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Understanding tree diversity in ultrabasic forests of Sulawesi, Indonesia for restoration and conservation planning

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Abstract. *Nasri, Nursaputra M, Hamzah AS, Larekeng SH, Arif AR, Ardiansyah A. 2026. Understanding tree diversity in ultrabasic forests of Sulawesi, Indonesia for restoration and conservation planning. Asian J For 10: r100102. https://doi.org/10.13057/asianjfor/r100102.* Ultrabasic (or ultramafic) forests in Sulawesi, Indonesia, support high endemism but remain understudied, especially in disturbed and reclaimed areas. This study assessed tree diversity and composition across five forest cover types: High-Density Forest (HDF), Moderate-Density Forest (MDF), Low-Density Forest (LDF), Reclaimed Forest (RF), and Shrub (S), within an ultrabasic mining landscape in East Luwu. A total of 143 adult-tree species were recorded, including 17 endemic species to Sulawesi and 6 endangered species. HDF exhibited the highest species richness (30 species/cluster) and basal area (17.79 m^2/ha), while RF and S had the lowest. Diversity was significantly different among forest types (p<0.05), with HDF and MDF also showing the highest community similarity (Morisita Similarity Index=0.60). In contrast, RF and S showed distinct species compositions, dominated by pioneer or generalist species. The presence of threatened endemic species, such as *Diospyros celebica*, *Hopea celebica,* and *Vatica flavovirens*, was mostly confined to undisturbed forests. Cluster analysis based on plant families revealed a close taxonomic relationship between MDF and LDF. These findings underscore the importance of intact ultrabasic forests as biodiversity reservoirs for endemic and threatened species. While reclaimed areas support vegetation recovery, they require enhanced efforts to increase native species richness, functional diversity, and taxonomic representation. Protecting high-diversity forests is essential to sustain source populations for conservation and support more ecologically meaningful restoration outcomes.

Keywords: Biodiversity, endemism, forest density, Sulawesi, ultrabasic forest

INTRODUCTION

Sulawesi, Indonesia, is recognized for its unique ultrabasic (or ultramafic) forest ecosystems, characterized by soils rich in potentially toxic elements and low in essential nutrients (Vilela et al. 2020; Rendana et al. 2022; Garnica-Díaz et al. 2023). These challenging edaphic conditions have driven the evolution of highly specialized plant communities, making these forests global hotspots for biodiversity and endemism. The high species diversity and endemism of Sulawesi's ultrabasic forests play an important role in maintaining ecological stability and ecosystem services such as carbon storage and habitat provision (Haines-Young and Potschin 2010; Varkkey et al. 2018). Understanding the structure and function of these ecosystems is essential for developing science-based conservation strategies in one of the world's major tropical biodiversity regions.

The ultrabasic forests within the mining concession area in East Luwu, South Sulawesi, where open-cast nickel mining has been active since the late 1970s, provide a valuable opportunity to study interactions among forest structure, species diversity, and ecological processes. The extracted nickel is processed for export, and PT Vale Indonesia has implemented post-mining restoration, including revegetation and soil stabilization. While their ecological importance has been recognized, research on species composition, diversity indices, and implications for conservation and sustainable management remains limited (Oliver et al. 2015; Hartini and Aprilianti 2020). The flora exhibits high endemism to Sulawesi, with unique plants adapted to thrive in nutrient-poor soils. This results in forests with relatively low species richness but high endemism (Garnica-Díaz et al. 2023). Sulawesi contains some of the most extensive ultrabasic forests, which are home to numerous endemic species and hold economic importance due to nickel mining in East Luwu (Proctor 1992; Nasution et al. 2024; Pitopang et al. 2024).

Despite their ecological value, these forests face increasing threats from mining, deforestation, and land-use change, posing serious risks to biodiversity and ecosystem functions (Ekka et al. 2023; Shanmukha et al. 2024). Understanding how species diversity and endemism vary across forest densities and reclamation stages is crucial for designing effective conservation measures. A systematic approach to inventorying and analyzing vegetation across different forest types is therefore essential. To address this, the present study provides a detailed assessment of tree species diversity and endemism across varying forest densities and reclaimed areas, offering a scientific foundation for conservation and sustainable management in ultrabasic environments (Huang et al. 2024; Xie et al. 2024).

Forest density strongly influences species diversity and ecological stability. High-density forests generally support greater species richness and more stable ecological conditions than those with lower densities (Staab and Schuldt 2020; Coddington et al. 2023). Reclaimed forests and shrub areas, in contrast, often exhibit lower diversity, as they represent post-mining or regenerating vegetation on disturbed sites, including ridges. Despite this, they host endemic species such as *Pterophylla devogelii, Dillenia celebica*, and protected *Nepenthes*, highlighting their ecological value. This highlights the need for targeted restoration to enhance biodiversity in disturbed sites (Yan et al. 2022). The Shannon-Wiener Diversity Index and Morisita Similarity Index are widely used to evaluate species diversity and community similarity, providing insights into the ecological health of forest ecosystems (Lande 1996; Ajijah et al. 2022). By applying these indices, this study assesses diversity and similarity patterns among tree communities across forest densities and reclamation stages, contributing to a better understanding of ecological dynamics in ultrabasic forests. The presence of endemic species such as *Diospyros celebica*, *Hopea celebica*, and *Vatica flavovirens* further underscores the high conservation value of Sulawesi's ultrabasic forests (Lima et al. 2020; Martin et al. 2021).

However, comprehensive studies linking forest density, species diversity, and endemism in Sulawesi's ultrabasic forests are still limited. Most existing research focuses on general biodiversity or soil-plant interactions, leaving a gap in understanding how forest conditions influence species composition and endemism (Elmqvist et al. 2003; Oliver et al. 2015). While the general relationship between disturbance and biodiversity is well established, such patterns have not been specifically quantified in Sulawesi's ultrabasic ecosystems, particularly within post-mining landscapes. This study contributes to filling this gap by examining diversity and endemism across different forest densities, including reclaimed areas, within the mining concession of the ultrabasic forests in East Luwu. This post-disturbance context provides applied insights for ecological restoration in ultrabasic environments. We hypothesize that (i) tree diversity is highest in intact, high-density forests and lowest in reclaimed or shrub-dominated areas; (ii) endemic and endangered species are concentrated in less disturbed forests; and (iii) species and taxonomic similarity decrease with increasing disturbance or land-cover change. By integrating species- and taxonomic-level analyses, this study provides an integrated approach to evaluating diversity and community similarity, generating insights that support the development of targeted conservation and restoration strategies to preserve Sulawesi's unique ultrabasic ecosystems.

MATERIALS AND METHODS

Study site and research subject

This study was conducted in the ultrabasic forest areas located within the concession area of PT Vale Indonesia in East Luwu District, South Sulawesi Province, Indonesia (Figure 1). The geographical coordinates of the site are approximately S: 2°3'45" and E: 121°7'23″. The study was carried out in 2020 and focused on five dominant land-cover types in ultrabasic forest landscapes: High-Density Forest (HDF), Moderate-Density Forest (MDF), Low-Density Forest (LDF), Reclaimed Forest (RF), and Shrubs (S) (Figure 2). The classification of land-cover types was based on Normalized Difference Vegetation Index (NDVI) values derived from remote sensing analysis using the Google Earth Engine platform (Nursaputra et al. 2021).

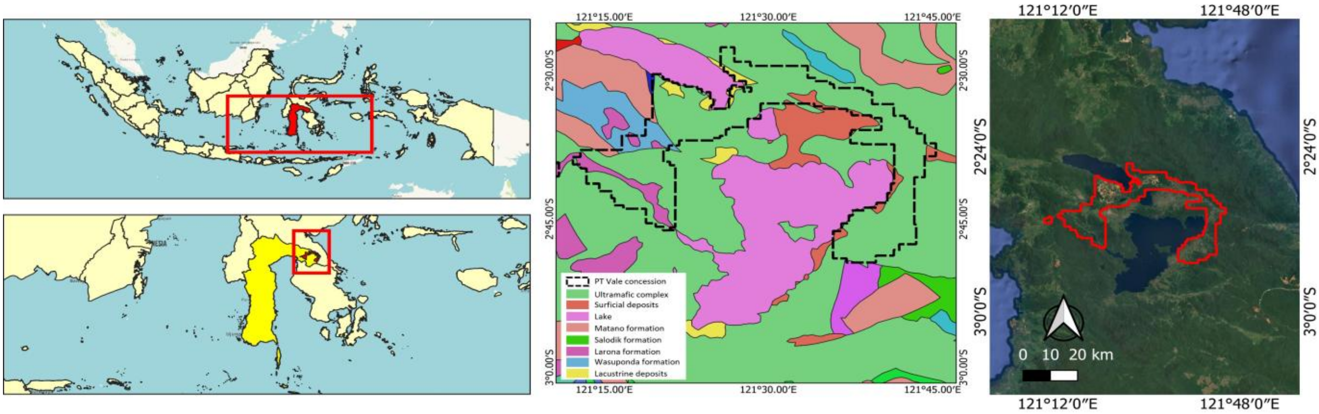

Figure 1. Study area in the PT Vale Indonesia concession area, South Sulawesi Province, Indonesia. The center panel shows geological formations, including ultramafic complexes

Data collection and plot design

A stratified purposive sampling approach was used to represent the variation in land systems and land cover types across the mining area (Table 1 and Figure 2). Each land cover type was surveyed using square-shaped clusters measuring 100 m × 100 m. Within each cluster, five circular plots were established, at each corner and at the center, each with a radius of 17.8 m (0.1 ha), resulting in a total sampled area of 0.5 ha per cluster (Figure 3; Ministry of Environment and Forestry 2017). Subplots were nested within each main plot to sample different growth stages: Seedlings (SD): radius 1 m; defined as individuals <1.5 m in height; Saplings (SP): radius 2 m; defined as individuals ≥1.5 m in height and DBH<10 cm; Adult Trees (AT): radius 17.8 m; defined as individuals with DBH≥10 cm.

Table 1. Distribution of the number of plots within each land cover and geographic information

Land cover	Clusters	Land cover by GIS	Geological formation	Elevation (m)	Coordinates
High-Density Forest (HDF)	VU-01	High-Density Forest	Ultramafic	474	2.5072°, 121.3241°
	VU-02	High-Density Forest	Ultramafic	647	2.5668°, 121.4651°
	VU-05	High-Density Forest	Surficial deposits	492	2.5417°, 121.5496°
	VU-06	High-Density Forest	Bancu Wasuponda	538	2.6159°, 121.2834°
	VU-07	High-Density Forest	Larona	558	2.6121°, 121.7174°
	VU-08	High-Density Forest	Ultramafic	518	2.5584°, 121.6282°
	VU-16	High-Density Forest	Ultramafic	532	2.5368°, 121.5362°
Moderate-Density Forest (MDF)	VU-10	Moderate-Density Forest	Ultramafic	544	2.5148°, 121.4782°
	VU-11	Moderate-Density Forest	Ultramafic	833	2.5669°, 121.3338°
	VU-13	Moderate-Density Forest	Ultramafic	525	2.5861°, 121.3899°
Low-Density Forest (LDF)	VU-04	Low-Density Forest	Lacustrine deposits	416	2.5233°, 121.4714°
	VU-09	Low-Density Forest	Ultramafic	433	2.5900°, 121.6776°
	VU-14	Low-Density Forest	Ultramafic	458	2.6190°, 121.7134°
Reclaimed Forest (RF)	VU-12	Moderate-Density Forest	Ultramafic	531	2.5648°, 121.3989°
	VU-15	Low-Density Forest	Ultramafic	632	2.5679°, 121.3706°
Shrubs (S)	VU-17	Shrubs	Ultramafic	535	2.6156°, 121.2883°
	VU-18	Shrubs	Ultramafic	396	2.5320°, 121.4760°
	VU-19	Shrubs	Larona	596	2.6199°, 121.7037°

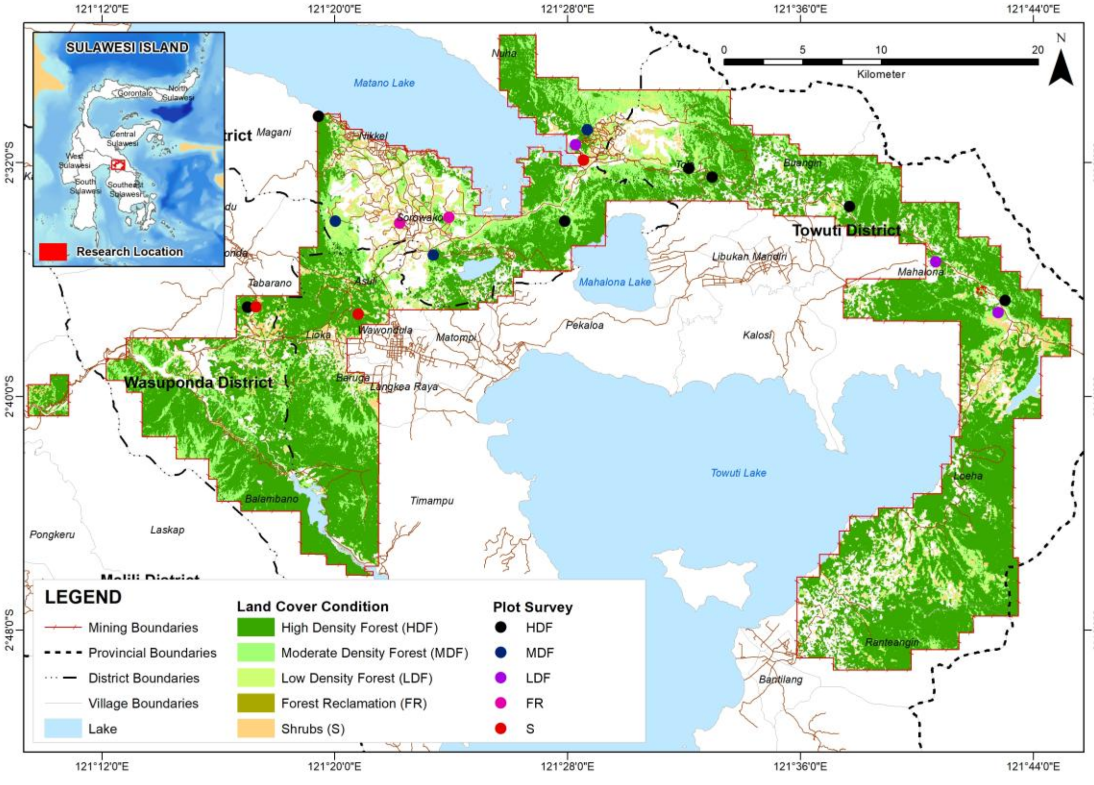

Figure 2. Distribution of study plots in the PT Vale Indonesia concession area, South Sulawesi Province, Indonesia

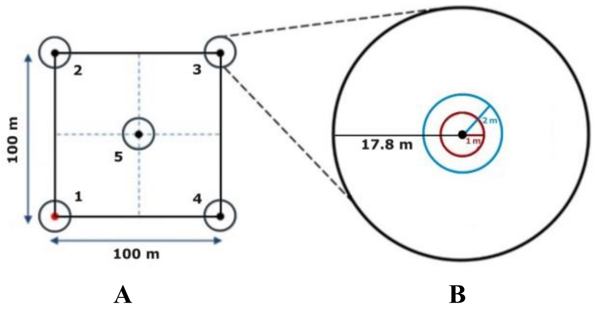

Figure 3. A. Cluster design with a square size of 100×100 m. B. Plot design with a circle size of a radius of 17.8 m for adult trees, 2 m for saplings, and 1 m for seedlings

A total of 18 clusters were distributed across the five land cover types as follows: 7 clusters (3.5 ha) for high-density forest, 3 clusters (1.5 ha) for moderate-density forest, 3 clusters (1.5 ha) for low-density forest, 2 clusters (1.0 ha) for reclaimed forest, and 3 clusters (1.5 ha) for shrubs (Table 1 and Figure 2). Reclaimed forest plots included areas planted in previous revegetation efforts, namely VU-12 (Betsy block, planted in 2002) and VU-15 (Watulabu-South block, planted in 2004).

Data analysis

Species diversity was calculated using the Shannon-Wiener Diversity Index (Shannon 1948):

$$H' = -\sum_{i=1}^{S} pi \ \mathrm{In}\ pi$$

Where, S is the total number of species, and pi is the proportion of individuals belonging to species i. Species similarity between land cover types was assessed using the Morisita Similarity Index (Morisita 1959):

$$C_D = \frac{2\sum_{i=1}^{S} x_i y_i}{(D_x + D_y)\, XY}$$

Where, x_i is the number of times species i is represented in the total X from one sample; y_i is the number of times species i is represented in the total Y from another sample; D_x and D_y are the Simpson's Index value for the x and y samples, respectively; and S is the number of unique species. The Morisita Similarity Index ranges from 0 to 1, where 0 indicates no similarity and 1 indicates complete similarity in species composition.

To evaluate conservation significance, species were assessed for endemicity and IUCN Red List status, including information on population trends and distribution. Taxonomic similarity among forest types was further assessed through two-way hierarchical clustering, based on species richness per plant family. Bray-Curtis Similarity Index and the Unweighted Pair Group Method with Arithmetic Mean (UPGMA) algorithm were used to cluster both families and forest types. All statistical analyses and visualizations were performed using PAST version 4.17c (Hammer and Harper 2001). Data were tested for normality and homogeneity; as assumptions for parametric tests were not met, the Kruskal-Wallis test with Dunn's post hoc was applied (p<0.05).

RESULTS AND DISCUSSION

Tree species diversity

Tree species diversity differed significantly among land-cover types and growth stages (Kruskal-Wallis test, p<0.05), as shown in Table 2 and Figures 4-5. The highest mean values for the number of species, individuals, and basal area were consistently recorded in High-Density Forest (HDF), while Reclaimed Forest (RF) and Shrub (S) showed the lowest values. Across all plots, a total of 143 adult-tree species, 114 saplings, and 93 seedlings were identified (Figure 4).

Basal area of adult trees also differed significantly among land cover types (p<0.05), with HDF showing the largest mean (17.79±2.17 m²/ha) and S the smallest (3.99±0.60 m²/ha) (Table 2). These variations reflected differences in dominant species composition across forest types (Table 3). In HDF and MDF, dominant species with the highest basal area included *Castanopsis buruana*, *Palaquium maliliense*, *Santiria laevigata*, and *Syzygium acuminatissimum*. In LDF, dominant contributors were *Melicope maliliensis*, *Alstonia macrophylla*, *Colona scabra*, and *D. celebica*. Meanwhile, pioneer or fast-growing species such as *Paraserianthes falcataria, Gymnostoma rumphianum,* and *P. devogelii* dominated the RF, and *P. devogelii*, *Alphitonia incana*, and *Metroxylon sagu* were prevalent in S.

Table 2. Distribution of number of individuals (N), number of species (S), and Basal Area (BA) of tree-level in each type of land cover

Land cover	Number of species (S)/cluster Mean ± SE			Number of individuals (N) /Ha Mean ± SE			Basal Area (BA) of AT (m^2/Ha) Mean ± SE
	AT	SP	SD	AT	SP	SD	
HDF	30±4^{a}	24±5^{a}	22±6^{a}	903±172^{a}	3561±411^{b}	43403±17549^{a}	17.79±2.17^{a}
MDF	28±5^{abc}	18±6^{ab}	18±10^{ab}	1015±212^{a}	6614±2677^{a}	38854±31456^{a}	13.06±7.55^{ab}
LDF	20±3^{b}	17±4^{ab}	21±2^{a}	757±198^{ab}	6402±1191^{a}	47771±18228^{a}	14.68±3.33^{a}
RF	17±6^{b}	9±1^{b}	6±4^{b}	750±156^{ab}	4762±898^{ab}	15605±10359^{a}	12.43±5.62^{ab}
S	11±3^{c}	8±1^{b}	3±2^{b}	368±190^{b}	3439±1525^{ab}	4883±2047^{b}	3.99±0.60^{b}

Note: HDF: High-Density Forest, MDF: Moderate-Density Forest, LDF: Low-Density Forest, RF: Reclaimed Forest, S: Shrubs, AT: Adult Tree (DBH≥10 cm), SP: Sapling (Height≥1.5 m, DBH<10 cm), SD: Seedling (Height<1.5 m). Different letters denote significantly different means based on Kruskal-Wallis test followed by Dunn's post-hoc test (p<0.05)

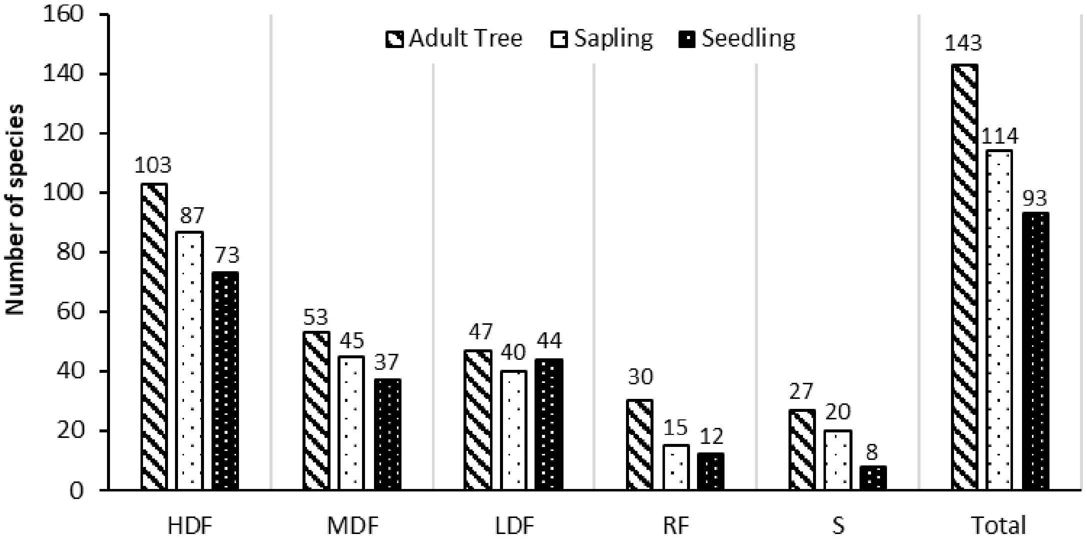

Figure 4. Total number of plant species recorded in each land cover type, standardized by total plot size. Plot sizes are as follows: HDF=3.5 ha; MDF, LDF, and S=1.5 ha; RF=1.0 ha. Note: HDF: High-Density Forest, MDF: Moderate-Density Forest, LDF: Low-Density Forest, RF: Reclaimed Forest, S: Shrubs

Table 3. Top ten dominant adult trees for the Basal Area (BA) in each type of land cover

Species	Family	Basal area (m^2/Ha)				
		HDF	MDF	LDF	RF	S
Canarium acutifolium var. *celebicum* Leenh.	Burseraceae	0.65	-	-	-	-
Xanthostemon petiolatus (Valeton) Peter G.Wilson	Myrtaceae	0.55	-	-	-	-
Villebrunea rubescens (Blume) Blume	Urticaceae	0.44	-	-	-	-
Castanopsis buruana Miq.	Fagaceae	0.86	0.95	0.28	-	0.16
Manilkara fasciculata (Warb.) H.J.Lam & Maas Geest.	Sapotaceae	0.63	-	0.26	-	-
Melicope maliliensis T.G.Hartley	Rutaceae	0.60	0.65	2.73	-	-
Palaquium maliliense P.Royen	Sapotaceae	1.03	1.85	-	-	-
Syzygium acuminatissimum (Blume) DC.	Myrtaceae	0.81	0.89	-	-	-
Santiria laevigata Blume	Burseraceae	0.80	0.84	-	-	-
Horsfieldia glabra (Blume) Warb.	Myristicaceae	0.61	1.33	-	-	-
Gironniera subaequalis Planch.	Cannabaceae	-	0.92	-	-	-
Knema matanensis W.J.de Wilde	Myristicaceae	-	0.91	-	-	-
Lithocarpus celebicus (Miq.) Rehder	Fagaceae	-	0.91	-	-	-
Ixora longifolia Sm.	Rubiaceae	-	0.73	-	0.19	0.15
Alstonia macrophylla Wall. ex G.Don	Apocynaceae	-	-	2.10	-	-
Sloetia elongata (Miq.) Koord.	Moraceae	-	-	1.48	-	-
Dillenia celebica Hoogland	Dilleniaceae	-	-	1.63	-	1.17
Pandanus sarasinorum Warb.	Pandanaceae	-	-	0.68	-	0.14
Garcinia celebica L.	Clusiaceae	-	-	0.56	-	-
Palaquium obovatum (Griff.) Engl.	Sapotaceae	-	-	0.27	-	-
Colona scabra (Sm.) Burret	Malvaceae	-	-	0.99	0.57	-
Paraserianthes falcataria (L.) I.C.Nielsen	Fabaceae	-	-	-	2.08	-
Cyathea contaminans (Hook.) Copel.	Cyatheaceae	-	-	-	0.88	-
Elmerrillia ovalis (Miq.) Dandy	Magnoliaceae	-	-	-	0.63	-
Trema orientalis (L.) Blume	Cannabaceae	-	-	-	0.45	-
Gymnostoma rumphianum (Miq.) L.A.S.Johnson	Casuarinaceae	-	-	-	0.42	-
Litsea glutinosa (Lour.) C.B.Rob.	Lauraceae	-	-	-	0.24	-
Ardisia copelandii Mez	Primulaceae	-	-	-	0.20	-
Pterophylla devogelii H.C.Hopkins Pillon & H.C.Hopkins	Cunoniaceae	-	-	-	0.80	0.20
Metroxylon sagu Rottb.	Arecaceae	-	-	-	-	0.44
Alphitonia incana (Roxb.) Teijsm. & Binn. ex Kurz	Rhamnaceae	-	-	-	-	0.37
Syzygium sp.	Myrtaceae	-	-	-	-	0.20
Artocarpus sericicarpus F.M.Jarrett	Moraceae	-	-	-	-	0.15
Other species		10.81	6.69	3.70	5.16	1.01
Total Basal Area (BA)		17.79	16.67	14.68	11.62	3.99
Number species		103	53	47	30	27

Note: -: Absent

Shannon-Wiener Diversity Index (*H'*) followed a consistent pattern across all growth stages (Figure 5). HDF recorded the highest diversity values in adult trees, saplings, and seedlings (*H'*≈2.8-2.9), followed by MDF and LDF. In contrast, RF and S exhibited significantly lower diversity (*H'*≈2.0-2.3 and <2.0, respectively), suggesting reduced structural complexity and limited ecological succession in disturbed or reclaimed habitats.

Priority tree species

The status, population trends, and distribution of priority tree species were assessed based on endemicity and IUCN Red List categories (Table 4). Of the 20 species listed, 17 were identified as endemic to Sulawesi. Six species were classified as Endangered (EN): *Dillenia celebica*, *Knema matanensis*, *H. celebica*, *V. flavovirens*, *Pterocarpus indicus*, and *Cinnamomum sulavesianum*. Population trends for these endangered species were either decreasing or unknown. In terms of spatial distribution, most endemic and threatened species were concentrated in High-Density Forest (HDF) and Moderate-Density Forest (MDF), with significantly fewer occurrences in Low-Density Forest (LDF), Reclaimed Forest (RF), and Shrub areas (S). Notably, species such as *D. celebica* and *P. devogelii* were found across all land-cover types, indicating broader ecological tolerance or dispersal. In contrast, *Agathis celebica*, *H. celebica*, and *D. celebica* were restricted to intact forests (HDF and MDF).

Table 4. Status and distribution of priority tree species in each type of land cover

Species	Family	End.	Conservation*		Distribution				
			Status	Population	HDF	MDF	LDF	RF	S
Agathis celebica (Koord.) Warb.	Araucariaceae	√	VU	Decreasing	√	√	-	-	-
Canarium acutifolium var. *celebicum* Leenh.	Burseraceae	√	LC	Decreasing	√	√	√	-	-
Cinnamomum sulavesianum Kosterm.	Lauraceae	√	EN	Unknown	√	√	-	-	-
Dillenia celebica Hoogland	Dilleniaceae	√	EN	Unknown	√	√	√	√	√
Diospyros celebica Bakh.	Ebenaceae	√	VU	Unspecified	√	-	-	-	-
Garcinia celebica L	Clusiaceae	-	LC	Unknown	√	√	√	-	-
Gymnacranthera maliliensis R.T.A.Schouten	Myristicaceae	√	NT	Unspecified	√	√	-	-	-
Hopea celebica Burck	Dipterocarpaceae	√	EN	Decreasing	√	√	-	-	-
Kjelbergiodendron celebicum (Koord.) Merr.	Myrtaceae	√	LC	Stable	√	√	-	√	√
Knema matanensis W.J.de Wilde	Myristicaceae	√	EN	Unknown	√	√	-	-	√
Lithocarpus celebicus (Miq.) Rehder	Fagaceae	-	LC	Stable	√	√	-	-	-
Melicope maliliensis T.G.Hartley	Rutaceae	√	-	-	√	√	√	-	√
Palaquium maliliense P.Royen	Sapotaceae	√	-	-	√	√	-	-	-
Pterocarpus indicus Willd.	Fabaceae	-	EN	Decreasing	√	-	-	-	-
Pterospermum celebicum Miq.	Malvaceae	√	LC	Stable	√	-	√	√	-
Sarcotheca celebica Veldkamp	Oxalidaceae	√	NT	Unspecified	√	√	√	-	-
Stemonurus celebicus Valeton	Stemonuraceae	√	VU	Unknown	√	√	√	-	-
Terminalia supitiana Koord.	Combretaceae	√	-	-	√	√	√	-	-
Vatica flavovirens Slooten	Dipterocarpaceae	√	EN	Decreasing	√	√	-	-	-
Pterophylla devogelii H.C.Hopkins Pillon & H.C.Hopkins	Cunoniaceae	√	-	-	√	√	√	√	√

Note: End.: Endemic, LC: Least Concern, NT: Near Threatened, VU: Vulnerable, EN: Endangered, *: IUCN Red List 2024, √: Present, -: Absent, HDF: High-Density Forest, MDF: Moderate-Density Forest, LDF: Low-Density Forest, RF: Reclaimed Forest, S: Shrubs

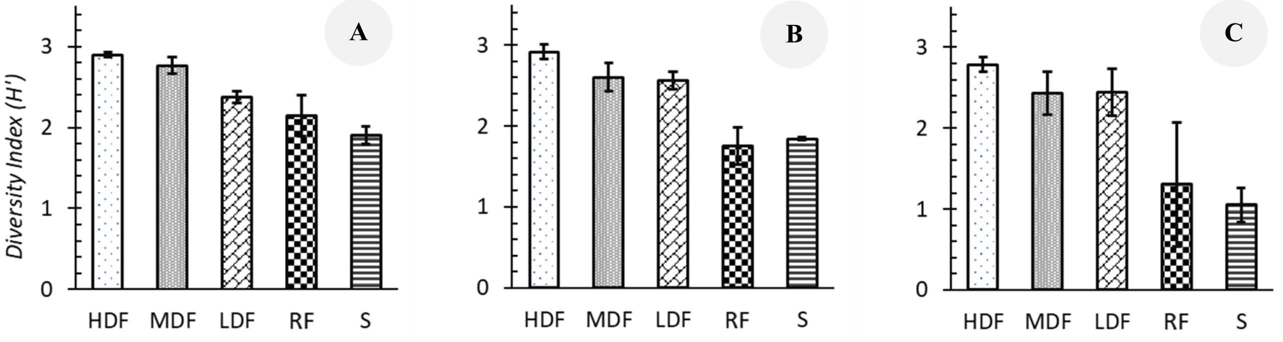

Figure 5. Shannon-Wiener Diversity Index (*H'*) of tree-level plants by growth stage. A. Adult Tree, B. Sapling, and C. Seedling across different land cover types per cluster. Note: HDF: High-Density Forest, MDF: Moderate-Density Forest, LDF: Low-Density Forest, RF: Reclaimed Forest, S: Shrubs

Community similarity and clustering

Species-level similarity based on Morisita Similarity Index (IS) revealed considerable differences in species composition across forest types (Table 5). The highest similarity was observed between HDF and MDF (0.60), followed by LDF and S (0.44). The lowest similarity values occurred between HDF and RF (0.07), and between MDF and S (0.08), indicating considerable variation in species composition across forest types.

Taxonomic-level similarity was assessed using two-way hierarchical clustering based on the number of species per plant family. The analysis applied the Bray-Curtis Similarity Index with the UPGMA algorithm (Figure 6). Two-way hierarchical clustering revealed that MDF and LDF shared the highest taxonomic similarity, forming a distinct cluster, while S, HDF, and RF each formed separate branches, indicating divergent family-level composition. The heatmap also showed that several plant families, including Moraceae, Myrtaceae, Sapotaceae, Euphorbiaceae, and Rubiaceae, were represented across multiple forest types, suggesting patterns of family-level taxonomic overlap.

Discussion

This study provides important insights into tree diversity, structure, and conservation status across forest cover types in the ultrabasic ecosystems of the PT Vale Indonesia concession area. The significant variation in species richness and basal area among land cover types reflects both natural heterogeneity and anthropogenic disturbance gradients. HDF exhibited the greatest diversity, structural complexity, and basal area, which suggests a relatively stable ecosystem condition. The high Shannon-Wiener Diversity Index (*H′*) values observed in HDF across all growth stages (adult trees, saplings, and seedlings) indicate a well-developed community structure and functioning ecosystem processes (Bakr et al. 2024).

Table 5. Morisita Similarity Index among forest density types (HDF, MDF, LDF, RF, and S), calculated based on the number of individuals per species in each forest type

Land cover	HDF	MDF	LDF	RF	S
HDF	1	0.60	0.29	0.07	0.20
MDF	0.60	1	0.18	0.26	0.08
LDF	0.29	0.18	1	0.13	0.44
RF	0.07	0.26	0.13	1	0.21
S	0.20	0.08	0.44	0.21	1

Note: HDF: High-Density Forest, MDF: Moderate-Density Forest, LDF: Low-Density Forest, RF: Reclaimed Forest, S: Shrubs

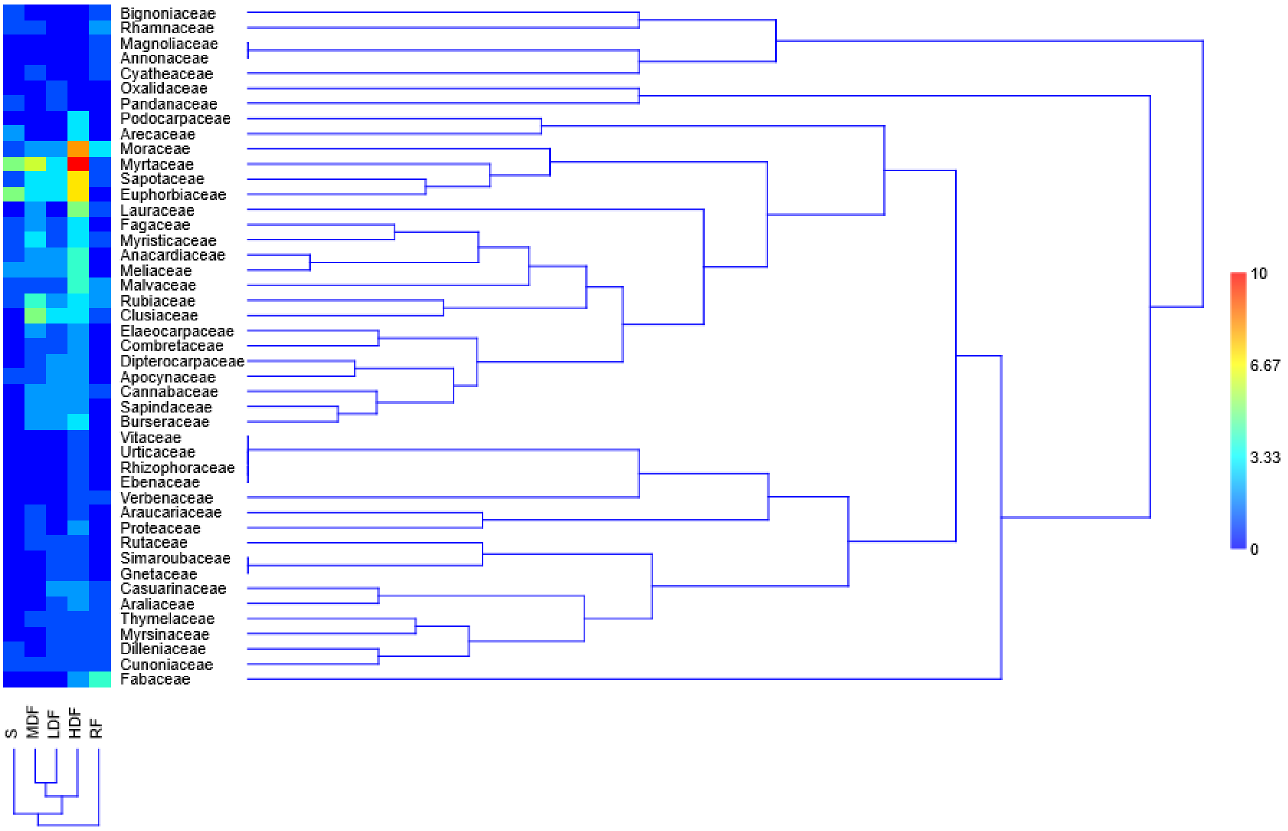

Figure 6. Two-way hierarchical clustering of land cover types and plant families based on the number of species per family, using the Bray-Curtis Similarity Index and UPGMA algorithm. The color gradient (blue-red) indicates species richness per family per land cover type. Note: HDF: High-Density Forest, MDF: Moderate-Density Forest, LDF: Low-Density Forest, RF: Reclaimed Forest, S: Shrubs

Moderate-density forests (MDF) and low-density forests (LDF) also supported relatively high diversity, though with lower basal area, reflecting the dominance of smaller trees and younger successional stages influenced by past disturbances such as logging or vehicular access (Basile et al. 2021; Loke and Chisholm 2022). In contrast, Reclaimed Forests (RF) and Shrubs (S) areas exhibited significantly lower diversity and basal area, with community composition dominated by disturbance-adapted or pioneer species. The low H' values recorded in these areas indicate degraded conditions and reduced ecosystem resilience, underscoring the need for targeted restoration efforts (Höhl et al. 2020; Arneth et al. 2021).

The presence of 17 endemic tree species, most of which are restricted to Sulawesi, highlights the critical conservation value of these ultrabasic forests. Several of these species, including *H. celebica*, *V. flavovirens*, and *P. indicus*, are listed as Endangered on the IUCN Red List, with population trends declining or unknown (IUCN 2025). Their limited distribution and specialized habitat requirements emphasize the need for site-specific protection and recovery strategies (Lima et al. 2020; Martin et al. 2021). Given their ecological significance, these species should also be prioritized for inclusion in restoration programs, particularly in reclaimed areas, to improve biodiversity value and support forest succession. Some species, such as *P. devogelii* were found across all land cover types, suggesting their adaptability and potential role in forest regeneration and ecological restoration (Fischer et al. 2021; Bayliss et al. 2024).

Variation in basal area across forest types further illustrates structural differences and successional stages. Although HDF had the highest basal area, it remains relatively low compared to undisturbed tropical forests, likely due to previous selective logging and other operational impacts. Both HDF and MDF had high tree densities but were dominated by small-diameter stems, reflecting a recovering structure following disturbance (Martin et al. 2022). In comparison, LDF showed a higher average basal area due to the presence of fewer but larger individuals. RF and S recorded the lowest basal areas, consistent with their younger successional status and lower carbon storage.

The Morisita Similarity Index revealed notable species-level differences among forest types. The highest similarity occurred between HDF and MDF (0.60), while the lowest values were between HDF and RF (0.07) and between MDF and S (0.08), indicating strong compositional divergence. These patterns may be linked to variations in microclimate, soil conditions, disturbance intensity, and successional stage (Gavito et al. 2021; Atkins et al. 2023). At the taxonomic level, two-way hierarchical clustering based on species richness per plant family (Using Bray-Curtis Similarity Index and UPGMA algorithm) revealed that MDF and HDF formed one cluster, while LDF, S, and RF grouped separately. These ecosystem groupings reflect shared taxonomic profiles and may be indicative of similar ecological functions or environmental filters (Chazdon 2019; Dagne and Birhanu 2023). Several plant families, including Moraceae, Myrtaceae, Sapotaceae, Euphorbiaceae, and Rubiaceae, were widespread across forest types, though often represented by different species, indicating their ecological tolerance and structural importance. Their broad distribution across successional stages also highlights their potential utility in restoration plantings aimed at re-establishing forest functionality and biodiversity.

The findings of this study carry significant implications for conservation, forest rehabilitation, and land-use planning in ultrabasic forest ecosystems. The presence of high diversity, including endemic and endangered species, coupled with varying levels of degradation, highlights the urgency of implementing effective, site-specific management strategies. Restoration efforts should prioritize the protection of high-diversity areas while enhancing resilience and ecological function in degraded forests (McCollum et al. 2022; Anshor et al. 2023). Integrated approaches that combine habitat preservation, species-specific conservation actions, and the application of both ecological and genomic tools can support long-term ecosystem sustainability (Viljoen and Kruger 2020; Onley et al. 2021; Brown et al. 2022; Pérez-Granados and López-Iborra 2022). However, the data confirm that reclamation areas have not yet achieved ecological equivalence with natural forests in terms of species composition, diversity, and structure. Therefore, future restoration should go beyond soil stabilization or vegetation cover and aim to promote functional and taxonomic diversity, including endemic and threatened species. This could include using local propagules, promoting natural regeneration, and long-term monitoring of community composition.

Finally, integrating species-level and taxonomic-level assessments, as done in this study, enhances our understanding of ecological filters and succession dynamics in ultrabasic landscapes. Such multi-level data are essential to guide science-based restoration and biodiversity conservation policies, especially in mining contexts where ecological functions must be recovered.

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