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Potential Use of *Shorea leprosula* for Rehabilitation of Degraded Tropical Production Forest Ecosystems

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ABSTRACT

The diverse forests in Indonesia require proper management to preserve their delicate ecosystems. Limited production forests (HPT) are prone to damage and require careful rehabilitation to restore them to their original state. Native tree species such as *Shorea leprosula* are essential for the success of land and forest rehabilitation in HPT areas. This study aimed to assess the potential of *S. leprosula* species for HPT rehabilitation by examining its growth in the Gunung Dahu Research Forest (GDRF) by measuring the percentage of live plants, tree growth, and soil improvements under *S. leprosula* stand in sloping land. The results showed that *S. leprosula* had fast (1.25 cm/year) to very fast (1.79 cm/year) diameter growth, a dense canopy cover with a leaf area index of 2.88, and improved soil physical (soil moisture of 55.54%, topsoil thickness of 6.2 cm, and litter thickness of 16 cm) and chemical properties (pH of 5.2, soil organic carbon of 3.85, total nitrogen of 0.3, carbon-to-nitrogen ratio of 12.8, available phosphorus of 35.3, and exchangeable potassium of 0.76). Therefore, the successful rehabilitation of *S. leprosula* in GDRF indicates that it can potentially rehabilitate other HPT areas with similar environmental and site conditions.

1. Introduction

The restoration of forested ecosystems has become a growing concern on a global scale over the last few decades. One of the leading contributors to global climate change is Indonesia, which has been responsible for significant emissions resulting from deforestation (Basuki et al. 2022). It is widely accepted that the primary cause of climate change is the conversion of forests and land, which releases substantial amounts of greenhouse gases into the atmosphere. The primary actions required to stabilize the climate include avoiding further deforestation and increasing reforestation, which have long been recognized as critical steps to achieve successful forest rehabilitation (Austin et al. 2020). A thorough comprehension of the diverse conditions of forests, particularly those in Indonesia, is essential to achieving effective forest rehabilitation.

Indonesia's government divides forests based on their function, consisting of protection forest, conservation forest, and production forest. A production forest is a forest area that produces forest products in the form of timber or non-timber. Based on the Indonesia Ministry of Forestry Regulation Number 50 of 2009, production forests are further divided into permanent production forest (*Hutan Produksi*/HP), convertible production forest (*Hutan Produksi dapat Dikonversi*/HPK), and limited production forest (*Hutan Produksi Terbatas*/HPT) based on factors such as slope class, soil type, and rain intensity. HPT refers to a forest region prone to damage if large-scale forest exploitation occurs, such as in HP. Therefore, special regulations are imposed on HPT in its production business. Due to the high susceptibility of HPT to damage, a succession of treatments is necessary to guarantee the efficacy of rehabilitation, both during the logging process and afterward. In production forest management, productivity becomes a criterion that should be considered. Productivity itself depends on on-site quality and the development of silvicultural techniques. The main challenge in rehabilitating logged overproduction forests is creating growth site conditions suitable for the growth of dipterocarp species (Pamoengkas 2010). The growth of Southeast Asian dipterocarp forests varies from 8 m^3/ha/year (Appanah and Weinland 1993) to 17 m^3/ha/year (Evans 1982). Based on the findings, the new planting technique (line planting) is implemented to accelerate the growth of dipterocarps species.

Limited production forests have at least one or more of the following criteria: slopes up to 40%, high rain intensity (> 27.7 mm/day of rain), erosion-sensitive soils with slopes > 15% (Indonesian Government Regulation Number 23 of 2021 and Indonesian Minister of Agriculture Decree Number 837/Kpts/Um/11/1980). The Gunung Dahu Research Forest (GDRF) area has topographic characteristics that similarly reflect the conditions of HPT (slopes < 40%). According to Rachmat et al. (2021), GDRF was built to assess the adaptability of species from the family Dipterocarpaceae and test them using various rehabilitation techniques and patterns. In 26 years, GDRF has evolved into a thriving experimental site for restoring hilly terrain, serving as a prime example for rehabilitating HPT in the tropical forests of Indonesia.

For the rehabilitation process to be successful, specific knowledge and experience in soil characteristics, plant species selection that match the site conditions, planting techniques, and vegetation maintenance after the plantation are required (Mills et al. 2015). Dupuy and Chazdon (2008) suggested that the choice of management system for secondary forests can strongly influence the direction and rate of succession. Management systems that mimic natural canopy gaps could enhance tree species diversity and favor the regeneration of shade-tolerant species, potentially accelerating the convergence of secondary stand to old-growth forest composition. Selecting the appropriate plant species is essential in ensuring the degraded forest ecosystem can recover to its initial state. In selecting plant species, it is important to consider their tolerance to degraded soil conditions and their potential to restore the vegetation structure and composition (Humsa and Srivastava 2015). Native timber trees are often preferred for forest rehabilitation because they have adapted to the local conditions and are better suited to restoring the ecological integrity of the forest (Lu et al. 2017). It is estimated that dipterocarp species' growth and regeneration rate has decreased in the logged-over forest. Many logged-over forests still contain enough residual dipterocarp trees to give rise to a sufficient supply of ephemeral seedling stock.

Due to repeated selective cutting, residual dipterocarp trees are scarce or lack high-valued timber. An additional source of valuable timber could be obtained by planting dipterocarps in line. Enrichment planting is applied to add natural regeneration where this is insufficient. The best-known enrichment planting method is line planting, which has several variants throughout the tropics (Lamprecht 1989). The most important conditions for the success of line planting are light control, species choice, and tending intensively (Weidelt 1996). The most critical treatment is an improvement of light conditions of the seedlings and saplings by release cutting or canopy opening.

For these reasons, it is important to understand the potential of the native timber trees to increase vegetation structure and composition following the rehabilitation process. Rehabilitation using native plants effectively enhances biodiversity and restores forest resilience, as shown by some research (Baughman et al. 2022; Lu et al. 2017). Besides, native species show necessary adaptation for establishment in steep slope environments (Gastauer et al. 2022). This study aims to assess the prospects for limited production forest rehabilitation using *Shorea leprosula* species based on the growth of *S. leprosula* in GDRF.

2. Materials and Methods

2.1. Study Site Description

The research was conducted in Gunung Dahu Research Forest (GDRF) in January–April 2022. The research plot is located in Leuwiliang, Bogor Regency, Indonesia (**Fig. 1**). In general, GDRF receives rainfall for about 27.0 mm/day (BPS 2023) and has a type B climate with 80% relative humidity with an average temperature of 30ºC (Rachmat et al. 2018). The study plot has hilly and steep topography with a slope range between 15–45% and an altitude ranging from 550–900 meters above sea level. The soil type in GDRF is generally reddish-brown latosol (inceptisol), classified as moderately erosion-sensitive soil (Rachmat et al. 2018). With these factors, GDRF has a score of 140, which perfectly reflects the condition of limited production forest (HPT score: 125–174) based on the Minister of Agriculture Number 837/Kpts/Um/1980.

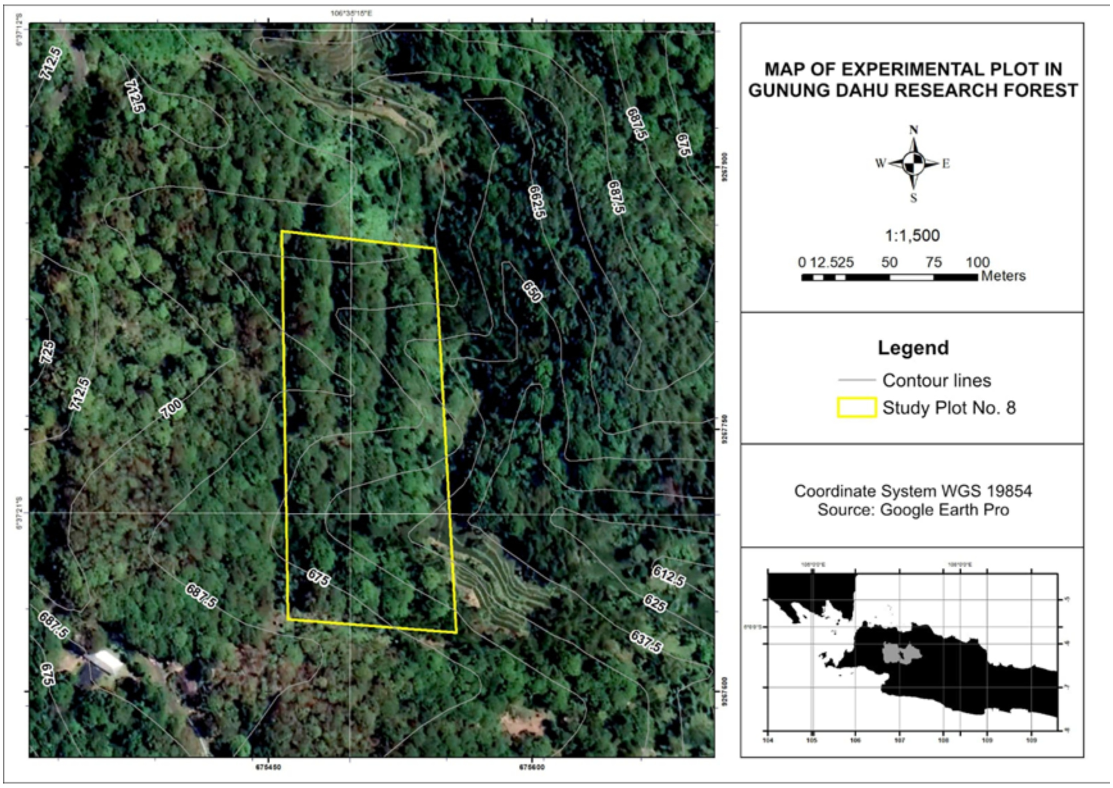

Fig. 1. Map of experimental plots in GDRF, Bogor, Indonesia.

2.2. Sample Plot

The study plots cover an area of 100 m × 100 m (1 ha). The research plots were selected on the line planting technique for *S. leprosula* (**Fig. 2**). The line planting pattern is a planting pattern consisting of planting lines and spacing lines (**Fig. 1** and **Fig. 2**). Plants were planted in planting lines with a spacing of 2 m × 2 m along a 10 m × 100 m lane. The research plot consisted of 3 planting lanes that cut across two hillsides facing each other (**Fig. 1**). The slope class is used as a sampling parameter, which is divided into three classes, namely mild (15–25%), steep (> 25–45%) and very steep (> 45%).

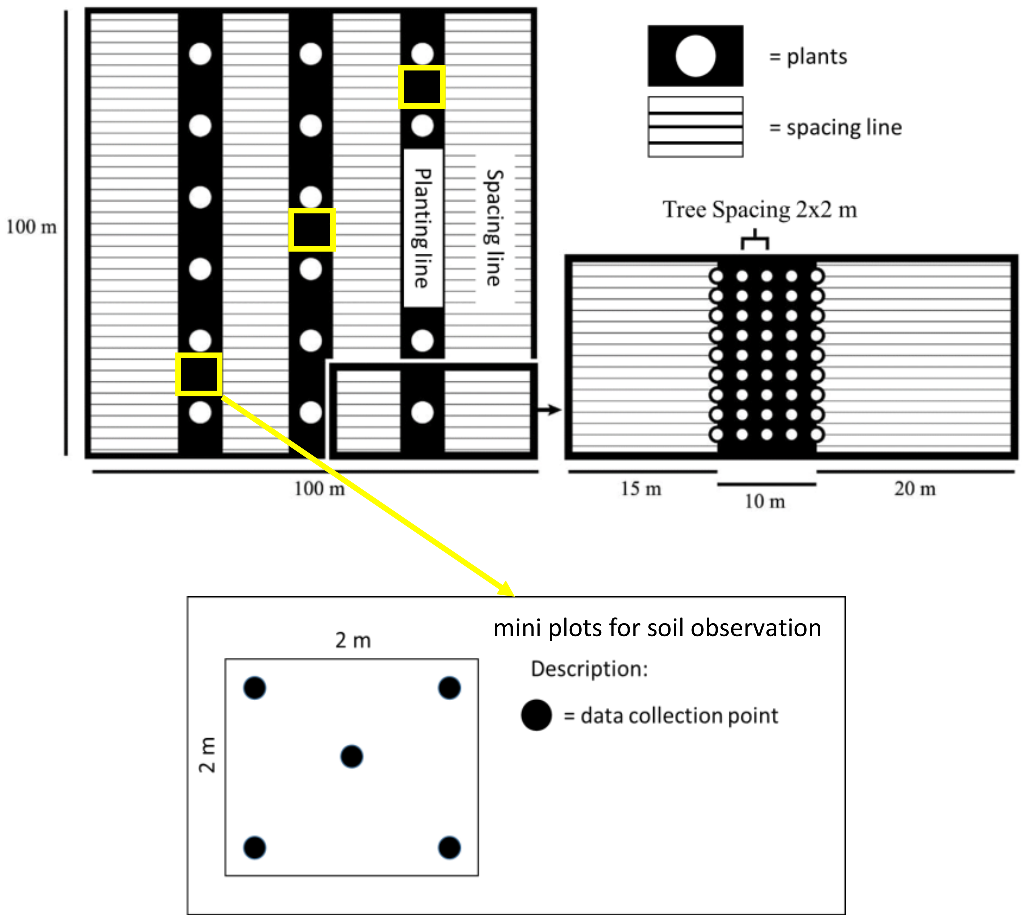

Fig. 2. Study plot layout.

2.3. Materials

The materials used in the study were *S. leprosula* stands planted with a line planting pattern (Plot number 8), soil samples from different slope range classes, soil borer, ruler, phi-band, camera with fish eye lens, and haga hypsometer tools.

2.4. Observation parameters

The observed parameters were tree height and diameters, canopy cover, soil physical (soil water content, topsoil, and litter thickness) and chemical (pH, soil organic carbon, total nitrogen, carbon-to-nitrogen ratio, available phosphorus, and exchangeable potassium) properties, natural regenerations and understory vegetation. The secondary data used is data collected indirectly in the form of an overview and map of the research location, previous year's data, climatic conditions, and other data related to this research based on documents and previous research data (Attarik et al. 2021; BPS 2023; Rachmat et al. 2020).

2.5. Data Collection

2.5.1. Trees diameter and total height mean annual increment (MAI) measurement

Growth data was collected using the census method, in which every tree was measured. The tree diameter at breast height (DBH) was measured using a phi-band, and the tree's total height was measured using a haga hypsometer.

2.5.2. Leaf area index (LAI) measurement

Canopy cover was measured by taking canopy photos at various slope classes and slope positions using a fisheye camera lens. Canopy photos were then processed using the Hemiview application to obtain Leaf Area Index (LAI) values as canopy cover values. The LAI value was then interpreted into the type of canopy shade according to Wickramathilaka (2022).

2.5.3. Soil and natural regeneration

Soil samples were obtained compositely at 5 points on each class and slope position using a soil sampler. Topsoil and litter thickness were measured by digging the soil for 50 cm at each topographic parameter. Natural regenerations were observed in a 2 m × 2 m mini-plot (**Fig. 2**) along with the soil sample.

2.6. Data Analysis

2.6.1. Diameter and total tree height mean annual increment (MAI)

Data on diameter and height were obtained to calculate the MAI value, following the Equation 1 and Equation 2.

$$Idi = \frac{di}{ti} \tag{1}$$

$$Ihi = \frac{hi}{ti} \tag{2}$$

where *Idi* is diameter MAI in year-i (cm/year), *Ihi* is height MAI in year-i (m/year), *di* is the average diameter in the-i planting year (cm), *hi* is the average height in the-i planting year (m), and *ti* is plant age in the-i planting year (year).

2.6.2. Soil physical and chemical properties

Soil samples were sent to the SEAMEO BIOTROP soil laboratory to be analyzed for physical (soil water content) and chemical (pH, soil organic carbon, total nitrogen, carbon-to-nitrogen ratio, available phosphorus, and exchangeable potassium) properties.

2.6.3. Effect of slope on trees growth

Growth data were analyzed using the ANOVA Test with a 95% confidence level to determine the effect of slope classes on each growth parameter.

3. Results and Discussion

3.1. Growth Prospects of Shorea leprosula

Land and forest rehabilitation (RHL) programs are intricate and lengthy processes requiring thorough evaluation. It is crucial to use a diverse set of indicators to understand their success comprehensively. These indicators include land and forest dynamics, soil quality, water availability, biodiversity, socio-economic impacts, and institutional changes. While a survival rate of ≥ 60% of planted trees is a standard metric for success, this alone does not capture the full scope of RHL outcomes due to its long-term and multifaceted nature. Meanwhile, according to Indrajaya et al. (2022), RHL can be declared successful if the planted vegetation can survive, grow, and reproduce independently at an adequate level for a long time.

As a research site, GDRF's topography reflects the topographic conditions of Indonesia's natural forests, which vary from flat to sloping and steep slopes. This makes GDRF play a significant role in natural forest rehabilitation efforts where various techniques and planting patterns are applied to multiple species within Dipterocarpacae families (Attarik et al. 2021). One of the planting patterns tested on *S. leprosula* species in GDRF is the line planting pattern. The line planting pattern provides unplanted lines called spacing lines that give space for plants in the planting lines to receive optimal sunlight and provide biodiversity conservation (Rachmat et al. 2020). This makes the line planting pattern suitable to be applied in logged natural forests and HPT in Indonesia because it can improve its plants' growth performance and provide a conservation function (Iskandar et al. 2017; Pamoengkas and Prasetia 2014).

The research plots in Plot 8 were planted using the line planting technique with a spacing of 2 m × 2 m and were planted in three planting lines measuring 10 m × 100 m. The spacing arrangement in the planting lines resulted in 250 trees in one planting line, with 750 plants per hectare. During the research, only 244 trees were found in the research plot. The details of tree survival in each planting line are presented in **Fig. 3**. Extreme topographic conditions led to high tree mortality (Lan et al. 2020). However, the canopy cover conditions in the research plots remained relatively dense (**Fig. 4**), with LAI values ranging from 1.4 to 3.4. A dense canopy cover prevents soil erosion by intercepting the rainfall, reducing its impact on the forest floor, and minimizing soil damage.

The selection of native species for ecological restoration is much more complex and challenging than selecting plant materials for monoculture plantations (Meli et al. 2014; Stanturf et al. 2014; Vogel et al. 2015). Some native species are slow-growing and require a stable climate to grow optimally, which can prolong the rehabilitation process (Heidi et al. 2022). *S. leprosula* is a timber species known for its use in veneers, and it is widely planted on TPTI-SILIN systems (Indonesia's Selective Cutting System in natural forests enhanced with intensive silvicultural practices). This species is also known as the native timber of West Indonesian natural forests. Among the species in the Dipterocarpaceae family, *S. leprosula* is classified as a fast-growing species with an average diameter increment of 1.47–2.09 cm/year (Kamarubayana et al. 2019). Still, it is also a climax species that occupies the top canopy layers in natural forests. In its early stages, *S. leprosula* requires about 74–100% light, so the canopy is categorized as dense (Duryat et al. 2023) to support optimal growth. In this case, the line planting technique can provide these conditions and is suitable for planting *S. leprosula*.

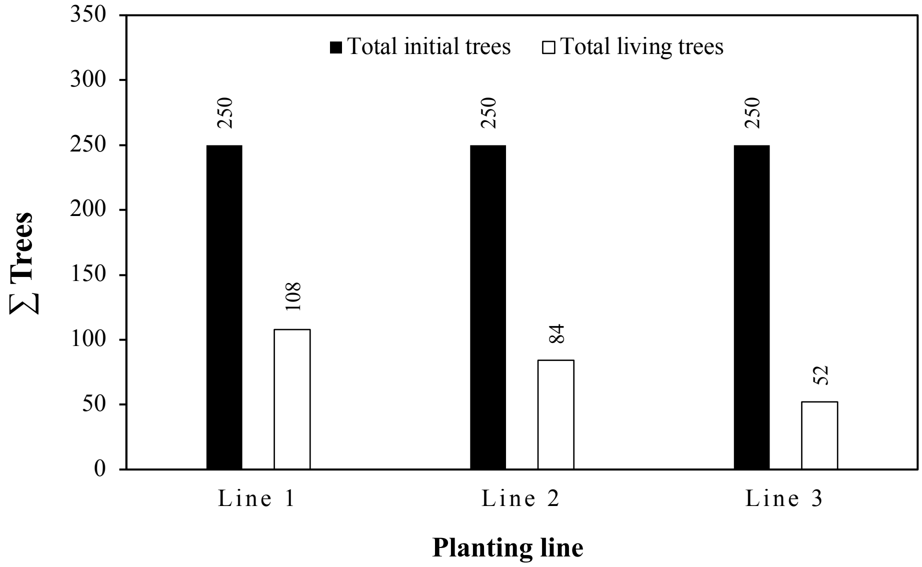

Fig. 3. Comparison of tree survival in each planting line.

Fig. 4. Dense canopy cover on very steep slopes.

The GDRF location is quite extreme for the growth of *S. leprosula* because this species naturally grows and is distributed in lowland dipterocarp forests with an altitude of 0–500 m above sea level (Widiyatno et al. 2020). The research plot is a Dipterocarpacae plantation forest located 713 m above sea level, so it is categorized as a hilly dipterocarp forest. Compared to its natural habitat, this condition is elevated enough for *S. leprosula* to thrive. The tree's growth can be seen in **Table 1**. Even though the elevation of the research plot is too high for the natural habitat of *S. leprosula*, this species can grow well, as indicated by the diameter increment that can reach the fast (1.25 cm/year) to the very fast (1.79 cm/year) category (Afiana et al. 2021; Attarik et al. 2021). However, the diameter increment is not significantly influenced by differences in slope class.

Similar data were also obtained by Pamoengkas et al. (2020), where the diameter increment of *S. leprosula* was found to be insignificant at various slope class variations. In addition, research by Abugre and Agbeshie (2021) also showed that slope gradients did not significantly affect the diameter of various tree species. Interestingly, the plant height increment in different slope classes showed an increase in plant height increments when the slope class was steeper (Attarik et al. 2021). This rapid plant growth rate indicates that applying line planting patterns in *S. leprosula* is very effective on sloping lands, so it is prospective for planting in HPT.

Table 1. Recapitulation of *S. leprosula* growth on various slope classes

Slope Class	MAI of height (m/year)*	MAI of diameter (cm/year)	LAI*
Mild (15–25%)	0.779 ± 0.033a	1.12	1.408 ± 0.102a
Steep (> 25–45%)	0.983 ± 0.029b	1.07	2.235 ± 0.107b
Very steep (> 45%)	0.987 ± 0.043b	1.25	3.371 ± 0.107c

Note: * are significantly affected by slope with Anova test results with a 95% confidence interval.

In forest rehabilitation programs, the availability of seedlings is essential to support planting activities and is a success factor for rehabilitation activities. The abundance of natural seedlings in the research plot was only found in the very steep slope class, precisely in the valley position, with a density of 13.888 individual seedlings per hectare (individual/ha). Seed dispersal of Dipterocarpaceae species is strongly influenced by wind because the fruit has a wing structure. In addition, in other flatter GDRF slopes, the abundance of natural seedlings can reach 929 individuals/ha (Malinda et al. 2022). The distribution of natural seedlings concentrated at a point such as in the valley in the research plot will eventually form a pure stand of *S. leprosula* to be used as a source of natural seedlings potentially. A similar phenomenon was found for *Shorea peltata* in Bukit Tigapuluh, where on sloping sites, *S. peltata* saplings were concentrated in the valley (Subiakto et al. 2016). In addition, another study stated that GDRF could be designated as an identified seed stand for *Shorea pinanga* (Rachmat et al. 2021). The existence of *S. leprosula* saplings in the GDRF area proves that choosing this species for rehabilitation in HPT is ecologically appropriate since its natural ability to regenerate is already in progress.

3.2. Soil Characteristics in Gunung Dahu Research Forest

Restoration of degraded and open production forests takes a very long time and is challenging to restore to its original condition. Especially in tropical rainforests with high rainfall that experience intensive erosion, the nutrients in the forest site are drastically reduced (Olivera et al. 2019; Panagos et al. 2017). Understanding the water balance in forest ecosystems is very important so that the available water can be adequately managed so plants can utilize it. Although the soil is rich in nutrients, without enough water, the nutrients will not be available for plant growth (Utomo et al. 2016). Therefore, in addition to reforestation or planting activities, site management and understanding site conditions are essential for soil conservation and are the keys to successful rehabilitation efforts (Hartati and Sudarmadji 2016).

The research plots in GDRF had relatively moist soil content ranging from 51–55% (**Table 2**). Soil water content was higher on the valley slope, where water tended to collect. *S. leprosula* can grow on poorly drained soils. However, in the sapling phase, *S. leprosula* requires at least 60% moisture content to support its optimal growth, which was available in the research plots (Panjaitan et al. 2012). The thick litter layer in the research plot (6.7–16.4 cm) is due to *S. leprosula's* good litter productivity, which later decomposed to form topsoil (Widiyatno et al. 2020). Inputs of litter enrich the soil with nutrients by decomposition. This natural nutrient supply reduces the need for intensive fertilizer inputs, making rehabilitation more sustainable and cost-effective. Soil types in the research plot were classified as reddish brown latosol (inceptisol) with a clay structure (Rachmat et al. 2020). Soils with a clay structure had high cohesion potential due to the large amounts of clay colloids. This soil structure can prevent excessive erosion from surface runoff (Afandi et al. 2021).

Table 2. Soil physical properties at different slope classes

Sample	N (individual/ha)	Water content (dry base %)	Topsoil (cm)	Litter thickness (cm)
Mild	49	54.36 (moist)	5.3	10.6
Steep	101	51.88 (moist)	6.2	16.4
Very steep	81	55.54 (moist)	4.6	6.7

The pH of the research plot is on the acidic side, measuring 5.2, which is typical of tropical rainforest soils due to the high level of microorganism activity during decomposition. The soil organic carbon, total nitrogen, and available phosphorus contents are classified as high, medium, and low (**Table 3**). Additionally, these contents tend to increase with the increase in slope class. The exchangeable potassium value and carbon-to-nitrogen ratio in the research plot are classified as low. A low carbon-to-nitrogen ratio indicates that the soil is more likely to supply nitrogen to plants.

Table 3. Soil chemical properties at different slope classes

Sample	pH	SOC	Total N (%)	C/N ratio	Available P (ppm)	Exchangeable K
Mild	5.2 (acid)	3.29 (high)	0.24 (moderate)	13.7(low)	35.3 (high)	0.75 (low)
Steep	5.2 (acid)	3.71 (high)	0.28 (moderate)	13.3(low)	33.7 (high)	0.75 (low)
Very steep	5.2 (acid)	3.85 (high)	0.3 (moderate)	12.8(low)	32.9 (high)	0.76 (low)

Note: SOC = soil organic carbon.

Generally, the soil properties were higher on the very steep slope (**Table 2** and **Table 3**), meaning the steep slopes could support better plant growth. This also seems to be why the tree's diameter, height, and canopy cover were higher on the steep slope. These nutrients support plant growth, contributing to better diameter growth, height, and canopy cover. This happened because the very steep slopes were located at the bottom of the slope next to the valley. This position will benefit plants by allowing them to accumulate soil and obtain nutrients transported by erosion from the top of the slope.

The robust growth of *S. leprosula* in the soil conditions present at GDRF is a testament to its exceptional adaptability to degraded lands. The species' innate ability for self-pruning effectively synergizes with its growth environment, facilitating a rapid recovery of damaged ecosystems. Additionally, *S. leprosula's* capacity for robust canopy closure rapidly mitigates soil damage caused by rainwater erosion, further enhancing its ecological restorative potential.

The prospect of rehabilitation in limited production forests using *S. leprosula* planted with line planting has enormous potential to develop. Even in steep slope classes, the growth of diameter and height of *S. leprosula* plants can reach the fast-very fast category. Canopy cover is also relatively dense, which can reduce soil damage due to erosion. *S. leprosula's* ability to produce litter means it can supply nutrients well without intensive fertilizer inputs. Generally, soil nutrient content was higher in the steep slope class. The high soil fertility in the very steep slope class supports plant growth so that both diameter growth, height, and canopy cover are better in the very steep slope class.

4. Conclusions

The prospect of rehabilitation in limited production forests using *S. leprosula* planted with line planting has enormous potential to develop. Even in an area with steep slopes, *S. leprosula* has shown promising growth rates with an MAI of 1.79 cm/year, suitable for rehabilitation in challenging terrain. Canopy cover is also relatively dense, which is advantageous for preventing soil erosion. *S. leprosula's* ability to produce litter reduces the need for intensive fertilizer inputs, making the rehabilitation process more sustainable and cost-effective. The soil in the very steep slope class was found to be particularly fertile, with higher levels of water content (55%) and soil organic carbon (3.85), as well as significant levels of total nitrogen (0.3%) and available phosphorus (32.9). These nutrients support plant growth, contributing to better diameter growth, height, and canopy cover on steep slopes. Recommendation: The rehabilitation results using *S. leprosula* species in the GDFR can be used as a policy basis for a limited production forest rehabilitation program using *S. leprosula* species. For this reason, increasing the research scale can be expanded to various locations.

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