

Agroforestry-based plant diversity and its implications for ecosystem restoration in Gunung Leuser National Park, Indonesia

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Abstract. Saraan M, Rahmawaty, Harahap RH, Hilmi E, Delvian, Sibarani R. 2025. Agroforestry-based plant diversity and its implications for ecosystem restoration in Gunung Leuser National Park, Indonesia. *Biodiversitas* 26: 6367-6377. The Indonesian government promoted conservation partnership schemes in Gunung Leuser National Park (GLNP) to resolve land-use conflicts while supporting ecosystem restoration and local livelihoods, where communities implement agroforestry that combines native species and Multi-Purpose Tree Species (MPTS). However, empirical evidence on plant diversity and vegetation composition within these systems remains limited. This study analyzes vegetation structure, species composition and plant diversity in conservation partnership areas and assess their contribution to ecosystem recovery, including provides recommendations for sustainable management. Vegetation surveys were conducted on 1-ha plots across three stations representing upper, middle, and lower areas. Species composition, dominance, and diversity were quantified using Importance Value, Shannon–Wiener and Margalef Species Richness Index. The upper area was dominated by native dipterocarps (*Dryobalanops aromatica*), while lower areas were characterized by cultivated MPTS (*Parkia speciosa*), reflecting trade-offs between natural regeneration and livelihood-oriented agroforestry practices. Species diversity ranged from moderate to high, with native species concentrated near rehabilitation zones and cultivated species in lower areas, which are intensively managed by communities. Overall, agroforestry within conservation partnership enhances biodiversity, supports ecological recovery, and strengthens livelihoods while offering scalable pathways for integrating restoration and biodiversity enhancement with community-based forest management. Strengthening native-species enrichment is recommended to balance ecological objectives with community needs and guide large-scale restoration policies.

Keywords: Agroforestry, conservation partnership, species composition, vegetation analysis, vegetation structure

INTRODUCTION

Forests comprise diverse vegetation communities that shape distinct physiognomies as species adapt to local habitats over time (Rawana et al. 2022). This vegetation underpins key ecosystem services, including water regulation, erosion control, climate stabilization, and biodiversity conservation (Oktaviani et al. 2017; Warda et al. 2024), while also supporting forest-dependent community livelihoods through the provision of food, medicine, energy, and income (Ridwan et al. 2022).

Balancing conservation and local livelihoods are challenging in protected areas with strict access rules. Gunung Leuser National Park (GLNP), Indonesia, covering nearly 1 million ha across North Sumatra and Aceh, still faces deforestation driven by agriculture, illegal logging, and land conversion, especially in buffer zones (Condro et al. 2022). These pressures have altered vegetation structure, reduced biodiversity and threatened ecosystem resilience.

Indonesia has promoted community-based forest management through the Social Forestry under Ministerial Regulation No. P.9/MENLHK/SETJEN/KUM.1/3/2021 (Ministry of Environment and Forestry 2021). Conservation

partnerships support agroforestry, silvopasture, and silvofishery as mechanism to link restoration with livelihoods (Gunawan et al. 2022). It is implemented through collaboration between park authorities and Conservation Farmers Groups, allowing them to restore degraded forest while improving household welfare (Saipurrozi et al. 2018; Pohan and Abidin 2024).

These initiatives are grounded in ecological restoration principles, defined as assisting degraded ecosystems to recover toward their pre-disturbance structure, composition, and functions (Gann et al. 2019). In GLNP, restoration is essential to counter degradation, restore ecological functions, and sustain ecosystem services and biodiversity (Sloan et al. 2018; Rahmawaty et al. 2025). Tree diversity plays a crucial role in these processes by enhancing structural complexity, supporting natural regeneration, regulating microclimates, and contributing to storage and soil nutrient cycling (Song et al. 2020; Ouyang et al. 2021; Aye and Shibata 2023).

Accordingly, tree diversity provides a robust ecological indicator for assessing restoration outcomes and anticipating long-term ecosystem stability in conservation partnership areas. Vegetation analysis is widely applied to evaluate

restoration effectiveness because it captures species composition, vegetation structure, ecological functions and the effectiveness of restoration actions (Nafeesa et al. 2021; Petropavlovsky and Varchenko 2021).

Agroforestry, particularly MPTS-based, are increasingly recognized as a multifunctional restoration strategy. Empirical evidence shows that it can restore degraded landscapes, enhance biodiversity, stabilize microclimates, sequester carbon, improve water retention, and accelerate soil recovery while supporting local livelihoods (Miller et al. 2019; Rahmawaty et al. 2019; Harahap et al. 2024). Globally, a meta-analysis of Latin American mountain agroecosystems found that agroforestry improves biological activity, soil-based ecosystem functions, and species diversity compared to conventional practices, highlighting its scalability for restoration (Visscher et al. 2023). Similar evidence from Brazil's Atlantic Forest demonstrates that agroforestry improves soil moisture, microclimate regulation, and biodiversity through habitat connectivity, thereby linking ecosystem recovery with sustainable livelihoods (Shenan-Farpón et al. 2021).

Despite these advantages, empirical assessments of tree species composition, dominance, and structural attributes in conservation partnership areas of GLNP remain limited. Recent studies in GLNP have primarily focused on land-use impacts on wildlife habitats (Patana et al. 2023) and community participation in restoration (Khatimah et al. 2019). Specifically, analyses that integrate tree-level species diversity, dominance, and Important Value Index (IVI) across conservation partnership gradients are still scarce, constraining robust and comprehensive evaluation of restoration outcomes.

This study uses the IVI, Shannon-Wiener Diversity Index (H'), and Margalef Species Richness Index (DMg). Ivi captures species dominance and structural recovery,

while H' and DMg reflect plant diversity, evenness, and species richness as indicators of ecosystem stability and regeneration. Together, these indices provide a robust framework for evaluating vegetation recovery across conservation partnership areas.

This study addresses this gap by examining vegetation structure, species composition, and diversity in conservation partnership of GLNP. Specifically, it asks: (i) How does plant diversity vary among agroforestry stations? (ii) How do dominant species contribute to ecological restoration? and (iii) Which management practices can improve ecological resilience and community livelihoods?. The objectives are to (i) assess vegetation structure, species composition, and biodiversity; (ii) identify dominant species and their ecological functions related to restoration; and (iii) propose evidence-based management recommendations to enhance resilience while sustaining livelihoods.

MATERIALS AND METHODS

Study area

The study was conducted in the Gunung Leuser National Park (GLNP) conservation partnership area managed by the Conservation Functional Group (CFG) of Bamban Makmur in Bukit Mas Village, Besitang Sub-district, Langkat, North Sumatra, Indonesia ($3^{\circ}56'22.80''$ to $3^{\circ}57'11.63''N$; $98^{\circ}6'52.72''$ to $98^{\circ}7'24.72''E$; 50 to 200 m asl) (Figure 1). The site has a humid tropical climate with 2,500 to 3,000 mm annual rainfall, an October to April rainy season, mean temperatures of 24 to 30°C, and humidity above 80%.

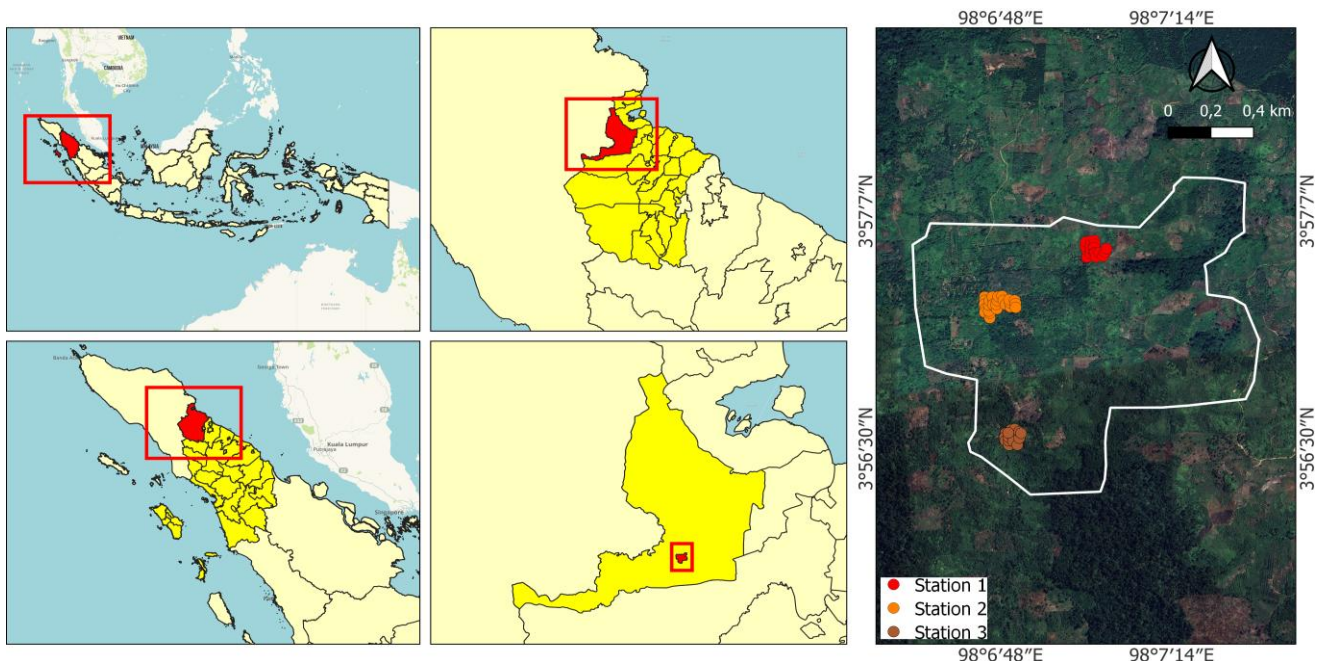


Figure 1. Map the location of the study area in the conservation partnership area of Gunung Leuser National Park (GLNP), Besitang Sub-district, Langkat, North Sumatra, Indonesia

Methods

Vegetation data, focused on tree diversity, were collected using a combination of quadrat plots and line transects (Chen 2023), with plots systematically and purposively placed across three stations. The stations were determined through purposive sampling, based on vegetation condition, land cover, and management practices, to represent the ecological variability within the conservation partnership area adequately. This approach follows Dharmawan et al. (2023), who demonstrated that stratified purposive sampling effectively captures habitat variation in vegetation rehabilitation program in Sumatra and Kalimantan. As species composition and vegetation structure are influenced by prior degradation, land cover, and land-use history, ecological stratification is more appropriate than purely random plot placement.

Purposive sampling may introduce selection bias and limit statistical generalization. However, it aligns with the objective, assessing ecological variation along a restoration–management gradient rather than estimating population-level parameters. This study represents a baseline assessment across three purposively selected stations conducted within a single season; therefore, broader spatial heterogeneity, temporal dynamics, wildlife interactions, abiotic drivers, and multi-actor governance processes were not fully captured. These limitations are detailed in the Limitations section.

Three stations were established: Station 1 (upper area), adjacent to primary forest with closed canopy and near-natural species assemblages. Station 2 (middle area), in the center of the site, dominated by community-based agroforestry with more open canopy. Station 3 (lower area), near the GLNP boundary with high anthropogenic pressure, sparse vegetation, and a greater risk of degradation.

Each station comprised 25 systematically distributed plots, spaced ± 50 m apart along contour-based transects, resulting 75 plots (3 ha). Data analysis in this study focused on tree level, collected from 20 m x 20 m plots, a design widely used in forest vegetation studies and effective for representing community structure (Quon et al. 2020). Recorded data included species identify, Diameter at Breast Height (DBH), total height, and key morphological characteristics. Smaller nested subplots (10 m x 10 m, 5 m x 5 m, and 2 m x 2 m) were established for other vegetation level as part of the field design but were not included in the analysis (Figure 2). Lower level was excluded because tree composition provides more robust indicators of long-term restoration and ecosystem function than early regeneration, which is highly variable in managed restoration landscapes.

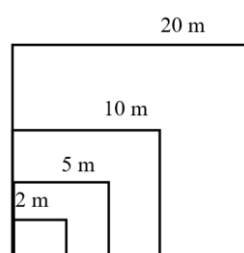


Figure 2. Plot of plant observations

To ensure taxonomic accuracy, all recorded plants were labeled and, where necessary, collected for verification following specimen collection guidelines (Ridwan et al. 2022). This procedure ensured consistency in taxonomic determination and minimized potential errors.

Data analysis

Data analysis using a comparative-descriptive approach using standardized vegetation index calculated separately for each station. The analysis focused on species composition, dominance, and diversity along restoration-management gradient, rather than on statistical test. Inferential statistics were not applied as stations were defined through purposive ecological stratification, which does not meet the assumptions required for population-level inference.

Important Value Index (IVI)

The vegetation analysis was conducted using the IVI, which integrates three key ecological parameters: density, frequency, and dominance. These parameters provide a holistic assessment of species abundance, distribution, and contribution within the community (Ruticumugambi et al. 2024). The following formulas were applied:

$$\text{Density (D)} = \frac{\text{Number of individuals of a species}}{\text{Area of whole plot (ha)}}$$

$$\text{Relative Density (RD}_i\text{)} = \left(\frac{\text{Density of species}}{\text{Total density of all species}} \right) \times 100\%$$

$$\text{Frequency (F)} = \frac{\text{Density of plots found of a species}}{\text{Total of plots}}$$

$$\text{Relative Frequency (RF}_i\text{)} = \left(\frac{\text{Frequency of a species}}{\text{Frequency of all species}} \right) \times 100\%$$

$$\text{Dominance (D)} = \frac{\text{Basal area of species}}{\text{Area of whole sample plot}}$$

$$\text{Relative Dominance (RD}_0i\text{)} = \left(\frac{\text{Dominance of a species}}{\text{Dominance of all species}} \right) \times 100\%$$

$$\text{IVI} = \text{RF} + \text{RD} + \text{RD}_0$$

Shannon-Wiener Diversity Index (H')

The Shannon-Wiener Diversity Index (H'), a widely applied metric that integrates species richness and evenness to characterize community heterogeneity (Omayio and Mzungu 2019). It is calculated using the formula:

$$H' = - \sum P_i \ln P_i$$

H' : Shannon-Wiener Diversity Index, $P_i = \left(\frac{n_i}{N} \right)$, N_i : Number of individuals to- i , \ln : Natural logarithm, N : Total individuals

The Shannon-Wiener Diversity Index values were categorized as low diversity ($H' < 1$), moderate diversity ($H' = 1-3$), and high diversity ($H' > 3$).

Margalef's Species Richness Index (DMg)

The Species Richness Index (R) reflects the diversity of species within a region by calculating the number of species present. The formula is as follows (Magurran 2004):

$$DMg: \frac{(S-1)}{\ln(N)}$$

DMg: Species Richness Index, *S*: Total number of species identified in plot, *N*: Total number of individuals

The Species Richness Index is categorized as Low: ($DMg < 3.5$), Moderate: ($3.5 \leq DMg \leq 5.0$), and High ($DMg > 5.0$).

RESULTS AND DISCUSSION

Structural composition of tree communities in conservation partnership areas

This study conducted analysis by examining vegetation composition and structure of tree-level IVI across the three observation stations, providing a quantitative foundation for understanding species dominance, ecological roles, and

structural composition in the conservation partnership area. The IVI is essential to describe the extent of influence a plant has on its community and is calculated by summing Relative Frequency (RF), Relative Density (RD), and Relative Dominance (RDo), thereby offering a robust indicator of each species' ecological significance and competitive status within the forest community. The following table presents the IVI values for all tree species recorded across Stations 1, 2, and 3, forming the empirical basis for subsequent ecological interpretation and management recommendations.

Important Value Index (IVI) in Station 1

The results of vegetation analysis at the tree-level in Station 1 showed a structurally complex and compositionally diverse assemblage characteristic of recovering mixed forest ecosystem. It is recorded 19 tree species, representing a mixture of dipterocarps, fruit bearing species, pioneers, and cultivated species. The total IVI of 300 confirms balanced calculation across RDi, RF, and RD, providing a robust basis for interpreting ecological structure and species roles (Table 1).

Table 1. The Importance Value Index (IVI) value of all tree level species recorded in Gunung Leuser National Park, Indonesia

| Latin name | Family | RDi | RF | RD | IVI (%) |
|--|------------------|-------|-------|-------|---------|
| Station 1 | | | | | |
| <i>Dryobalanops aromatica</i> C.F.Gaertn. | Dipterocarpaceae | 10.20 | 6.06 | 25.41 | 41.67 |
| <i>Nephelium cuspidatum</i> Blume | Sapindaceae | 14.29 | 9.09 | 12.66 | 36.04 |
| <i>Dipterocarpus grandiflorus</i> (Blanco) Blanco | Dipterocarpaceae | 12.24 | 12.12 | 6.58 | 30.94 |
| <i>Archidendron pauciflorum</i> (Benth.) I.C.Nielsen | Fabaceae | 8.16 | 12.12 | 4.85 | 25.14 |
| <i>Parkia speciosa</i> Hassk. | Fabaceae | 8.16 | 9.09 | 2.69 | 19.94 |
| <i>Sloetia elongata</i> (Miq.) Koord. | Moraceae | 6.12 | 6.06 | 6.81 | 18.99 |
| <i>Shorea coriacea</i> Burck | Dipterocarpaceae | 4.08 | 3.03 | 10.22 | 17.34 |
| <i>Xylopia malayana</i> Hook.f. & Thomson | Annonaceae | 6.12 | 6.06 | 4.05 | 16.23 |
| <i>Baccaurea motleyana</i> (Müll.Arg.) Müll.Arg. | Phyllanthaceae | 6.12 | 6.06 | 2.26 | 14.44 |
| <i>Koompassia malaccensis</i> Maingay | Fabaceae | 2.04 | 3.03 | 9.03 | 14.11 |
| <i>Shorea javanica</i> Koord. & Valetton | Dipterocarpaceae | 4.08 | 3.03 | 3.88 | 10.99 |
| <i>Anthoshorea dealbata</i> (Foxw.) P.S.Ashton & J.Heck. | Dipterocarpaceae | 4.08 | 3.03 | 2.44 | 9.55 |
| <i>Macaranga triloba</i> (Thunb.) Müll.Arg. | Euphorbiaceae | 2.04 | 3.03 | 3.42 | 8.49 |
| <i>Kayea beccariana</i> Baill. | Calophyllaceae | 2.04 | 3.03 | 1.47 | 6.54 |
| <i>Artocarpus odoratissimus</i> Blanco | Moraceae | 2.04 | 3.03 | 1.34 | 6.41 |
| <i>Artocarpus kemando</i> Miq. | Moraceae | 2.04 | 3.03 | 0.99 | 6.06 |
| <i>Shorea</i> sp. | Dipterocarpaceae | 2.04 | 3.03 | 0.86 | 5.93 |
| <i>Aleurites moluccana</i> (L.) Willd. | Euphorbiaceae | 2.04 | 3.03 | 0.53 | 5.60 |
| <i>Durio zibethinus</i> Murray | Malvaceae | 2.04 | 3.03 | 0.51 | 5.58 |
| | | | | | 300.00 |
| Station 2 | | | | | |
| <i>Parkia speciosa</i> Hassk. | Fabaceae | 51.16 | 45.83 | 40.83 | 137.83 |
| <i>Hevea brasiliensis</i> (Willd. ex A.Juss.) Müll.Arg. | Euphorbiaceae | 32.56 | 25.00 | 39.99 | 97.55 |
| <i>Archidendron pauciflorum</i> (Benth.) I.C.Nielsen | Fabaceae | 9.30 | 16.67 | 13.46 | 39.43 |
| <i>Pometia pinnata</i> J.R.Forst. & G.Forst. | Sapindaceae | 2.33 | 4.17 | 2.04 | 8.53 |
| <i>Durio zibethinus</i> Murray | Malvaceae | 2.33 | 4.17 | 1.87 | 8.36 |
| <i>Artocarpus integer</i> (Thunb.) Merr. | Moraceae | 2.33 | 4.17 | 1.81 | 8.30 |
| | | | | | 300.00 |
| Station 3 | | | | | |
| <i>Parkia speciosa</i> Hassk. | Fabaceae | 77.55 | 70.00 | 82.39 | 229.95 |
| <i>Pometia pinnata</i> J.R.Forst. & G.Forst. | Sapindaceae | 8.16 | 10.00 | 6.51 | 24.68 |
| <i>Syzygium malaccense</i> (L.) Merr. & L.M.Perry | Myrtaceae | 6.12 | 6.67 | 4.89 | 17.68 |
| <i>Syzygium polyanthum</i> (Wight) Walp. | Myrtaceae | 2.04 | 3.33 | 1.77 | 7.14 |
| <i>Durio zibethinus</i> Murray | Malvaceae | 2.04 | 3.33 | 1.52 | 6.90 |
| <i>Nephelium lappaceum</i> L. | Sapindaceae | 2.04 | 3.33 | 1.48 | 6.85 |
| <i>Artocarpus odoratissimus</i> Blanco | Moraceae | 2.04 | 3.33 | 1.43 | 6.81 |
| | | | | | 300.00 |

Note: RD: Relative Density, RF: Relative Frequency, RDo: Relative Dominance, IVI: Important Value Index

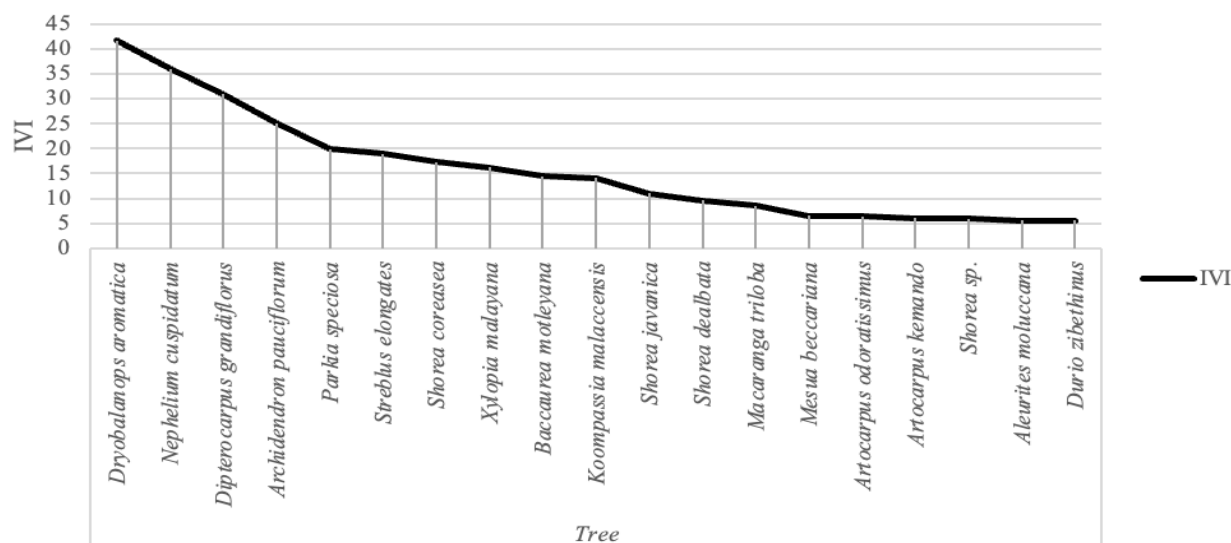


Figure 3. Importance Value Index (IVI, %) of dominant species in Station 1 of Gunung Leuser National Park, Indonesia

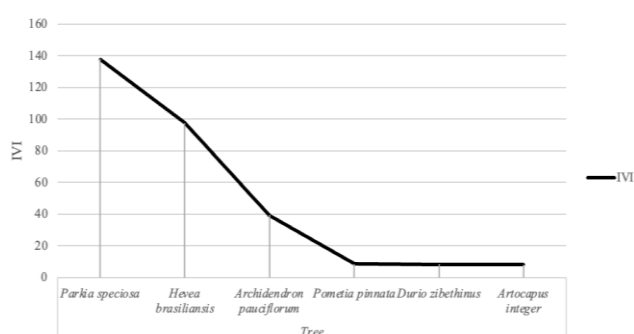


Figure 4. Importance Value Index (IVI, %) of dominant species at tree level in Station 2 of Gunung Leuser National Park, Indonesia

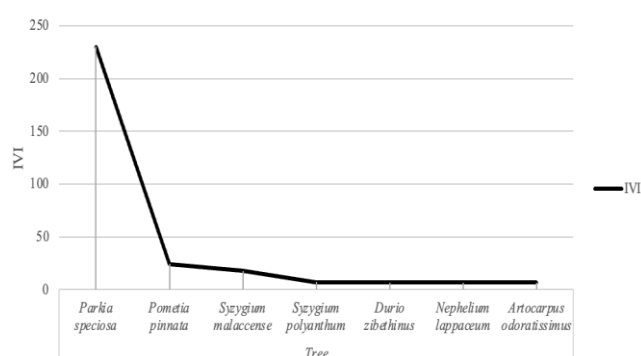


Figure 5. Importance Value Index (IVI, %) of dominant species in Station 3 of Gunung Leuser National Park, Indonesia

The most dominant species was *Dryobalanops aromatica* C.F.Gaertn. with IVI (41.67), followed by *Nephelium cuspidatum* Blume (36.04%), and *Dipterocarpus grandiflorus* (Blanco) Blanco (30.94%), which also recorded high value of RDi, RF, and RD, collectively shaving the upper canopy structure. The species distribution of tree levels is further illustrated in Figure 3.

In addition to IVI, the evaluation of RDi, RF, and RD provides a deeper perspective on species dynamics. Dominant species such as *D. aromatica* and *N. cuspidatum* showed high RDi and RF values, In contrast, species with very low RDi and RF, like *Aleurites moluccana* (L.) Willd. and *Durio zibethinus* Murray, occur rarely and in restricted plots. Table 1 presents the full IVI, RD, and RF values for all species.

Important Value Index (IVI) in Station 2

The vegetation analysis at Station 2 revealed a relatively high species diversity across 25 plots. A total of six species were identified at the tree level. *Parkia speciosa* Hassk strongly dominated Station 2 (IVIs of 137.83%),

consistently followed by higher values of RDi, RF, and RD. Although *Artocarpus integer* (Thunb.) Merr. recorded the lowest IVIs, their presence still contributed to structural stratification and habitat heterogeneity. The species distribution of tree levels is further illustrated in Figure 4.

Important Value Index (IVI) in Station 3

The result of vegetation analysis at Station 3 showed a stratified regeneration pattern. A total of seven species were identified at the tree level. *Parkia speciosa* still dominated Station 3 with a very high IVI value (229.95%), positioning it as an important species in these systems.

The combined RDi, RF, and RD values confirm that regeneration dynamics at Station 3 are driven by the dominance of *P. speciosa* with very high RD. The structural dominance of *P. speciosa* (RD = 82.39%). In contrast, *Artocarpus odoratissimus* Blanco showed the lowest IVI value (6.81%). The distribution of species in this station demonstrates active regeneration process within the agroforestry system. The species distribution is further illustrated in Figure 5.

Species diversity index in the conservation partnership area

The Tree-level species diversity was measured using the Shannon–Wiener Diversity Index (H') and Margalef Species Richness Index (DMg) across the three stations. The H' and DMG values of each station are presented in Table 2. Stations 1 and 2 recorded identical Shannon diversity index values of $H' = 1.19$, both are categorized as moderate diversity category. Meanwhile, Station 3 recorded a lower Shannon index with $H' = 0.89$, which is classified as low diversity.

In addition, the Margalef Species Richness Index values ranged from 1.30 to 1.54. The highest richness value was recorded at Station 3 (DMg = 1.54), followed by Station 2 (DMg = 1.33) and Station 1 (DMg = 1.30). According to these values, all three stations are categorized as low species-richness category. The diversity and richness values for each station are summarized in Table 2.

In this study, Station 1 demonstrates the highest diversity, marked with the presence of native dipterocarps (*D. aromatica*, *Shorea* spp.) coexistence with MPTS. This composition indicates structural complexity comparable to semi-natural forests. Station 2 represents an intermediate diversity, dominated by fast-growing pioneers (*Macaranga* spp., *Mallotus paniculatus* (Lam.) Müll.Arg.) and cultivated fruit trees (*D. zibethinus*, *Citrus* spp.). In contrast, Station 3 recorded the lowest diversity, particularly at the tree level ($H' < 1$), where dominated by *Theobroma cacao* L. and *P. speciosa*. Overall, the findings indicate that the species diversity index varies across stations and consistently reflects differences in vegetation structure and species composition in the GLNP landscape.

Table 3 describes the variation in species richness and composition across three stations within the conservation partnership area. Station 1 recorded the highest species diversity with 28 species, consisting of native dipterocarps (*D. grandiflorus*, *D. aromatica*, *Shorea coriacea* Burck, *Anthoshorea dealbata* (Foxw.) P.S.Ashton & J.Heck., *Shorea javanica* Koord. & Valetton, and *Shorea* sp.) integrated with MPTS (*D. zibethinus* and *P. speciosa*). Station 2 also showed relatively high species richness, dominated primarily by fast-growing pioneer species, including *Macaranga* sp. and *M. paniculatus* alongside MPTS. Conversely, Station 3 contains fewer species, dominated by cultivated species such as *A. integer*, and *Annona muricata* L.. These patterns indicate clear differences in species diversity and composition among the three stations.

Discussion

Species composition on tree communities in conservation partnership areas

The results of the vegetation analysis indicate that the conservation partnership areas are in undergoing active regeneration process shaped by interactions between historical disturbance, community agroforestry practices, and species-specific ecological traits. Station 1 showed the dominance of *D. aromatica*, followed by *N. cuspidatum*

and *D. grandiflorus*, which confirms the integration of forest tree species into community-managed agroforestry practices. This presence of dominant dipterocarpaceae is consistent with the widely recognized role of dipterocarpaceae in maintaining forest structure, regulating ecosystem processes, and contributing to long-term carbon storage (Pratiwi et al. 2024; Raj et al. 2024). Collectively, the species composition indicates an ongoing ecological succession shaped by community-based agroforestry practices, where cultivated fruit trees and native dipterocarps jointly reinforce ecological recovery while contributing to local livelihoods. These findings suggest that multi-species agroforestry systems can be a viable and scalable strategy for ecological restoration in conservation landscapes (Murniati et al. 2022).

The dominance of *P. speciosa* and other MPTS in Station 2 reflecting strong anthropogenic selection for multi-purpose livelihood benefits, particularly its preferential preservation for economic and household uses. This configuration suggests that ecological recovery and livelihood provisioning are occurring concurrently, although native forest components remain secondary. The strong structural role of *P. speciosa* contrasts with the minor contribution of species such as *A. integer*, which support vertical stratification but contributes minimum to overall dominance. The low representation of native taxa indicates reduced taxonomic redundancy despite adequate functional provisioning. These conditions underscore the need for enrichment planting and facilitated natural regeneration to strengthen ecological resilience while sustaining community-based agroforestry.

Station 3 reflects an ongoing and dynamic regeneration process, indicating a maturing agroforestry system. The station is strongly dominated by *P. speciosa*, positioning it as an important species in these systems. Its dominance likely reflects targeted planting due to socio-economic benefits and ecological functions such as nitrogen fixation and soil fertility enrichment (Zhang et al. 2023). Meanwhile, heavy reliance on a single species may reduce ecosystem resilience and threat biodiversity, ultimately undermining long-term restoration objectives. Conversely, species such as *A. odoratissimus* Blanco, with the lowest IVI, represent limited shade tolerance and reduced competitiveness under these conditions.

Table 2. Species Diversity Index (H') and Margalef Index (DMg) across stations in Gunung Leuser National Park, Indonesia

| Growth level | Shannon's Diversity Index (H') | Category | Margalef Species Richness Index (DMg) | |
|------------------|------------------------------------|----------|---------------------------------------|----------|
| | | | Index | Category |
| Station 1 (tree) | 1.19 | Moderate | 1.3 | Low |
| Station 2 (tree) | 1.19 | Moderate | 1.33 | Low |
| Station 3 (tree) | 0.89 | Low | 1.54 | Low |

Table 3. Species found at Stations 1, 2, and 3 in Gunung Leuser National Park, Indonesia

| Family | Latin name | Station 1 | Station 2 | Station 3 |
|------------------|--|-----------|-----------|-----------|
| Anacardiaceae | <i>Mangifera indica</i> L. | + | - | + |
| Annonaceae | <i>Annona muricata</i> L. | - | - | + |
| | <i>Annona squamosa</i> L. | + | - | - |
| Arecaceae | <i>Arenga pinnata</i> (Wurmb) Merr. | - | + | - |
| Clusiaceae | <i>Garcinia mangostana</i> L. | - | + | - |
| | <i>Kayea beccariana</i> Baill. | + | - | - |
| Dipterocarpaceae | <i>Dipterocarpus grandiflorus</i> (Blanco) Blanco | + | - | - |
| | <i>Dryobalanops aromatica</i> C.F.Gaertn. | + | - | - |
| | <i>Shorea coriacea</i> Burck | + | - | - |
| | <i>Anthoshorea dealbata</i> (Foxw.) P.S.Ashton & J.Heck. | + | - | - |
| | <i>Shorea javanica</i> Koord. & Valetton | + | - | - |
| Euphorbiaceae | <i>Shorea</i> sp. | + | - | - |
| | <i>Aleurites moluccana</i> (L.) Willd. | + | - | - |
| | <i>Hevea brasiliensis</i> (Willd. ex A.Juss.) Müll.Arg. | - | + | - |
| | <i>Macaranga rhizinoides</i> (Blume) Müll.Arg. | - | + | - |
| | <i>Macaranga tanarius</i> (L.) Müll.Arg. | - | + | - |
| | <i>Macaranga triloba</i> (Thunb.) Müll.Arg. | + | - | - |
| Fabaceae | <i>Mallotus paniculatus</i> (Lam.) Müll.Arg. | - | + | - |
| | <i>Archidendron pauciflorum</i> (Benth.) I.C.Nielsen | + | - | + |
| | <i>Koompassia malaccensis</i> Maingay | + | - | - |
| Lauraceae | <i>Parkia speciosa</i> Hassk. | + | + | + |
| | <i>Persea americana</i> Mill. | + | + | + |
| Malvaceae | <i>Durio zibethinus</i> Murray | + | + | + |
| | <i>Theobroma cacao</i> L. | + | + | + |
| Meliaceae | <i>Lansium domesticum</i> Corrêa | + | + | + |
| | <i>Melia azedarach</i> L. | - | + | - |
| Moraceae | <i>Toona sureni</i> (Blume) Merr. | - | + | - |
| | <i>Artocarpus heterophyllus</i> Lam. | - | + | - |
| | <i>Artocarpus integer</i> (Thunb.) Merr. | + | + | + |
| | <i>Artocarpus kemando</i> Miq. | + | - | - |
| | <i>Artocarpus odoratissimus</i> Blanco | + | - | + |
| Myrtaceae | <i>Sloetia elongata</i> (Miq.) Koord | + | - | - |
| | <i>Psidium guajava</i> L. | - | + | + |
| | <i>Syzygium aqueum</i> (Burm.fil.) Alston | + | - | - |
| | <i>Syzygium malaccense</i> (L.) Merr. & L.M.Perry | - | - | + |
| Myrtaceae | <i>Syzygium polyanthum</i> (Wight) Walp. | - | + | + |
| | <i>Xylopia malayana</i> Hook.f. & Thomson | + | - | - |
| Nyctaginaceae | <i>Mirabilis jalapa</i> L. | - | - | + |
| Oxalidaceae | <i>Averrhoa bilimbi</i> L. | - | - | + |
| Phyllanthaceae | <i>Baccaurea motleyana</i> (Müll.Arg.) Müll.Arg. | + | - | - |
| Rubiaceae | <i>Discospermum malaccense</i> (Hook.f.) Kuntze | + | - | - |
| Rustaceae | <i>Citrus ×aurantiifolia</i> (Christm.) Swingle | - | + | + |
| | <i>Citrus ×limon</i> (L.) Osbeck | - | + | - |
| | <i>Citrus ×microcarpa</i> Bunge | - | - | + |
| | <i>Nephelium cuspidatum</i> Blume | + | + | - |
| | <i>Nephelium lappaceum</i> L. | + | + | + |
| Sapindaceae | <i>Pometia pinnata</i> J.R.Forst. & G.Forst. | - | + | + |

Note: +: Present, -: Absent

The structural dominance of *P. speciosa* likely reduces sub-canopy light availability due to its broad and dense canopy, which limits light penetration to the lower level, consequently constraining the recruitment of native species that require higher irradiance for germination and early growth. This pattern is consistent with broader evidence that single canopy species can significantly reduce understory light levels, thereby limiting regeneration processes and altering tree composition (Kitajima et al. 2005). These patterns underscore the need for forest management and restoration strategies that explicitly integrate light dynamics and species-specific regeneration

requirements to sustain biodiversity and ecosystem function (Makana and Thomas 2005).

Species composition and ecological succession: Pathways of vegetation recovery

The species composition and successional dynamics observed across the three stations highlight how ecological trajectories are strongly shaped by historical land-use and community management practices by CFGs. Stations 1 and 2, which show comparatively higher species richness and greater structural diversity, reflect ecological conditions in which natural regeneration processes remain sustained.

These findings align with broader evidence demonstrating that mixed-species agroforestry enhances successional dynamics and biodiversity persistence (Santos et al. 2022; Wiryono et al. 2022). In contrast, Station 3 showed the dominance of cultivated species, suggesting a vegetation structure more strongly shaped by livelihood-oriented management interventions. Where this configuration supports household benefits, it also limits native species and reduces structural diversity, symptomatic of sustained anthropogenic disturbance.

The designed cultivation of fruit-bearing and MPTS such as *Lansium domesticum* Corrêa, *Nephelium lappaceum* L., *A. integer*, and *D. zibethinus* by CFGs reflects their dual ecological and socio-economic importance. Beyond sustaining local livelihoods, these species provide critical resources for frugivorous fauna, thereby enhancing seed dispersal and the natural regeneration process. Their coexistence with nitrogen-fixing species (e.g., *P. speciosa*, *Archidendron pauciflorum* (Benth.) I.C.Nielsen) and pioneers such as *Macaranga* spp., recognized as dominant colonizers that create microhabitats for slow-growing species (Yuliansyah et al. 2019), form a stratified successional pathway that facilitates the recruitment of dipterocarps (e.g., *S. javanica*, *D. grandiflorus*), essential for restoring ecological complexity in degraded forests (Thüs et al. 2021).

These disparities underscore that restoration strategies in conservation partnership areas should be differentiated rather than uniform approaches. In areas where natural regeneration processes remain functional, such as Stations 1 and 2, restoration efforts should strategically prioritize the protection and enrichment of slow-growing native species. Conversely, in Station 3, which is dominated by sustained human-driven management, adaptive restoration interventions are required to reintroduce ecological filters that facilitate the recruitment of late-successional species and the re-establishment of canopy stratification. Collectively, the findings reaffirm that restoration models must be tailored to disturbance histories, particularly given the pivotal role of slow-growing species in long-term ecosystem recovery and carbon stability (Changkija et al. 2023).

Overall, the results underscore the strong influence of land-use history and the intensity of CFG management on vegetation structure and biodiversity within agroforestry systems, consistent with previous studies by Murniati et al. (2022) and Santos et al. (2022). At the same time, the application of diversity index in this study demonstrates their value as practical decision-support tools for guiding adaptive restoration planning, when interpreted alongside management histories at Stations 1-3, these indicators can help conservation partnerships align biodiversity enhancement with community livelihood strategies across the GLNP landscape.

Roles of dominant species and native-economics trade-offs

Across the stations, species dominance patterns reflect both ecological performance and CFGs livelihood strategies. The occurrence of MPTS, such as *P. speciosa* and *T. cacao*, are intentionally retained by CFGs because they ensure

continuous household benefits while also contributing to canopy development. Similarly, fruit trees like *N. lappaceum* and *D. zibethinus* integrate socio-economic imperatives with biodiversity conservation by sustaining wildlife-mediated seed dispersal (Wiryono et al. 2022). Although these species offer ecological advantages and economic benefits, their overreliance risks homogenizing vegetation structure and ultimately reducing ecosystem resilience (Zhang et al. 2023).

The principal difference is rooted in whether dominant species facilitate or inhibit successional progression. In Stations 1 and 2, their occurrence complements natural regeneration processes and reinforces ecological turnover. Conversely, in Station 3, the same management decisions function as a stabilizing filter that delays the transition toward late-successional forest structure. This distinction highlights that restoration outcomes are determined not only by which species dominate, but also by how management facilitates their ecological function over time.

Restoration implication: Successional pathway

The findings demonstrate that agroforestry-based conservation partnerships possess strong potential strong potential to support ecosystem recovery when native and cultivated species coexist within diversified canopy. The integration of fast-growing pioneer species with slow-growing species, facilitates successional pathways that accelerate canopy recovery, enhance biodiversity, and improve carbon sequestration. Empirical evidence from *Macaranga*-dominated fallows (Yuliansyah et al. 2019) and resin-based *S. javanica* agroforests (Nurlia et al. 2024) demonstrates the effectiveness of combining ecologically functional and economically valuable species in sustaining long-term restoration. In contrast, Agroforestry-based conservation partnerships in GLNP depend more on livelihood-oriented fruit trees and MPTS, which support livelihood but risk structural homogenization when not followed by native species enrichment.

Complementary practices, particularly enrichment planting, retention of nitrogen-fixing species, and Assisted Natural Regeneration (ANR), further significantly strengthen ecological resilience and livelihood benefits (Murniati et al. 2022). The vegetation profiles across stations clarify the need for adaptive restoration within the landscape. Stations 1 and 2, with higher diversity and structural heterogeneity, function as ecological reservoirs that facilitate broader landscape recovery. In contrast, Station 3 requires targeted enrichment planting of underrepresented native species, diversification of MPTS, and canopy reconfiguration to restore the successional pathway. The application of species diversity index in this study demonstrates its practical value as decision-support tools for adaptive restoration planning, allowing the park authority to identify ecological constraints and evaluate progress within community-based systems.

Socio-economic relevance

Beyond ecological configurations, the conservation partnership model supports livelihood resilience by enabling communities to maintain and diversify income

through MPTS cultivation. Evidence from South and Southeast Asia confirms that diversified agroforestry strengthens household economies, diversifies income sources, stabilizes food security, and enriches biodiversity while increasing soil fertility and carbon sequestration over time (Bajracharya et al. 2023; Raj et al. 2024; Hoque et al. 2025)

Moreover, agroforestry also contributes to social transformation by strengthening local institutions. In this context, the conservation partnership program facilitated by GLNP and Pesona Tropis Alam Indonesia (PETAI) Foundation has enhanced governance capacity among CFGs through training in organizational governance, work plan, participatory planning, and sustainable agroforestry practice. These programs have strengthened local institutions, improved collective management, while simultaneously diversified household incomes. However, empirical evidence also shows that restoration projects with limited community participation often succeed only in the short term without ensuring sustainability, while community-led initiatives are more effective in maintaining ecological and social outcomes over time (Ullah et al. 2024).

Accordingly, the integration of native species with agroforestry systems must be designed to complement, rather than replace, existing local livelihood strategies, positioning the role of conservation partnerships for co-producing restoration strategies that harmonize ecological objectives with socio-economic resilience (Mlambo et al. 2025).

Limitation, this study has several limitations that should be acknowledged. First, the lack of direct wildlife data constrains validation of wildlife-mediated seed dispersal, making the interpretations of plant–wildlife interactions largely indirect. Second, the spatial scope was limited to three stations, which may not fully represent the ecological heterogeneity of the broader GLNP landscape. Third, abiotic variables were not comprehensively assessed across stations, limiting the ability to establish causal links between vegetation patterns and environmental drivers. Fourth, the sampling was conducted within a single season, which may restrict the ability to capture temporal variations in vegetation composition and phenological processes. Finally, the analysis primarily focused on CFGs, without assessing broader multi-actor dynamics involving government institutions, NGOs, and private stakeholders that are likely to influence restoration governance. Nonetheless, this study aimed to establish a baseline assessment of species composition and vegetation structure in the conservation partnership area rather than to capture seasonal dynamics. The findings, therefore, provide an important foundation for future multi-seasonal monitoring to evaluate phenological and successional variations over time. Addressing these gaps through integrative ecological, environmental, and governance approaches will be essential to advance a more comprehensive understanding of conservation partnership agroforestry systems.

In conclusion, this study demonstrates that species composition, vegetation structure, and diversity in agroforestry-based conservation partnership areas of GLNP vary across sites in response to differences in management intensity and local conditions. The coexistence of native

dipterocarps with high-value fruit and cultivated MPTS indicates that community-managed agroforestry can support both biodiversity conservation and local livelihood. The variation in IVI, species richness and diversity index across stations indicates that native forest species persist most strongly in less-disturbed areas, while cultivated and pioneer species become more dominant in intensively managed sites. These findings highlight the importance of maintaining species heterogeneity to sustain ecological resilience within conservation partnership areas. From a restoration perspective, enrichment planting of native dipterocarps in areas dominated by cultivated trees, combined with the retention of nitrogen-fixing and pioneer species through ANR, can restore canopy heterogeneity and regeneration processes. These findings reinforce the need for context-specific restoration strategies that integrate ecological and socio-economic dimensions. Two key priorities emerge to mainstream this model within national restoration agendas: (i) strengthening institutional support and adaptive policy frameworks for community-based restoration; and (ii) establishing long-term ecological monitoring to ensure its effective implementation and sustainability. In general, conservation partnership-based agroforestry represents a viable governance model for integrating restoration and community livelihoods in protected tropical landscapes particularly when implemented through context-specific management and supported by strong governance arrangements.

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