having the highest number of species, comprising 11 species from 10 families (35%) (Table 3).

Each guild exhibits distinct growth characteristics, which have become increasingly evident with age in 2023. These differences arise from species-specific genetic traits [32], influencing adaptability and competitiveness [31]. Species with similar adaptability and competition strategies are grouped into the same guild, although

taxonomic relationships do not always correspond to overlapping niches [31]. The degree of competition within each guild depends on the resource utilization patterns [30]. Among all guilds, CST demonstrated the highest level of resource competition, increasing the likelihood of species elimination due to competitive pressure [21]. Table 3 shows the species composition of each guild in the experimental plots.

Table 3. Species composition within each tree guild in experimental plots.

No.	Guild	Percentage (%)	Number of species	Members		
				Family	Local name	Species
1	CFI	6	2	Elaocarpaceae	Janitri/Ganitri	<i>Elaeocarpus angustifolius</i>
				Meliaceae	Kecapi	<i>Sandoricum koetjape</i>
2	CFT	6	2	Bignoniaceae	Jakaranda	<i>Jacaranda mimosifolia</i>
				Fabaceae	Angsana	<i>Pterocarpus indicus</i>
3	CSI	10	3	Calophyllaceae	Nyamplung	<i>Calophyllum inophyllum</i>
				Lamiaceae	Jati	<i>Tectona grandis</i>
				Salicaceae	Rukam	<i>Flacourtia rukam</i>
4	CST	35	11	Anacardiaceae	Rengas Burung	<i>Buchanania arborescens</i>
				Dipterocarpaceae	Meranti Tembaga	<i>Shorea leprosula</i>
				Dipterocarpaceae	Resak	<i>Vatica pauciflora</i>
				Ebenaceae	Eboni	<i>Diospyros celebica</i>
				Fabaceae	Merbau	<i>Intsia bijuga</i>
				Malvaceae	Durian	<i>Durio zibethinus</i>
				Moraceae	Terep/Benda	<i>Artocarpus elasticus</i>
				Phyllanthaceae	Buni	<i>Antidesma bunius</i>
				Salicaceae	Lobi-lobi	<i>Flacourtia inermis</i>
				Sapotaceae	Tanjung	<i>Mimusops elengi</i>
				Thymelaeaceae	Gaharu	<i>Aquilaria malaccensis</i>
				Apocynaceae	Pulai	<i>Alstonia scholaris</i>
				Bignoniaceae	Kunto Bimo	<i>Kigelia africana</i>
				Fabaceae	Petai	<i>Parkia speciosa</i>
				Lythraceae	Bungur	<i>Lagerstroemia speciosa</i>
				Malvaceae	Kepuh	<i>Sterculia foetida</i>
5	PFI	31	10	Meliaceae	Mindi	<i>Melia azedarach</i>
				Moraceae	Biola cantik	<i>Ficus lyrata</i>
				Myrtaceae	Ekaliptus	<i>Eucalyptus deglupta</i>
				Sapindaceae	Matoa	<i>Pometia pinnata</i>
				Sapindaceae	Rambutan	<i>Nephelium lappaceum</i>
				Malvaceae	Bayur	<i>Pterospermum javanicum</i>
				Myrtaceae	Jamblang	<i>Syzygium cumini</i>
				Fabaceae	Asam Jawa	<i>Tamarindus indica</i>
				Gentianaceae	Tembesu	<i>Cyrtophyllum fragrans</i>
Total		100	32			

Competition among species within a guild can disrupt tree growth and development, potentially leading to tree mortality and a declining population of certain species [8]. As shown in Figure 4. , the populations of several species across different guilds have decreased due to competition factors [7]. However, the CFT (Climax-Fast-Tolerant) guild remained stable, likely because of low intra and interspecific competition [30].

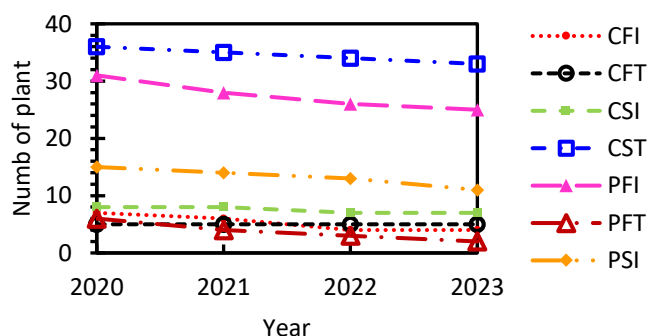


Figure 4. Changes in the number of individuals per species within each guild. Guilds are categorized based on natural behavior and niche characteristics.

Tree Distributions and Competitions

Figure 5 illustrates the distribution of trees within the experimental plot and the process of natural tree selection. This process is driven by competition among trees, which can be quantified using the Hegyi Competition Index. Higher competition levels increase the likelihood of tree elimination, as individuals compete for limited resources. The Hegyi Competition Index used applied to analyze DBH measurements and individual tree distances collected in the field [8]. This analysis provides insights into both the overall CI and CI_i , helping assess competition intensity within the plot.

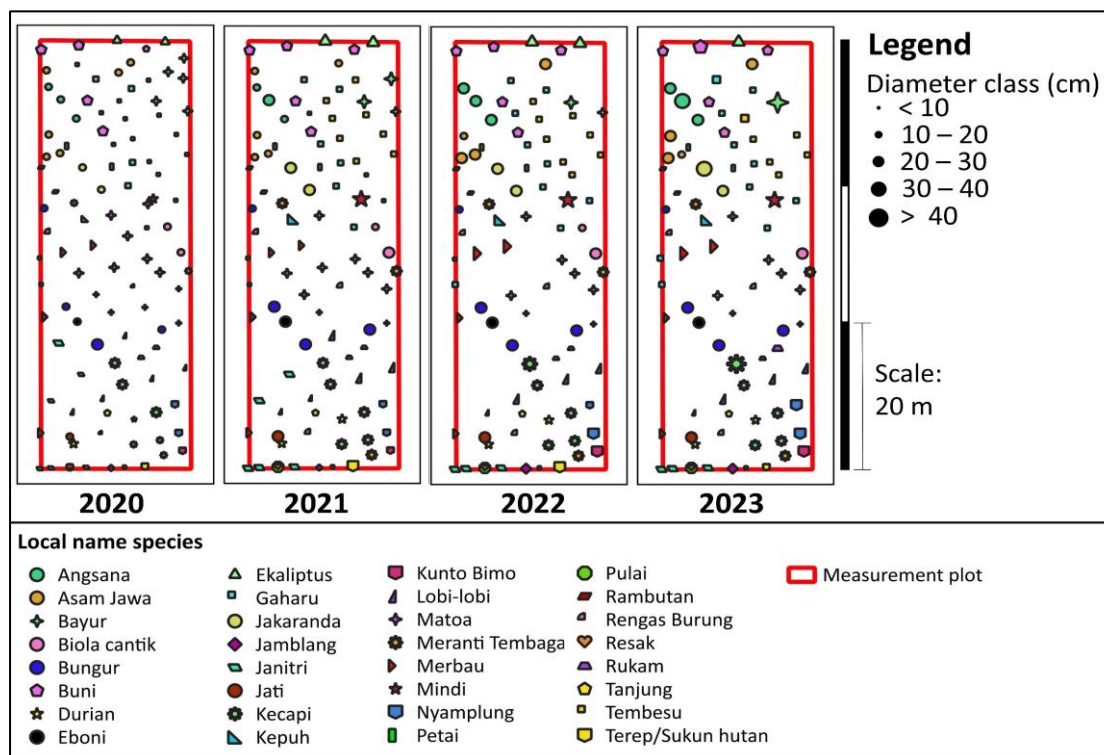


Figure 5. Spatial distribution of trees over time within the experimental plot. Tree names are presented in the local nomenclature (refer to Table 1 and Table 3 for scientific names). Different colors and marker shapes represent distinct species, whereas marker size corresponds to diameter class.

Tree Above-Ground Biomass and CO₂ Sequestration

Biomass measurement and analysis provided insights into the growth conditions of each tree guild. Species within the guild exhibited similar patterns of resource utilization, particularly in terms of nutrient requirements and responses to environmental factors. Among the guilds present in the experimental plot, CST (Climax—Slow growing—Tolerance) exhibited the highest biomass growth, as shown in Figure 6. The accumulated CO₂ sequestration for each guild from July 20, 2020, to July 29, 2023, is presented in Figure 7. The CST guild dominates the site, likely because of its superior spatial expansion capabilities compared to other guilds.

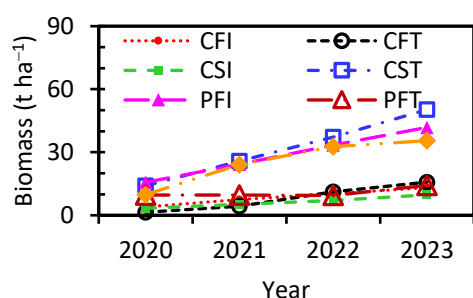


Figure 6. Annual changes in tree biomass across guilds. The CST guild exhibited the highest biomass accumulation.

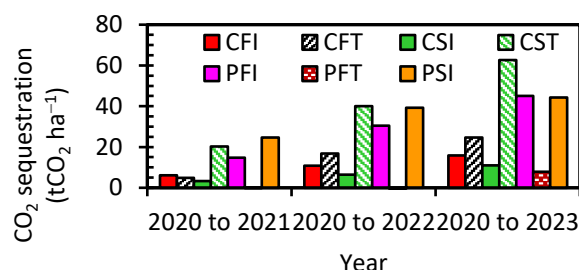


Figure 7. Annual accumulation of CO₂ sequestration across guilds.

Discussion

Weather Effect on Trees in Forest Development

Bedegung provides a suitable environment for establishing a lowland biodiversity park, supporting the conservation of local plant species with ecological value [33]. However, unpredictable and extreme weather conditions adversely affect forest growth performance, increasing the risk of tree mortality and structural damage including main trunk fractures. These findings underscore the vulnerability of forest ecosystems to weather events and their potential long-term consequences on forest stability. The collected climate data indicate that 2016 recorded the highest annual rainfall (R) of 3,503.2 mm year⁻¹, with a daily average of 16.37 mm day⁻¹. In contrast, 2019 had the lowest annual rainfall, measuring 2,031.5 mm year⁻¹ with a daily average of 7.1 mm day⁻¹. Monthly rainfall (R) variations at this location affected the average RH. The highest RH was observed in 2018 (87.7%), whereas the lowest RH was recorded in 2023 (79.78%). The average air temperature (T_a) remained low during the wet months and generally did not reach extreme levels. However, in 2023, an anomalous temperature increase occurred, with the annual average T_a reaching 28.82 °C, exceeding the typical values recorded in previous years [34]. This anomaly was primarily caused by the intensification of El Niño, which strengthened in June 2023 and weakened by December 2023 [35].

An anomaly was also observed in March 2018, when the maximum wind speed (u) reached 18 ms⁻¹. According to the Beaufort classification, this wind speed corresponds to a Gale (wind force number 8), which is strong enough to break tree branches, alter the canopy structure, and reduce tree height [36]. High winds in 2018 contributed to another climatic anomaly in 2019, characterized by increased SS exposure. In 2019, the total sunshine duration was 1,755 h year⁻¹, with a daily average of 4.94 hours day⁻¹. These conditions indicate that 2019 had the least cloud cover, likely due to the extreme strengthening of the Indian Ocean Dipole Mode Positive (DM+) [37].

Anomalous weather patterns and unpredictable climate dynamics are among the key impacts of global climate change [1]. These factors disrupt tree growth and increase the risk of mortality. A study by Itter et al. [38] in Minnesota, USA, monitored 15 tree species across 2,291 individuals in the Superior National Forest. The findings confirmed that climate change, both directly and indirectly, triggered a decline in tree growth performance. Similarly, Magalhães et al. [9] reported that climate change intensifies stress stimuli in trees, increasing the likelihood of mortality in rehabilitated forests. Therefore, the weather has a significant influence on tree development. To achieve optimal results for land rehabilitation, it is necessary to identify species capable of withstanding extreme weather conditions driven by climate change.

Forest Succession Stage

During the early stages of land rehabilitation, tree species selection is primarily based on the availability of local seeds and their natural ability to regenerate with minimal human intervention. The objective of this study was to encourage natural forest growth and to facilitate ecosystem succession. However, between 2020 and 2023, tree density (D_x) in the experimental plot declined. In 2020, the density was 900 ind ha⁻¹, decreasing to 833.33 ind ha⁻¹ in 2021, 766.67 ind ha⁻¹ in 2022, and finally 725 ind ha⁻¹ in 2023. This decline was driven by limiting factors affecting tree growth and mortality, including internal and external stressors, both biotic and abiotic, which intensified competition among trees [39–43].

In ecological dynamics, forest vegetation undergoes distinct developmental phases, including stand initiation, stem exclusion (forest development), understory reinitiation (canopy transition), and steady-state (gap dynamics) [6,17,44]. As illustrated in Figure 8, forest succession in Bedegung progressed from stand initiation

to the gap dynamics phase, reflecting the natural development process of rehabilitated forest ecosystems. In the early stages of forest succession, pioneer species occupy open spaces, facilitating the initial establishment of vegetation. However, owing to their relatively short lifespan, these species have gradually declined, creating space for the growth of climax species. Over time, longer-lived climax species have replaced pioneers, establishing a more stable and diverse forest structure. The ecological processes in Bedegung involve a variety of local species, as the forest was rehabilitated with a mixture of pioneer and climax trees [7]. By 2023, Bedegung transitioned from the canopy transition stage to the gap dynamics phase, characterized by the emergence of seedlings and the decline of certain pioneer species.

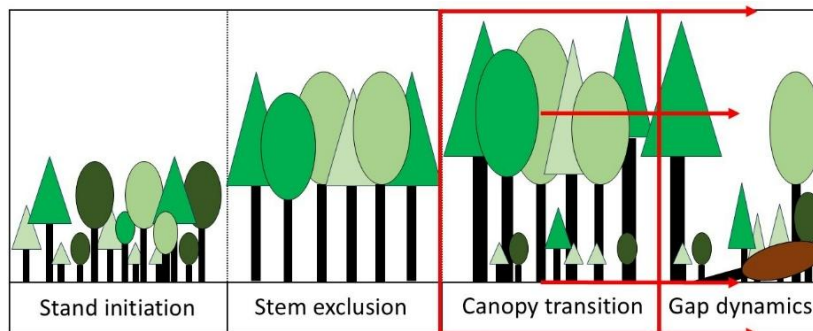


Figure 8. The forest development phases (modified from Bartels et al. [17]). Bedegung transitions from the canopy transition stage to the gap dynamics phase, as indicated by red boxes and arrows. This transition is evident through the emergence of seedlings in the canopy transition phase and the creation of growing space for climax species owing to the decline of several mature pioneer trees.

The natural succession process in Bedegung visually demonstrated the physical success of land rehabilitation. The natural regeneration observed in this area represents the desired outcome of sustainable forest development. The succession process in Bedegung progressed from the canopy transition stage [17] to the gap dynamics phase, as indicated by the emergence of three seedling species from existing stands in the experimental plot, alongside three newly arriving species [17]. The decline in mature trees is evident in the decreasing number of individuals (Figure 4), which resulted in a lower population density. However, the presence of seedlings confirms that parent trees have reached maturity and have successfully regenerated [17]. Seedling density analysis identified *Merbau* (*Intsia bijuga*) as the densest seedling species in 2023, with a density (D_{s2023}) reaching 9,166.67 ind ha⁻¹. The high number of *Merbau* seedlings is consistent with its growth characteristics as a pioneer species in natural forest succession, which is known for its rapid reproductive cycle [45].

Three new seedling species emerged from outside the experimental plot: *Pucuk Merah* (*Syzygium myrtifolium*), *Mahang* (*Macaranga bancana*), and Robusta coffee (*Coffea canephora*). These species establish themselves in the area through natural seed dispersal mechanisms, which are influenced by both biotic factors (wild animals and insects) and abiotic factors (wind and water flow) [46,47]. Among all the regenerating species, *Merbau* (*Intsia bijuga*) exhibited the highest regeneration rate, with an f_{s2023} value of 0.67, indicating that it occupied two of the three subplots in the experimental plot. This suggests that *Merbau* seedlings are naturally more widely dispersed, contributing to accelerated forest rehabilitation and succession. Given its strong natural regeneration capacity, *Merbau* is considered one of the most suitable species for rejuvenating Indonesia's tropical lowland forests [48,49], including Bedegung and its surrounding areas.

Species diversity in the experimental plot increased naturally with the addition of these three new seedling species, even though they were still juveniles. Their presence highlights the positive impact of Bedegung's efforts to enhance ecosystem resilience through natural succession. This progression suggests that a secondary forest ecosystem has begun to establish, leading to the succession stage advancing into the canopy transition phase by 2023 [17]. The emergence of seedlings in the experimental plot is a positive indicator of forest development in Bedegung [17]. Naturally growing seedlings demonstrate the ability to adapt and thrive within their habitats and environmental conditions. Additionally, the increasing species diversity in Bedegung fosters a more complex ecological balance [30]. The presence of these seedlings is crucial for the sustainability of land rehabilitation efforts, ensuring ongoing regeneration and species continuity in Bedegung [50,51].

Number of Trees and Competition Dynamics

In 2020, when the first measurements were conducted, the experimental plot contained 32 species belonging to 20 families. By 2023, the number of species and families will remain unchanged. However, the total number of individual trees has gradually declined, decreasing from 108 individuals in 2020 to 100 in 2021, 92 in 2022, and 87 in 2023. This decline in individual trees directly contributed to the annual reduction in tree density index (D_x) within the experimental plot [52]. In the experimental plot, the decline in the number of individual trees was primarily driven by natural competition, which served to regulate density [9]. This competition occurred at both intra-specific (within the same species) and inter-specific (between different species) levels [30]. Between 2021 and 2023, the death of several individuals has created growth opportunities for the remaining trees. As a result, competition is reduced, allowing for better resource allocation and enhancing the growth potential of surviving individuals. Adequate space availability is a critical factor for ensuring optimal tree growth in rehabilitated forest ecosystems.

Trees compete for essential resources such as light, water, and nutrients, and this competition plays a crucial role in determining their growth and structural strength [8,31]. Trees that successfully outcompete their neighbors develop sturdier and more resilient structures, enhancing their ability to withstand extreme weather conditions. Conversely, trees that struggle with competition often become weaker, making them more vulnerable to environmental stressors and have higher mortality risks [9]. The Hegyi competition index (CI_i) quantifies a tree's competitive status by evaluating the intensity of competition it faces from its surrounding neighbors. A lower CI_i value indicates reduced competition, granting the tree better access to resources, which enhances growth and resilience. A tree's relative strength can be expressed mathematically as $1/CI_i$, meaning that trees with lower competition index values exhibit greater competitive strength, while those with higher CI_i values face a competitive disadvantage. In 2020, *Asam Jawa* (*Tamarindus indica*), with a diameter class of < 10 cm, was the weakest tree because of its high competition, reflected in its $1/CI_i$ value of 0.20. Unfortunately, it did not survive and died the following year, resulting in a CI_i value of 0. By 2021, another tree, *Tanjung* (*Mimusops elengi*), also within the < 10 cm diameter class, became the next weakest tree, with a $1/CI_i$ value of 0.29. Unlike *Asam Jawa*, *Tanjung* survived and continued to experience the highest competition in 2022 and 2023, maintaining a $1/CI_i$ value of 0.27 in both years.

The $1/CI_i$ value is particularly useful for identifying strong individuals that can be prioritized for long-term ecosystem control [8]. Based on this identification, the strongest individual from year to year is *Bayur* (*Pterospermum javanicum*), which will win the competition in 2023. The $1/CI_i$ values increased progressively over time, reflecting its growing dominance, starting at 0.62 in 2020, rising to 0.85 in 2021, then 1.65 in 2022, and finally reaching 4.38 in 2023 [8]. Figure 9 illustrates the annual distribution of competition among the individual trees. The dashed box encloses the tree with the highest competitive strength. A higher competition index ($1/CI_i$) indicates a greater ability to withstand mortality risk [8]. The figure also depicts the node sizes, where larger nodes correspond to stronger competitors. The weakest tree, represented by the black-boxed node (indicating the most contested individual), faced severe competitive stress in 2020. As a result, it failed to survive the competition with neighboring trees and died the following year [31].

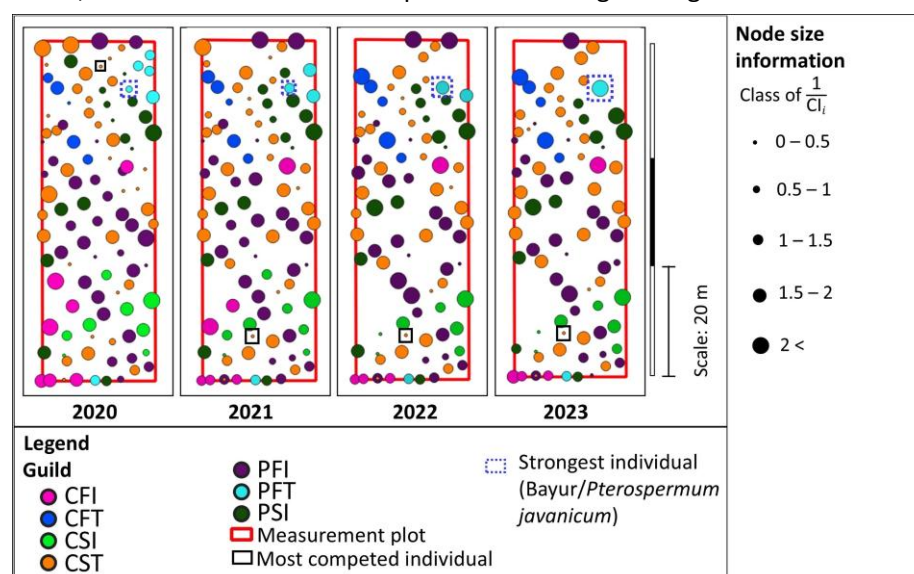


Figure 9. Annual distribution of individual competition ($1/CI_i$) for each tree.

Most Contributing Trees to CO₂ Sequestration

As biomass accumulation increases, the amount of stored carbon is directly correlated with the CO₂ sequestered [53,54]. Between 2020 and 2023, a total of 211.44 tCO₂ ha⁻¹ was sequestered from July 20, 2020, to July 29, 2023, with an average annual sequestration rate of 69.91 tCO₂ ha⁻¹ y⁻¹. However, this value was lower than the CO₂ sequestration rates observed in rehabilitated tropical dry lowland forests aged 19 to 23 years in Southeast Asia, where sequestration generally reached 198.18 ± 72.73 tCO₂ ha⁻¹ y⁻¹ [55]. This difference is primarily due to Bedegung being a young forest, only seven years old as of 2023. Similarly, CO₂ sequestration in Bedegung is lower than that in naturally regenerated forests [55].

The relatively low CO₂ sequestration in Bedegung is primarily due to its young forest age and limited silvicultural techniques [11]. In 2023, Bedegung was still considered a young forest, having only reached seven years since rehabilitation began. Additionally, the silvicultural techniques implemented to date remain incomplete and insufficient for maximizing growth and carbon sequestration. Until 2023, forest management activities were limited to pruning lower branches and removing weeds from tree stands. This limited intervention contributed to stunted tree growth, thereby reducing the CO₂ sequestration capacity. Extreme weather events in recent years have exacerbated this situation, causing tree damage and mortality. Additionally, intense competition among trees further hinders the growth rate of weaker individuals, negatively affecting overall forest health and carbon storage potential.

In recent years, extreme weather events have significantly shaped forest dynamics, frequently causing substantial damage to trees and altering the ecosystem processes. Strong winds and storms have led to branch breakage, tree uprooting, and the formation of large canopy gaps, making forests more vulnerable to environmental stressors [38]. Intense and irregular rainfall has contributed to flooding and soil saturation, weakening root systems and increasing the risk of tree mortality [37]. Meanwhile, prolonged droughts have exacerbated forest decline by making trees more susceptible to pests, diseases, and physiological stress [56]. Additionally, extreme temperatures, such as heat waves, disrupt have disrupted growth cycles and lowered tree survival rates [38,57]. Collectively, these severe weather events have destabilized forest structures, disrupted regeneration patterns, and threatened long-term ecosystem resilience.

Despite the relative resilience of the Bedegung Forest, its long-term stability remains dependent on proactive and well-planned management strategies [57]. The sporadic tree mortality observed between 2020 and 2023 highlights the detrimental effects of minimal interventions on forest development. Given Bedegung's ecological importance in supporting South Sumatran biodiversity and its critical role in CO₂ sequestration for climate change mitigation, targeted conservation efforts and adaptive management practices are crucial to ensuring continued sustainability [1]. The presence of extreme weather and intense competition among trees must be mitigated through improved forest management [58]. Beyond routine activities, such as growth monitoring, pruning, and weeding, additional silvicultural treatments, including planned thinning, fertilization, treatment of sick trees, and pest eradication, must be implemented [59,60]. These measures are expected to positively contribute to the ecosystem succession process, ensuring a more stable and resilient forest.

A decline in the number of individuals within a particular guild directly affects the CO₂ sequestration capacity. For instance, CST guild, which had 36 individuals in 2020, was reduced to 33 individuals by 2023. Consequently, its CO₂ sequestration capacity has declined, making it less effective for carbon sequestration. This decline is particularly concerning because CST guild has been a consistent contributor to long-term CO₂ sequestration. If the population remained stable, the CO₂ absorption would have been higher. This is due to the relatively large population size of CST compared to other guilds, despite its slow growth rates. Similar to climax species, trees in this guild thrive in highly competitive environments. However, these conditions also contribute to their slower growth [7].

In 2021 and 2022, the PFT guild exhibited negative CO₂ sequestration rates compared to the baseline in 2020 (see figure 10). This decline was primarily due to the loss of two individuals in 2021 and one individual in 2022, which contributed to a decrease in the CO₂ sequestration rates for the guild. However, despite the loss of one individual by 2023, the PFT species exceeded the CO₂ sequestration breakeven point established in 2020, indicating a high growth rate within the guild. By 2023, the PFT guild recorded the highest increase in CO₂ sequestration compared to 2022, even though the population declined by four individuals. This additional sequestration level reached 7.83 tCO₂ ha⁻¹, with an estimated annual CO₂ sequestration increase of 4.43 ± 3.52 tCO₂ ind⁻¹ ha⁻¹ y⁻¹. Figure 11 shows the annual CO₂ sequestration rate for each guild in Bedegung from 2020 to 2023.

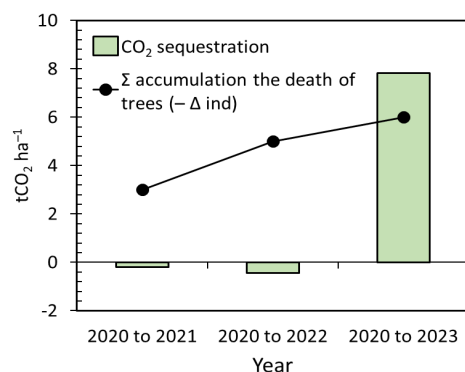


Figure 10. Cumulative CO₂ sequestration and tree mortality in the PFT guild.

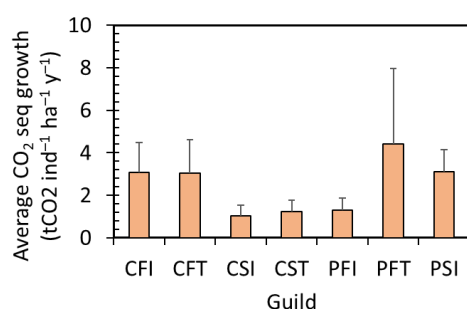


Figure 11. CO₂ sequestration growth for each guild. The vertical lines on each bar represent standard deviations.

The PFT guild in the experimental plot comprised two species: *Bayur* (*Pterospermum javanicum*) and *Jamblang* (*Syzygium cummini*). Both species share similar natural resource utilization patterns, aligned with the pioneer-fast-growing-shade-tolerant (PFT) guild. Pioneer species could be used during rehabilitation to restore environmental conditions [7]. Fast-growing species accelerate ecological recovery, whereas shade-tolerant species thrive in low-light conditions, giving them a competitive advantage over the species [45].

Among all trees in the plot, a single *Bayur* Tree (*Pterospermum javanicum*, tree no. 11) exhibited the highest growth rate and successfully outperformed its neighboring trees. This tree recorded a DBH increment of $8.23 \pm 2.77 \text{ cm y}^{-1}$ and a CO₂ sequestration rate of $10.02 \pm 6.98 \text{ tCO}_2 \text{ ind}^{-1} \text{ y}^{-1}$. *Bayur*'s dominance was further confirmed by its Competition Index (CI_i), which reflects its ability to eliminate nearby trees. In 2020, the CI_i value was 1.60, gradually decreasing over the years 0.23 until 2023, indicating that *Bayur* had successfully suppressed competition. Figure 12 shows how *Bayur* eliminated neighboring trees. Originally, it faced seven competitors, but by 2023, only two individual trees remained.

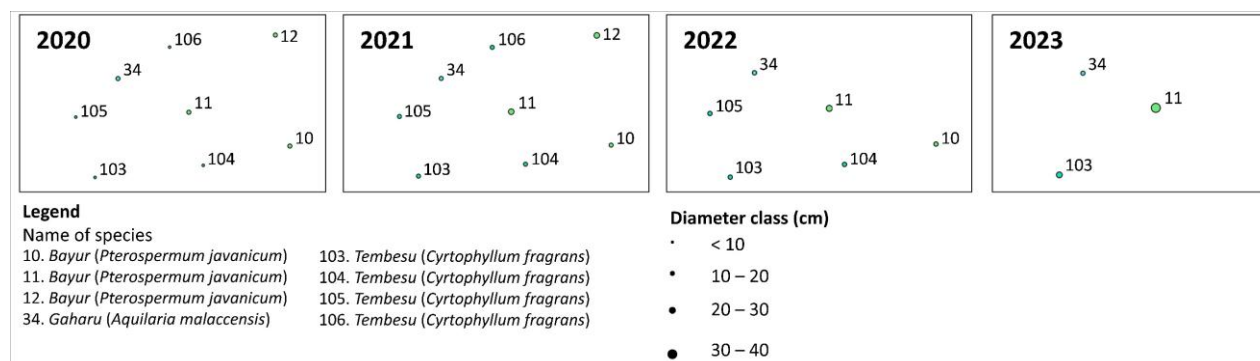


Figure 12. Annual spatial changes in the layout of *Bayur* and neighboring trees (2020–2023). The figure illustrates the competitive dynamics among the trees in the experimental plot. Tree number: *Bayur* (No. 10–12), and *Gaharu* (No. 34), *Tembesu* (No. 103–106). Tree No. 11 emerged as the dominant competitor.

Based on observations and analyses, *Bayur* (*Pterospermum javanicum*) has been identified as the primary species contributing to CO₂ sequestration in Bedegung. Additionally, this species exhibits exceptional competitive strength, enabling it to outcompete neighboring trees and dominate forest succession. These findings align with the research by Purnomo et al. [61], which classified *Bayur* as a high-biomass accumulating species with rapid growth rates. Given these characteristics, *Bayur* has significant potential as a key species for forest rehabilitation planning, contributing to climate change mitigation efforts.

Necessary Forest Treatment

Despite ongoing efforts, forest management interventions in Bedegung have remained minimal and insufficient. Current management practices rely on limited knowledge and outdated technology. Between 2020 and 2023, the primary routine management actions included pruning the lower branches to promote vertical tree growth. Periodic weed removal reduces the competition for soil nutrients. However, without complementary and integrated management strategies, these actions alone may lead to increased trunk brittleness, making trees more vulnerable to pests and diseases [11,60]. A more comprehensive and scientifically informed approach is required to ensure effective and sustainable forest management. Following the investigation, it was determined that special measures were necessary to enhance the quality of the Bedegung area. One recommended approach is the uprooting technique, which allows the preservation of naturally grown seedlings [62]. These seeds can then be transferred to alternative planting media such as polybags or trays in a nursery outside the forest. This process ensures that young plants are properly maintained until they reach a suitable age for replanting within and beyond the Bedegung area [25].

Tree thinning in the Bedegung area is important to reduce competition among trees [15,16]. However, trees that contribute significantly to forest rehabilitation must be preserved [44]. Efforts to reduce tree density can follow systematic or random thinning methods [60,63]. The systematic method selects trees for removal based on minimum spacing requirements [48]. In mature secondary lowland tropical forests, the typical tree spacing ranges from 10 to 20 meters [25,45]. Applying this minimum distance to Bedegung can help determine the trees to be cut. By removing trees within this range, root and canopy contact is minimized, allowing the remaining trees to optimize nutrient absorption and sunlight utilization, thereby improving growth conditions. The second method for tree selection is the random approach, which involves removing trees affected by environmental stress, pests, or disease [15,16,60]. This method, known as incidental thinning, helps prevent the spread of pests and diseases to neighboring trees and individuals of the same species or genus. However, it is crucial to consider carbon sequestration as a key objective of land rehabilitation in Bedegung. Therefore, our findings indicate that *Bayur* (*Pterospermum javanicum*) should be preserved due to its significant carbon absorption capacity [44,55].

The next step is to treat sick trees, especially those that can still be saved and do not pose a risk of disease transmission. This involves pest and disease management, which can be conducted using mechanical, biological, or chemical approaches. Mechanical control involves removing infected trees and is best performed by trained professionals, such as arborists or silviculturists, who specialize in tree treatment and care techniques. Biological control relies on natural predators to manage pest populations, such as Robber Flies (Family Asilidae), which prey on stem borer insects [64]. Chemical control is an effective yet last-resort option for pest eradication. This method utilizes chemical pesticides, which can be toxic to forest pests but may have long-term negative impacts on forest management and ecological balance. Therefore, chemical treatments should only be used in urgent situations in which other methods have proven ineffective.

Systemic treatment is also necessary for fungus-infected trees to prevent the spread of infection and eliminate pathogenic fungi [6,58,59]. However, these preventive measures can be resource-intensive and costly, making it necessary to explore cost-effective collaborative treatment techniques, including traditional methods [65]. One example is spraying wood vinegar (liquid smoke), which has been shown to eradicate insects and fungi [66]. However, careful consideration of dose and treatment frequency is crucial to ensure effective recovery. Professional guidance is necessary to ensure proper treatment and care, allowing infected trees to regain their optimal growth. Fertilization is important to optimize the growth of trees in Bedegung, as it enhances nutrient absorption and promotes healthy development [41]. The type and timing of fertilizer application should be adjusted seasonally to maximize its effectiveness. During the dry season, compost fertilizer and regular watering are recommended to improve nutrient uptake and increase soil moisture content [67]. In contrast, during the rainy season, manure should be applied by burying it around tree roots, allowing nutrients to gradually seep into the soil [68].

Regular weed removal around tree roots is essential for promoting tree growth because weeds compete with trees for nutrients. Eliminating weeds helps to reduce the risk of nutrient deficiencies, ensuring that trees receive adequate resources [42]. This practice should be complemented by soil loosening, which enhances water absorption while maintaining the soil temperature and humidity [11]. Additionally, removing dead-standing trees is important to minimize canopy disturbances and provide space for other trees to grow. However, this process must be carried out carefully to avoid damaging healthy thriving trees. Although logging and thinning may temporarily reduce carbon storage, optimizing the growth of the desired tree species remains essential for long-term sustainability [55].

Enhancing forest management through tree care activities is essential for maintaining forest health, which in turn supports ecosystem sustainability [69]. While most tree-care actions can be implemented comprehensively, thinning activities focus specifically on the removal of selected trees. The initial technical steps involved identifying trees that should be preserved, particularly those that contribute significantly to annual CO₂ sequestration, such as *Bayur* (*Pterospermum javanicum*) and *Jamblang* (*Syzygium cumini*), both members of the PFT guild. A 10 meters radius should be measured around these species to establish priority zones for conservation. Within these zones, climax-type trees should be prioritized for maintenance, whereas pioneer-type trees should be targeted for removal. However, it is equally important to preserve fast-growing trees to sustain the total annual CO₂ sequestration in Bedegung. Therefore, only the PSI guild, which consists of slow-growing, shade-intolerant pioneer species, should be considered for thinning. The PSI guild includes just two species: *Asam Jawa* (*Tamarindus indica*) and *Tembesu* (*Cyrtophyllum fragrans*). This targeted thinning approach helps to minimize biodiversity loss, thereby preserving the species diversity and ecological integrity of Bedegung.

The success of the rehabilitation efforts in Bedegung can lead to a progressive increase in CO₂ sequestration each year. Additionally, biodiversity in this area contributes to ecological resilience and serves as an essential reserve of germplasm, both locally and globally [1]. Because Bedegung lies outside the state forest zone, the local community has easier access to non-timber forest products, particularly forest fruit trees that offer economic potential. Several species produce marketable fruits, including *Janitri* (*Elaeocarpus angustifolius*), *Rukam* (*Flacourtia rukam*), *Durian* (*Durio zibethinus*), *Buni* (*Antidesma bunius*), *Lobi-lobi* (*Flacourtia inermis*), *Petai* (*Parkia speciosa*), *Mindi* (*Melia azedarach*), *Matoa* (*Pometia pinnata*), *Rambutan* (*Nephelium lappaceum*), and *Jamblang* (*Syzygium cumini*). These species enhance the economic benefits to local communities by enabling them to harvest and sell fruits and create alternative income sources. Thus, Bedegung not only contributes to climate change mitigation through carbon sequestration but also provides direct economic benefits to the surrounding community.

Conclusion

Tree growth in Bedegung is influenced by multiple factors, including weather conditions, competition among individuals, pest and disease disturbances, succession processes, and species-specific growth characteristics. Pioneer species exhibited greater resilience to external stress, fast-growing species had greater growth acceleration, and shade-tolerant species demonstrated greater competitive resistance. The pioneer–fast growing–shade tolerance (PFT) guild exhibited the most optimal growth, with the highest annual CO₂ sequestration estimated at $4.43 \pm 3.52 \text{ tCO}_2 \text{ ind}^{-1} \text{ ha}^{-1} \text{ y}^{-1}$. *Bayur* (*Pterospermum javanicum*), a member of the PFT guild, was identified as the optimal species, achieving the highest DBH increment of $8.23 \pm 2.77 \text{ cm y}^{-1}$ and CO₂ sequestration of $10.02 \pm 6.98 \text{ tCO}_2 \text{ ind}^{-1} \text{ y}^{-1}$. Additionally, *Bayur* exhibited strong competitive dominance, effectively eliminating surrounding trees. This ability is reflected in its increasing $1/CI_i$ value, which rose from 0.62 in 2020 to 4.38 in 2023. Initially, seven competing trees surrounded Bayur in 2020; however, by 2023, only two trees remained. To optimize forest management in Bedegung, the following actions are recommended: preserving seedlings and implementing thinning to reduce competition between trees, maintaining high carbon-absorbing trees, and treating trees affected by pests and diseases. Fertilizing, removing weeds, and cutting down dead standing trees. However, to balance CO₂ sequestration and competition, *Bayur* should receive intensive care to maintain its ecological role. Understanding tree competition dynamics is essential for determining optimal planting densities and guiding thinning strategies for forest rehabilitation effectiveness, contributing to climate change mitigation by fostering healthier and more resilient forest ecosystems.

Author Contributions

MAKB: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing – original draft and editing; **HO:** Methodology, Supervision, Writing – review; **AA:** Conceptualization, Resources, Validation; **ZAA:** Methodology, Investigation, Formal analysis; **DM:** Methodology, Investigation; and **KS:** Investigation, Project administration.

Conflicts of Interest

There is no conflict of interest in this research paper.

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