DAVAO RESEARCH JOURNAL
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ORIGINAL RESEARCH ARTICLE

Elevation-Driven Shifts in Species Diversity, Endemicity, and Vegetation Structure across the Mount Hamiguitan Range Wildlife Sanctuary, a UNESCO World Heritage Site in Davao Oriental, Philippines

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A B S T R A C T

Mount Hamiguitan Range Wildlife Sanctuary (MHRWS) in Davao Oriental, Philippines, is among the country's most ecologically diverse and geologically unique mountain ecosystems. Rising to 1,620 m above sea level and covering 6,834 ha, it is part of the Eastern Mindanao Biodiversity Corridor. Declared a national park in 2003 and designated a UNESCO World Heritage Site in 2014, Mt. Hamiguitan supports numerous endemic and threatened species through collaborative stewardship by national agencies, local governments, and indigenous communities. This study analyzed vegetation profiles and land cover types along Mt. Hamiguitan's elevational gradient to clarify biodiversity patterns and ecological zonation. 16 vegetation quadrats were systematically established at 100-m intervals from 140-1,620 m above sea level. Species composition, forest type, and mean diameter at breast height (DBH) were recorded and integrated with satellite-derived land cover data and GIS analysis to evaluate habitat distribution and human influence. Five major forest formations were identified: agroecosystem (75–420 m), dipterocarp forest (420–920 m), montane forest (920–1,160 m), mossy forest (1,160–1,350 m), and mossy-pygmy forest (1,160–1,620 m). Elevation strongly influenced shifts in species diversity, endemicity, and vegetation structure. Lower elevations were dominated by agriculturally influenced species such as *Ficus indica* and *Chrysophyllum cainito*, while higher zones supported stunted, endemic taxa including *Leptospermum flavescens* and *Tristaniopsis micrantha*, adapted to ultramafic soils and cooler, wind-exposed environments. The study underscores Mt. Hamiguitan's role as a vertically stratified refuge for endemic biodiversity and highlights the need to protect high-altitude forests, restore buffer zones, and monitor climate-driven species shifts.

Keywords: *Conservation Management, Endemism, Forest Stratification, Remote Sensing, Tropical Forest Ecosystem*

Submitted: 03 Dec 2025
Revised: 26 Dec 2025
Accepted: 09 Feb 2026
Published: 11 Mar 2026

OPEN ACCESS

How to cite: Ramos, R. L., Nemenzo-Calica, P., and Antonio, E. S. (2026). Elevation-Driven Shifts in Species Diversity, Endemicity, and Vegetation Structure across the Mount Hamiguitan Range Wildlife Sanctuary, a UNESCO World Heritage Site in Davao Oriental, Philippines *Davao Research Journal*, 17(1), 60–72. https://doi.org/10.59120/drj.v17i1.500

INTRODUCTION

Mount Hamiguitan Range Wildlife Sanctuary (MHRWS), located in southeastern Mindanao, Philippines, is a biologically rich and ecologically distinctive mountain ecosystem recognized for its exceptional conservation value at both national and international levels (Calag et al., 2009; Amoroso et al., 2016; Vidal et al., 2018). Rising from lowland forests to a peak elevation of 1,620 m above sea level and covering more than 6,800 ha, MHRWS exhibits pronounced elevational gradients that strongly influence vegetation structure, species composition, and patterns of endemicity (Calag et al., 2009; Amoroso et al., 2017; Daquiado et al., 2018).

Elevation is widely recognized as a key ecological driver shaping biodiversity in tropical mountain systems by altering temperature, moisture, soil characteristics, and habitat complexity. Numerous studies have demonstrated that elevational gradients affect plant abundance, forest structure, and species turnover, often resulting in distinct vegetation zones and increased specialization and endemism at higher elevations (Amoroso et al., 2016; Amoroso et al., 2018). Early vegetation studies in Mt. Hamiguitan, documented clear altitudinal zonation, including transitions from dipterocarp forests to montane, mossy, and the globally rare pygmy forest, a formation strongly associated with nutrient-poor soils and high-elevation conditions (Calag et al., 2009).

Beyond vegetation, elevational variation in Mt. Hamiguitan has also been shown to influence faunal diversity and distribution. Herpetofaunal inventories conducted within the sanctuary and its buffer zones revealed distinct assemblages associated with specific elevation ranges and habitat types, underscoring the role of elevation in structuring faunal communities (Vidal et al., 2018; Rosales et al., 2023). These studies reported a high diversity of amphibians and reptiles, including endemic and habitat-sensitive species, particularly in mid- to high-elevation forest zones. Such findings complement floristic studies and reinforce the importance of elevation-driven habitat heterogeneity in sustaining overall biodiversity within the sanctuary.

Comparatively, while other protected mountain ecosystems in Mindanao such as Mt. Apo Natural Park, Mt. Kitanglad Range Natural Park, and Mt. Malindang Natural Park reach higher maximum elevations, Mt. Hamiguitan is distinguished by its compressed elevational gradients and the close spatial juxtaposition of diverse forest types within a relatively limited area (Amoroso et al., 2017; Daquiado et al., 2018). This compression results in high habitat heterogeneity and biodiversity concentration, with unique features such as the pygmy forest occurring at lower elevations than those reported in other Philippine mountains.

Recent efforts to consolidate biodiversity knowledge through digital platforms, such as RDInfratech, further highlight Mt. Hamiguitan's role as a model site for integrated biodiversity research and conservation (Laureano et al., 2022). These initiatives emphasize the importance of synthesizing vegetation, faunal, and elevational data to better understand ecosystem dynamics and guide management strategies. Collectively, the strong elevational control on vegetation structure, high levelsof plant and faunal endemicity, and the presence of globally significant habitats underpin Mt. Hamiguitan's designation as a UNESCO World Heritage Site in 2014 (Medina et al., 2020; Mendoza et al., 2020).

Globally, ultramafic ecosystems are recognized for their ecological significance because their metal-rich, nutrient-poor soils impose strong physiological constraints on plant growth, resulting in specialized vegetation, distinct forest structure, and high levels of endemism, a pattern that has been well documented in Mount Hamiguitan Range Wildlife Sanctuary through floristic, vegetation, and faunal studies (Brady et al., 2005; Calag et al., 2009; Amoroso et al., 2016; Amoroso et al., 2017; Vidal et al., 2018; Laureano et al., 2022; Rosales et al., 2023). Mt. Hamiguitan exemplifies this pattern, harboring over 1,200 plant species, including 23 endemic orchids and a rich assemblage of trees across montane, dipterocarp, and pygmy forest zones (Amoroso et al. 2007). These forests thrive on ultramafic soils rich in nickel, iron, and cobalt, elements toxic to most plant species, highlighting both the resilience and scientific interest of its vegetation (Delmiguez Sr., 2021). Situated within the Eastern Mindanao Biodiversity Corridor, a conservation priority for its high endemism and vulnerability to anthropogenic pressures, Mt. Hamiguitan's ecosystems face threats from land-use change, resource extraction, and potential climate impacts (Celeste 2021; Mendoza et al. 2020).

Despite existing conservation efforts, comprehensive spatial information on forest distribution and tree species composition across the sanctuary's expanded area remains limited. This knowledge gap hinders effective monitoring of ecological changes and the implementation of targeted management strategies. Addressing this deficiency is crucial for ensuring long-term biodiversity conservation and ecosystem resilience.

In response, this study mapped forest types and identified the occurrence of key tree species within MHRWS using remote sensing and GIS-based spatial analysis. By focusing on vegetation patterns and endemic species distributions, the study provides baseline data that are critical for long-term ecological monitoring and informed forest management. Unlike previous studies that primarily compiled biodiversity inventories, this research emphasizes spatial variability and landscape-level forest delineation, thereby offering novel insights into forest structure and species assemblages.

The findings from this study contribute to understanding how ultramafic soils and elevation gradients shape tropical forest communities in one of the Philippines' most critical conservation areas. By integrating geospatial tools with vegetation and land-cover data, the research supports ongoing protection initiatives and provides transferable insights for conservation planning, landscape-level assessment, and habitat restoration in comparable tropical mountain ecosystems.

MATERIALS AND METHODS

Description of the study area

The study was conducted within the Mount Hamiguitan Range Wildlife Sanctuary (MHRWS; 6°45'–6°50' N, 126°12'–126°18' E), located in the southeastern portion of Mindanao Island, Philippines (Figure 1). The sanctuary covers approximately 6,834 ha, rising to 1,620 m above sea level, and features diverse ecosystems, including dipterocarp, montane, mossy, and pygmy forests (Calag et al., 2009; Amoroso et al., 2016). MHRWS lies within the municipalities of San Isidro and Governor Generoso, and the City of Mati, forming part of the Eastern Mindanao Biodiversity Corridor. The area is legally protected under Republic Act No. 9303, with management coordinated by the Department of Environment and Natural Resources (DENR) and the Mount Hamiguitan Range Wildlife Sanctuary Protected Area Management Board.

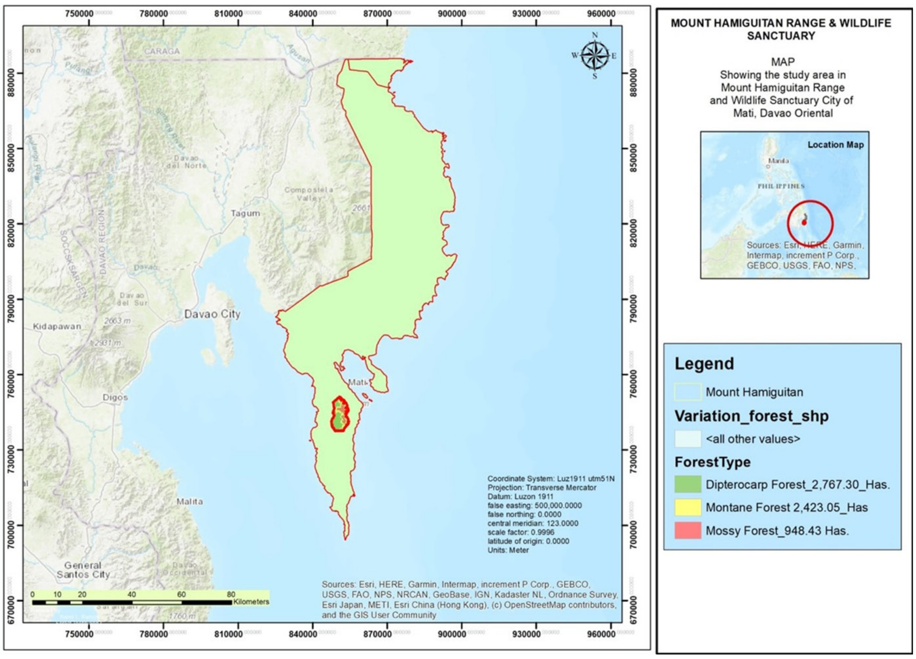

Figure 1. Map of the study area within the Mount Hamiguitan Range Wildlife Sanctuary (MHRWS), Davao Oriental, Philippines.

The region experiences a tropical climate with an average annual temperature of 24–27°C and mean annual rainfall of 2,000–2,500 mm, exhibiting marked seasonal variation associated with the Amihan and Habagat monsoon systems (Celeste 2021). Forest types are formally zoned based on elevation: dipterocarp forest (up to 400 m), lower montane forest (401–800 m), upper montane/mossy forest (801–1,200 m), and pygmy forest (1,201–1,620 m), reflecting changes in species composition and structure. The sanctuary's ultramafic soils, rich in nickel, iron, and cobalt, support specialized flora and high levels of endemism, including rare orchids and pitcher plants (Delmiguez Sr. 2021; Amoroso et al. 2007).

Data collection

Remote sensing and field-based methods were integrated to systematically assess vegetation across elevational gradients. A Digital Elevation Model (DEM) was generated from Interferometric Synthetic Aperture Radar (IFSAR) data obtained from the National Mapping and Resource Information Authority (NAMRIA), with a spatial resolution of 5 m collected in 2022. DEM preprocessing included projection to WGS 1984 UTM Zone 51N, slope correction, and clipping to the sanctuary boundary. Elevation contours were derived at 100-meter intervals to guide systematic quadrat placement along the mountain trail, ensuring coverage across all forest types.

Following standard tropical forest inventory protocols (Mueller-Dombois and Ellenberg 1974; Kent 2012; Brown et al. 2013), a total of 16 permanent 10 × 10 m plots were established along the elevational gradient of Mt. Hamiguitan, spanning 140–1,620 m asl. Plots were distributed across the five major forest/vegetation zones: three in the agro-ecosystem zone (140–300 m asl), four in the dipterocarp forest (400–700 m asl), four in the montane forest (800–1,100 m asl), three in the mossy forest (1,200–1,350 m asl), and two in the mossy-pygmy forest (1,400–1,620 m asl). Allocation was proportional to reflect differences in spatial extent, ecological heterogeneity, and accessibility, rather than equal replication per forest type. The 10 × 10 m plot size, widely used in Philippine and Southeast Asian forest studies (e.g., Amoroso et al. 2016; Buot and Okitsu 1998; Fernando et al. 2009), effectively captures tree diversity and stand structure while maintaining field efficiency and comparability with existing datasets.

To ensure the adequacy of plot size, species–area curves were generated (Figure 2) during preliminary sampling by sequentially adding sampling subplots and recording the cumulative number of plant or animal species encountered. Species accumulation was assessed visually, and sampling was considered sufficient when the curve showed a diminishing rate of new species addition and approached an asymptote, indicating that the sampled area adequately represented local plant or animal community composition.

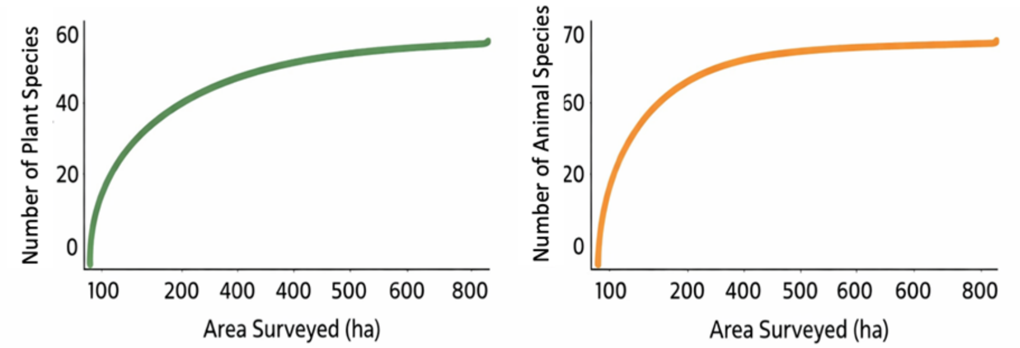

Figure 2. Species–area curves for plant and animal communities showing sampling adequacy and approach to asymptote.

Plots were oriented parallel to the slope and replicated at each elevation band to capture variability in species composition along the elevational gradient. Trees were defined as woody plants with a diameter at breast height (DBH) ≥ 10 cm, while shrubs were defined as woody plants with DBH < 10 cm or height < 3 m. Within each plot, all trees and shrubs were identified in situ using standard botanical field guides and taxonomic keys, including Fernando et al. (2019), Co's Digital Flora of the Philippines (2020), and Alcorn and Co's Field Guide to Philippine Trees (2018), supported by photographic documentation.

Field identification was assisted by expert foresters from DENR–CENRO Mati. No physical voucher specimens were collected due to protected area regulations; instead, unidentified taxa were assigned temporary field codes for subsequent verification. Some taxa could only be identified to the genus level, potentially representing rare or undescribed species. Geographic coordinates were recorded for all plots using GPS, and photographs were taken to document habitat characteristics and vegetation structure.

Data analysis

Vegetation data were analyzed to identify patterns of species composition and dominance across elevation bands. Diversity indices, including Shannon–Wiener (H') and Simpson (D), were calculated to quantify species richness and evenness. Computations were performed using PAST software (v.4.12), with standard formulas applied for manual verification where necessary. Forest types were classified based on dominant and commonly occurring species using quantitative thresholds of species importance value (IV), supported by literature (Mueller-Dombois and Ellenberg 1974; Fernando et al. 2008).

Regarding forest type delineation, the approximate extension of forest types was not solely inferred from the plots. Instead, a supervised classification was performed in ArcGIS 10.8 using Sentinel-2 imagery (10 m spatial resolution) and the DEM layer. Ground-truthing points were collected from each plot and along accessible transects to define training sites for each forest type. Post-classification accuracy assessment was conducted using a confusion matrix and Kappa statistic to validate the delineated boundaries (Congalton and Green 2019). All analyses were conducted within the Mount Hamiguitan Range Wildlife Sanctuary under the guidelines of the Protected Area Management Board (PAMB) Resolution No. 2025-22. Fieldwork adhered to ethical standards for biodiversity research, ensuring minimal disturbance to sensitive habitats.

Limitations included restricted access to steep slopes, reliance on a single elevational transect, and inability to collect voucher specimens; however, the integration of ground data with high-resolution remote sensing mitigated boundary uncertainty and improved spatial representation. The temporary codes and photographic records provide reproducible reference for future taxonomic verification and potential description of new species.

RESULTS

Mount Hamiguitan forest types

Based on Figure 3, which illustrates the distribution of forest types in Mt. Hamiguitan, five major forest formations are evident along the elevational gradient. The Agro-Ecosystem occupies the lowest zone, ranging from 75 to 420 m above sea level (asl). Above this lies the Dipterocarp Forest (420–920 m asl), followed by the Montane Forest (920–1,160 m asl). Higher still is the Mossy Forest (1,160–1,350 m asl), which slightly overlaps in elevation with the Mossy-Pygmy Forest (1,160–1,620 m asl). These forest types, as mapped in Figure 3, reflect the diverse ecological zones of Mt. Hamiguitan and its exceptional vertical biodiversity. Additionally, these zones illustrate the interplay between ecological processes and human activities, including agricultural use in the agro-ecosystem and active conservation management in the core protected areas.

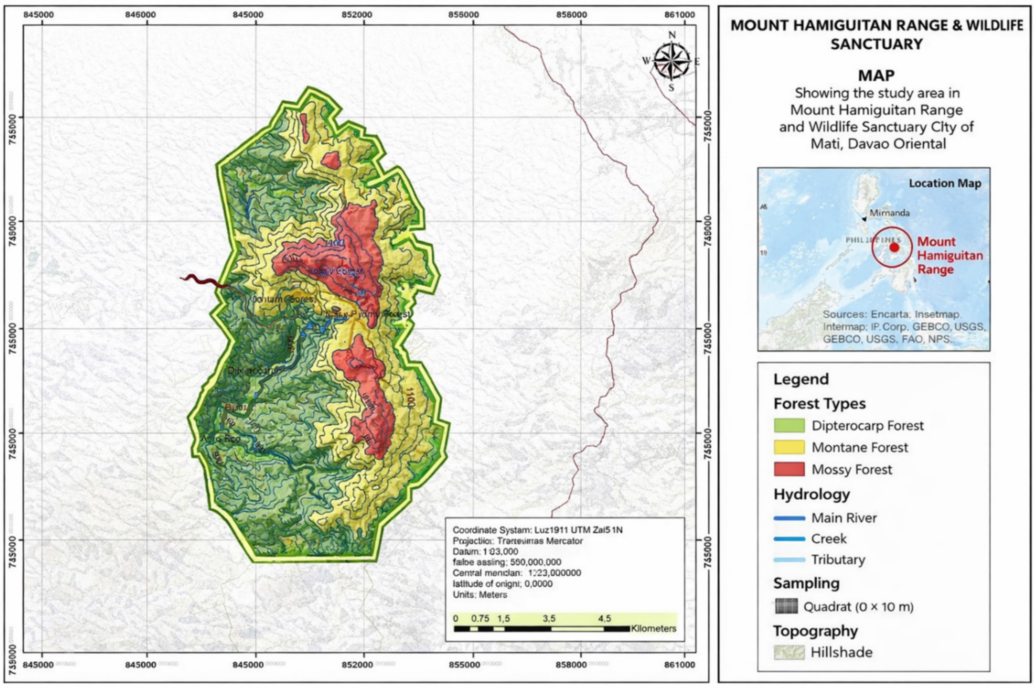

Figure 3. Map showing the distribution of forest types across different elevation zones in Mt. Hamiguitan, Davao Oriental, Philippines.

The agro-ecosystem zone, situated between 100 and 300 m above sea level, covers approximately 213.95 ha (Figure 4). This area is primarily dominated by coconut and banana plantations, interspersed with residual patches of dipterocarp forest. Located along the periphery of the Mount Hamiguitan Range Wildlife Sanctuary (MHRWS) and within its designated buffer zone, the zone shows clear signs of past human intervention. Notably, tree species such as *Shorea astylosa* and *Shorea ovata* were observed, representing remnants of the original primary forest. Local communities continue to cultivate crops in this area, while the presence of *Shorea* species highlights the potential for community-based reforestation initiatives.

Figure 4. The agro-ecosystem zone along the periphery of the Mount Hamiguitan Range Wildlife Sanctuary (MHRWS), Davao Oriental, Philippines. .

Situated between 420 and 920 m in elevation, the dipterocarp forest spans approximately 2,767 ha (Figure 5A). This forest type features the tallest trees among all five vegetation zones, with an average height of 13.6 m. Dominant species include *Shorea* spp., *Medinilla* spp., *Smilax* spp., *Lithocarpus llanosii*, and *Zanthoxylum diabolicum*, reflecting the structural complexity and high biodiversity of the area. The tallest individual tree recorded in this zone was an Elaeocarpus species, locally known as "Tipudlos," reaching 30.92 m in height. This zone provides critical ecological services, including carbon sequestration, soil stabilization, and habitat for diverse fauna (Plybour et al., 2025). As a protected area, human activity is largely restricted, ensuring minimal disturbance and preserving ecosystem integrity. While the forest supports valuable timber and non-timber forest products, any utilization is strictly regulated, offering potential economic benefits for surrounding communities under sustainable management practices. The relatively undisturbed nature of this elevation band, compared to lower agro-ecosystem areas, highlights its importance as a core conservation area within the sanctuary.

The montane forest is situated between elevations of approximately 920 and 1,200 m, covering around 2,423 ha (Figure 5B). Tree height in this zone averages 12 m and generally decreases with increasing elevation, reflecting adaptation to cooler temperatures, higher humidity, and thinner soils (Wang et al., 2024). Commonly observed species include *Agathis philippinensis*, *Cinnamomum mercadoi*, and the globally endangered orchid *Paphiopedilum ciliolare*, highlighting the high conservation value of this forest type. Other dominant species, such as *Falcatifolium gruezoi* and *Shorea polysperma*, contribute to structural complexity and biodiversity. This forest zone provides essential ecological services, including water regulation, carbon storage, and habitat for endemic wildlife. As a protected area, human activity is largely limited and regulated, primarily consisting of authorized scientific research, ecological monitoring, and controlled ecotourism.

Above 1,200 m in elevation, the mossy forest encompassed approximately 948 ha (Figure 5C). This vegetation type is characterized by high precipitation, cooler temperatures, and consistently high humidity, resulting in lower tree heights and the extensive growth of moss covering trunks, branches, and roots. Notable species in this zone include *Dacrydium elatum* and *Calophyllum blancoi*. This forest type also exhibited the highest recorded average diameter at breast height (DBH) of 24.21 cm. The species composition, stunted tree stature, and dense moss layers reflect adaptations to ultramafic soils, high rainfall, and persistent cloud cover. Human activity remains minimal and regulated.

At the summit, the mossy-pygmy forest covered approximately 1,516 ha (Figure 5D). Trees in this zone were markedly stunted, averaging only 1.4 m in height. The tallest specimen (*Agathis philippinensis*) reached 2.4 m. Vegetation is dominated by highly specialized species such as *Leptospermum flavescens*, *Wendlandia nervosa*, *Tristaniopsis micrantha*, and *Calophyllum blancoi*. This zone represents a critical conservation priority and harbors the distinctive "bonsai forest" phenomenon unique to Mt. Hamiguitan.

Figure 5. Forest types in Mount Hamiguitan Range Wildlife Sanctuary, Davao Oriental, Philippines: (A) Dipterocarp; (B) Montane; (C) Mossy; (D) Mossy-Pygmy. Source: Photographs taken by Mr. Ramil L. Ramos during field surveys.

Mt. Hamiguitan land cover and slope

Based on the 2020 land cover map provided by the National Mapping and Resource Information Authority (NAMRIA), the majority of the MHRWS was classified as Closed Forest, covering 4,194.93 ha (Figure 6A). Slope analysis revealed that more than 70% of the area consists of moderately steep to very steep slopes (>20%). Brush and shrubland accounted for 796.48 ha and were mainly located in Barangay Sergio Osmeña. Other land cover types included Open Forest (1,206.80 ha), Grassland (106.23 ha), Inland Water (19.15 ha), Open/Barren Land (11.85 ha), and Perennial Crops (17.84 ha). These perennial crops, such as bamboo and coconut, were primarily observed in the agro-ecosystem areas. Meanwhile, slope classification analysis revealed that 35.71% of MHRWS consisted of very steep slopes, ranging from 32% to 69% gradient, covering approximately 2,268.86 ha (Figure 6B). An additional 37.63% of the area had moderately steep slopes ranging from 20% to 32%, comprising 2,390.60 ha. The remaining 26.66% of the area had gentle to moderate slopes of 0% to 20%, accounting for about 1,692.83 ha. Slopes >20% dominate, highlighting both protection of high-elevation habitats and management challenges for restoration and sustainable development.

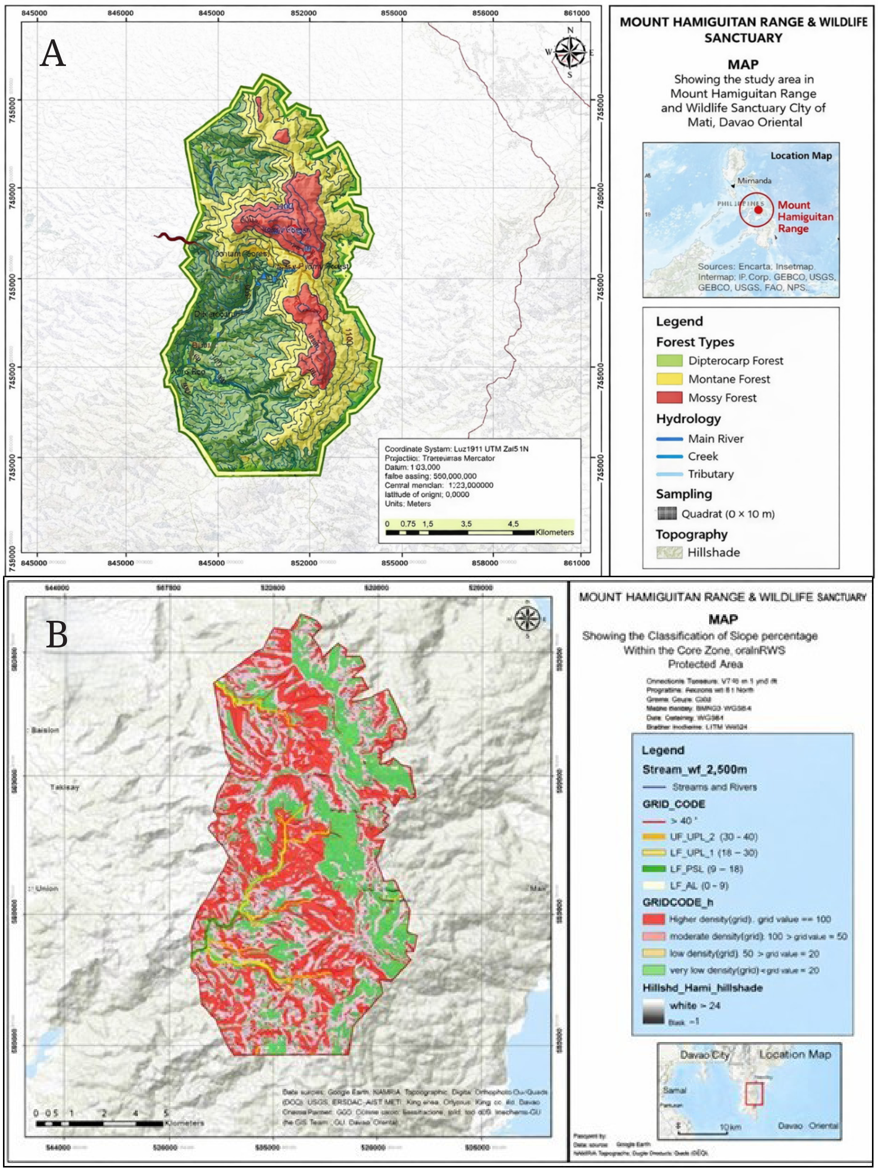

Figure 6. Maps showing the land cover (A) and slope (B) of Mt. Hamiguitan.

Vegetation pattern along the elevation gradient in Mt. Hamiguitan Elevation is a major determinant of vegetation composition within the Mt. Hamiguitan Range Wildlife Sanctuary (MHRWS). As elevation increases, endemicity rises significantly while tree height declines. Extreme dwarfism is evident at summit quadrats. To capture these patterns, a total of 16 vegetation quadrats were systematically established at 100 meter intervals, ranging from 140 to 1,620 m above sea level. Each quadrat displayed distinct tree species compositions and forest types corresponding to changes in elevation. A detailed summary of tree species per quadrat, including scientific names, average diameter at breast height (DBH), and forest type classification, is presented in Table 1. These data reveal a clear correlation between elevation and ecological characteristics, including species endemicity, tree morphology, and forest structure. As elevation increases, endemicity rises significantly, indicating that higher elevations harbor flora and fauna unique not only to the Philippines but specifically to this protected sanctuary. Concurrently, tree height generally decreases with elevation, reflecting adaptations to harsher environmental conditions, such as lower temperatures, thinner soils, and stronger winds.

Table 1. Common tree species observed across elevation gradients in Mt. Hamiguitan Range Wildlife Sanctuary.

Quadrat	Common name	Scientific name	Family	Average DBH (cm)	Forest type	Elevation (m)
1	Balete	*Ficus indica*	Moraceae	40	Agro-Eco	140
1	Kaimito	*Chrysophyllum cainito*	Sapotaceae	30	Agro-Eco	140
1	Binuang	*Octomeles sumatrana*	Datiscaceae	30	Agro-Eco	140
1	Hanagdong	*Trema orientalis*	Cannabaceae	12	Agro-Eco	140
2	Sagimsim	*Syzygium brevistylum*	Myrtaceae	12–20	Agro-Eco	200
2	Lubi-Lubi	*Ficus pseudopalma*	Moraceae	9–15	Agro-Eco	200
2	Bangkal	*Nauclea orientalis*	Rubiaceae	15	Agro-Eco	200
2	Bitanghol	*Calophyllum blancoi*	Calophyllaceae	16–25	Agro-Eco	200
2	Antipolo	*Artocarpus blancoi*	Moraceae	25	Agro-Eco	200
3	Sagimsim	*Syzygium brevistylum*	Myrtaceae	30–40	Dipterocarp	300
3	Lubi-Lubi	*Ficus pseudopalma*	Moraceae	12	Dipterocarp	300
3	Bangkal	*Nauclea orientalis*	Rubiaceae	15–20	Dipterocarp	300
3	Bitanghol	*Calophyllum blancoi*	Calophyllaceae	11–25	Dipterocarp	300
3	Aguho	*Casuarina equisetifolia*	Casuarinaceae	27	Dipterocarp	300
4	Magkono	*Xanthostemon verdugonianus*	Myrtaceae	30	Dipterocarp	400
4	Lauan (Red)	*Shorea negrosensis*	Dipterocarpaceae	40–50	Dipterocarp	400
4	Bangkal	*Nauclea orientalis*	Rubiaceae	35–50	Dipterocarp	400
4	Bitanghol	*Calophyllum blancoi*	Calophyllaceae	40	Dipterocarp	400
4	Tanguile	*Shorea polysperma*	Dipterocarpaceae	50–60	Dipterocarp	400
5	Kulipapa	*Teijsmanniodendron ahernianum*	Lamiaceae	40–50	Dipterocarp	500
5	Lauan (Red)	*Shorea negrosensis*	Dipterocarpaceae	40–50	Dipterocarp	500
5	Sagimsim	*Syzygium brevistylum*	Myrtaceae	50	Dipterocarp	500
5	Bitanghol	*Calophyllum blancoi*	Calophyllaceae	40–50	Dipterocarp	500
5	Egim	Unspecified	—	35–40	Dipterocarp	500
5	Malabayabas	*Tristaniopsis decorticata*	Myrtaceae	25–35	Dipterocarp	500
6	Kulipapa	*Teijsmanniodendron ahernianum*	Lamiaceae	25–35	Dipterocarp	600
6	Lauan (Red)	*Shorea negrosensis*	Dipterocarpaceae	30–45	Dipterocarp	600
6	Bitanghol	*Calophyllum blancoi*	Calophyllaceae	35–40	Dipterocarp	600
6	Tanguile	*Shorea polysperma*	Dipterocarpaceae	40–50	Dipterocarp	600
6	Antipolo	*Artocarpus blancoi*	Moraceae	40	Dipterocarp	600
7	Kulipapa	*Teijsmanniodendron ahernianum*	Lamiaceae	35–40	Dipterocarp	700
7	Lauan (Red)	*Shorea negrosensis*	Dipterocarpaceae	40–45	Dipterocarp	700
7	Bitanghol	*Calophyllum blancoi*	Calophyllaceae	50–60	Dipterocarp	700
7	Tanguile	*Shorea polysperma*	Dipterocarpaceae	50–60	Dipterocarp	700
7	Almaciga	*Agathis philippinensis*	Araucariaceae	50	Dipterocarp	700
8	Tinikaran	*Leptospermum flavescens*	Myrtaceae	12–15	Montane	800
8	Bitanghol	*Calophyllum blancoi*	Calophyllaceae	16–20	Montane	800
8	Kaningag	*Cinnamomum mercadoi*	Lauraceae	11	Montane	800
9	Tinikaran	*Leptospermum flavescens*	Myrtaceae	9–15	Montane	900
9	Bitanghol	*Calophyllum blancoi*	Calophyllaceae	12–15	Montane	900
10	Kamagong	*Diospyros blancoi*	Ebenaceae	25	Montane	1,000
11	Almaciga	*Agathis philippinensis*	Araucariaceae	11	Montane	1,100
11	Yakal	*Shorea astylosa*	Dipterocarpaceae	18–20	Montane	1,100
11	Cedar	*Dacrydium elatum*	Podocarpaceae	11	Montane	1,100
12	Yakal	*Shorea astylosa*	Dipterocarpaceae	25	Mossy	1,200
12	Cedar	*Dacrydium elatum*	Podocarpaceae	25	Mossy	1,200
13	Almaciga	*Agathis philippinensis*	Araucariaceae	13	Mossy	1,300
13	Tinikaran	*Leptospermum flavescens*	Myrtaceae	12–15	Mossy	1,300
15	Almaciga	*Agathis philippinensis*	Araucariaceae	8–10	Mossy	1,500
16	Tinikaran	*Leptospermum flavescens*	Myrtaceae	6–8	Moss	

Vegetation data across the 16 quadrats illustrate distinct shifts in species composition and forest types along the elevational gradient. At lower elevations, between 140 and 300 m asl (Quadrats 1–3), agro-ecosystems and lowland dipterocarp forests dominate, featuring species such as Balete (*Ficus indica*), Kaimito (*Chrysophyllum cainito*), Binuang (*Octomeles sumatrana*), Sagimsim (*Syzygium brevistylum*), and Bitanghol (*Calophyllum blancoi*). Trees in this zone display relatively large DBH values, ranging from 12 to 40 cm, reflecting both past human influence and the persistence of remnant native trees.

Transitioning to mid-elevations (Quadrats 4–7, 400–700 m asl), mature dipterocarp forests prevail. Dominant species include Lauan (*Shorea negrosensis*), Tanguile (*Shorea polysperma*), Kulipapa (*Teijsmanniodendron ahernianum*), Egim, and Almaciga (*Agathis philippinensis*). DBH values remain relatively large, ranging from 30 to 60 cm, demonstrating the presence of well-established trees within a structurally complex and ecologically stable forest system.

In the upper mid-elevations (Quadrats 8–11, 800–1,100 m asl), montane forests become prominent, characterized by species such as Tinikaran (*Leptospermum flavescens*), Kaningag (*Cinnamomum mercadoi*), and Yakal (*Shorea astylosa*). Tree height and biomass show a noticeable decline with increasing elevation, highlighting adaptive strategies to cooler temperatures, wind exposure, and shallow soils. At higher elevations, from 1,200 to 1,620 m asl (Quadrats 12–16), mossy and mossy-pygmy forests dominate the landscape. Trees in these zones are significantly shorter, with many exhibiting DBH values below 15 cm. Notable species include Almaciga, Tinikaran, Yakal, Cedar (*Dacrydium elatum*), and Bitanghol. In the highest quadrats, particularly 15 and 16, trees display extreme dwarfism, growing below knee height, reflecting the “bonsai forest” phenomenon unique to Mt. Hamiguitan’s summit. This stunting is attributed to ultramafic soils, high rainfall, low nutrient availability, and persistent environmental stressors. The elevational gradient in MHRWS not only supports unique structural and species diversity but also harbors one of the highest levels of endemic flora in the Philippines, making it distinct from other mountain ecosystems. Human activity is minimal at higher elevations, with occasional hikers carefully managed under the sanctuary’s regulations, ensuring minimal disturbance to sensitive habitats. The strong correlation between elevation, endemicity, and adaptive morphology underscores Mt. Hamiguitan’s exceptional conservation value and sets the stage for the discussion on biodiversity management, ecological resilience, and sustainable protection strategies.

Quantitative diversity analysis revealed clear patterns across elevation bands (Table 2). The Shannon–Wiener diversity index declined consistently from 2.89 in lowland dipterocarp forests to 1.72 in the mossy–pygmy forest, indicating decreasing species richness with increasing elevation. In contrast, Simpson’s index increased from 0.12 to 0.34, reflecting reduced evenness and increasing dominance of a few high-elevation specialists. These results demonstrate strong environmental filtering along the elevational gradient and provide quantitative support for the observed shifts in vegetation composition beyond descriptive forest classification.

Table 2. Biodiversity indices across elevation-based forest types in Mt. Hamiguitan Range Wildlife Sanctuary, Philippines.

Forest Type / Elevation Zone	Approx. Elevation Range (m asl)	Shannon–Wiener Index (*H′*)	Simpson’s Index (D)	Interpretation
Agro-ecosystem / Lowland Dipterocarp	140–300	2.89	0.12	High species richness and evenness; presence of both native and cultivated species
Dipterocarp forest	420–920	2.65	0.16	Structurally complex forest with diverse canopy species
Montane forest	920–1,100	2.21	0.23	Transitional zone with declining richness and increasing specialization
Mossy forest	1,200–1,350	1.94	0.28	Reduced diversity, dominance of stress-tolerant taxa
Mossy–Pygmy forest	1,350–1,620	1.72	0.34	Lowest diversity and evenness; dominance few highly specialized endemic species

Note: Shannon–Wiener Index (*H′*) reflects species richness and evenness, while Simpson’s Index (D) emphasizes dominance. Increasing D values indicate reduced evenness and greater dominance by fewer taxa.

Common tree species and associated faunal dependence

Table 3 presents common tree species recorded across elevation zones in Mt. Hamiguitan, together with their elevation range, ecological roles, and likely associated fauna. Several species were observed repeatedly across lowland, agro-ecosystem, dipterocarp, montane, and mossy forest zones, indicating broad ecological distribution. Lowland and agro-ecosystem zones were dominated by *Ficus indica, Ficus pseudopalma,* and *Syzygium brevistylum.* These species were frequently associated with frugivorous birds, fruit bats, arboreal mammals, and insects. Riparian and lowland forests also included *Nauclea orientalis* and *Calophyllum blancoi*, which occurred across multiple elevation ranges and were linked to diverse faunal groups. In dipterocarp forests, canopy-forming species such as *Shorea negrosensis, Shorea polysperma, Calophyllum blancoi,* and *Teijsmanniodendron ahernianum* were common. These species were associated with forest birds, rodents, insects, and other arboreal fauna. At higher elevations, particularly in montane, mossy, and mossy–pygmy forests, dominant species included *Leptospermum flavescens, Agathis philippinensis, Dacrydium elatum, Shorea astylosa,* and *Cinnamomum mercadoi.* These trees were primarily associated with insects, small birds, herpetofauna, and other fauna adapted to cooler and wind-exposed environments.

Table 3. Common tree species recorded across elevation zones in Mt. Hamiguitan, showing their ecological roles and likely associated fauna.

Common tree species (Scientific name)	Elevation / Forest type where common	Ecological role	Likely fauna supported
Balete (*Ficus indica*)	Lowland agro-ecosystem (140–200 m)	Keystone fruiting tree; year-round fig production	Frugivorous birds (*hornbills, pigeons*), fruit bats (*Pteropus* spp.), arboreal mammals, insects
Lubi-lubi (*Ficus pseudopalma*)	Agro-ecosystem to dipterocarp (200–300 m)	Food source and structural habitat	Birds, bats, butterflies, arboreal reptiles
Sagimsim (*Syzygium brevistylum*)	Agro-ecosystem to dipterocarp (200–500 m)	Nectar and fruit source	Nectar-feeding birds, insects, frugivorous bats
Bangkal (*Nauclea orientalis*)	Lowland to dipterocarp 200–400 m)	Riparian stabilizer, fruit provider	Amphibians, insects, birds associated with moist habitats
Bitanghol (*Calophyllum blancoi*)	Broad range: lowland to montane (200–900 m)	Canopy former; fruit and shade provider	Birds, mammals, insects; nesting substrate
Lauan and Tanguile (*Shorea negrosensis, S. polysperma*)	Dipterocarp forest (400–700 m)	Dominant canopy trees; mast fruiting	Forest birds, rodents, seed predators; insects
Kulipapa (*Teijsmanniodendron ahernianum*)	Dipterocarp forest (500–700 m)	Mid-canopy structural species	Arboreal mammals, birds, insects
Almaciga (*Agathis philippinensis*)	Dipterocarp to mossy forest (700–1,500 m)	Emergent tree; resin producer; long-lived	Birds of prey, epiphytes, arboreal fauna
Tinikaran (*Leptospermum flavescens*)	Montane to mossy-pygmy (800–1,620 m)	Dominant stunted species; stress-tolerant	Insects, small birds, herpetofauna adapted to cool habitats
Kaningag (*Cinnamomum mercadoi*)	Montane forest (800 m)	Aromatic leaves; u nderstorey diversity	Insects, birds; potential pollinator interactions
Yakal (*Shorea astylosa*)	Montane to mossy forest (1,100–1,200 m)	Structural hardwood species	Seed predators, birds, small mammals
Cedar (*Dacrydium elatum*)	Montane to mossy forest (1,100–1,200 m)	Conifer component of upper forests	Moss-dependent fauna, insects, birds
Kamagong (*Diospyros blancoi*)	Montane forest (1,000 m)	Dense hardwood; fruit-bearing	Frugivorous birds, mammals

DISCUSSION

Elevational gradients and forest differentiation

The stratification of forest types along the elevational gradient in the Mt. Hamiguitan Range Wildlife Sanctuary (MHRWS) reveals a vertically structured and ecologically distinct montane system. From the anthropogenically influenced agro-ecosystem at the base to the extreme environments of the mossy-pygmy forest at the summit, each elevational band supports a unique vegetation community. Elevation integrates multiple interacting stressors, declining temperature, increasing humidity, steepening slopes, ultramafic soil chemistry, and historical land use that progressively filter species from lowland to summit habitats (Vetaas 2021; Dani et al. 2023; Xing et al. 2023).

Rather than a gradual transition, Mt. Hamiguitan exhibits discrete vegetation formations aligned with clearly defined elevation bands, confirming its extreme vertical biodiversity and reinforcing its classification as a globally significant tropical montane ecosystem (Ashton et al. 2022; Amoroso et al. 2018). Human activities are present but spatially structured, with agriculture concentrated at lower elevations and regulated hiking and research activity at higher zones, resulting in minimal disturbance within core conservation areas (Celeste 2021; Mendoza et al. 2020).

Common tree species and associated faunal dependence

The repeated occurrence of key tree species across elevation gradients in Mt. Hamiguitan highlights their ecological importance beyond vegetation structure, particularly in sustaining faunal communities. In lowland and agro-ecosystem zones, the dominance of *Ficus indica, Ficus pseudopalma*, and *Syzygium brevistylum* is consistent with earlier floristic assessments in the buffer zones and vicinity of the Mt. Hamiguitan Range Wildlife Sanctuary, which reported high representation of fruit-bearing and disturbance-tolerant species in these areas (Amoroso et al., 2018). Such species are known to provide continuous food resources and habitat structure in human-influenced landscapes, supporting a wide range of fauna including birds, bats, insects, and arboreal vertebrates, as documented in faunal inventories within the sanctuary and its buffer zones (Medina et al., 2020; Rosales et al., 2023).

The persistence of these tree taxa in agro-ecosystems suggests that buffer zones in Mt. Hamiguitan continue to function as feeding grounds and movement corridors for wildlife. This observation aligns with findings from Mt. Hamiguitan–adjacent studies emphasizing the ecological value of peripheral and multiple-use zones in maintaining biodiversity and landscape connectivity (Amoroso et al., 2018; Mendoza et al., 2020; Mendoza et al., 2024). Similar patterns have been observed in other Southeast Asian lowland forests, where structurally diverse secondary and mixed-use forests support key ecological functions despite anthropogenic pressure (Anas et al., 2021; Atmoko et al., 2025).

In mid-elevation dipterocarp forests, canopy-forming species such as *Shorea negrosensis, Shorea polysperma, Calophyllum blancoi,* and *Teijsmanniodendron ahernianum* contribute substantially to forest structural complexity. Dipterocarps are well known for their dominance in tropical lowland and mid-montane forests and their role in shaping forest architecture, regeneration dynamics, and faunal habitat availability (Fernando et al., 2009; Ng et al., 2022; Thüs et al., 2021). Studies from Philippine dipterocarp forests and other tropical regions have shown that these large trees provide critical nesting, roosting, and foraging substrates for forest-dependent birds, mammals, and invertebrates (Aureo et al., 2021; Llait, 2024). Episodic mast fruiting, a characteristic feature of dipterocarp species, further enhances their ecological importance by driving pulses of faunal activity and influencing seed predator and disperser populations (Ng et al., 2022; Prohaska et al., 2023). At higher elevations, the transition toward stress-tolerant and stunted species reflects strong environmental filtering associated with lower temperatures, high wind exposure, and nutrient-poor soils. Similar declines in species richness with increasing elevation have been documented in Mt. Hamiguitan and other Philippine mountain systems, including Mt. Apo, Mt. Palali, and Balinsasayao Twin Lakes Natural Park (Amoroso et al., 2016; Manuel and Pascua; Aureo et al., 2021). Despite reduced diversity, montane and mossy forests harbor specialized plant communities that support fauna adapted to cooler and more extreme environments, including insects, birds, and herpetofauna (Vetaas, 2021; Decena et al., 2023).

The dominance of *Leptospermum flavescens* in summit and mossy–pygmy forests of Mt. Hamiguitan reflects strong edaphic and climatic constraints similar to those described in other tropical “sky island” systems. These environments are characterized by high habitat specialization and ecological isolation, often supporting narrowly distributed or endemic species (Love et al., 2023; Verrier & Mulder, 2024). Comparable pygmy forest formations in Mt. Hamiguitan have been linked to unique soil properties and hydrological conditions, reinforcing the role of abiotic filtering in shaping vegetation and associated fauna (Daquiado et al.; Wang et al., 2024).

Hence, the presence of key tree species across elevation zones underscores their role in maintaining faunal diversity and ecological processes throughout Mt. Hamiguitan. Consistent with broader elevational gradient studies, these findings emphasize that biodiversity conservation must encompass both species-rich lowland forests and structurally simplified but ecologically distinctive high-elevation habitats (Dani et al., 2023; Wani et al., 2022; Wani et al., 2023). Protecting the full elevational continuum of Mt. Hamiguitan is therefore essential for sustaining ecological connectivity, specialized wildlife, and long-term ecosystem resilience within this UNESCO World Heritage Site.

Biodiversity trends along elevation: declining diversity and increasing specialization

Quantitative diversity indices demonstrate a consistent decline in species richness and evenness with increasing elevation. The Shannon diversity index decreases from $H' = 2.89$ in lowland dipterocarp forests to $H' = 1.72$ in high-elevation mossy–pygmy zones, while Simpson’s dominance index increases from $D = 0.12$ to $D = 0.34$. These trends indicate progressive dominance by a smaller number of highly specialized taxa under increasing environmental stress. This shift from species-rich, structurally complex dipterocarp forests to species-poor but functionally specialized summit communities reflects strong environmental filtering, a pattern widely reported in tropical mountain systems (Wani et al. 2022; Wani et al. 2023; Aureo et al. 2021). Reduced tree height, simplified canopy structure, and increased endemicity at higher elevations are consistent responses to nutrient-poor ultramafic soils, wind exposure, and cooler temperatures (Daquiado et al.; Ashton et al. 2022). Importantly, the higher average DBH observed in mossy forests despite reduced height suggests slow growth rates and longevity, rather than competitive dominance, under persistent environmental stress (Prohaska et al. 2023).

Vertical zonation, species turnover, and forest structure

Abundance patterns show marked compositional turnover along elevation. Lowland zones are dominated by species such as *Ficus indica, Chrysophyllum cainito,* and *Calophyllum blancoi,* reflecting both native forest persistence and agricultural influence. At higher elevations, dominance shifts to *Leptospermum flavescens, Tristaniopsis micrantha,* and *Agathis philippinensis,* taxa adapted to cooler, nutrient-limited, and wind-exposed environments. These patterns confirm predictable elevation-driven changes in forest structure and function (Ng et al. 2022; Wani et al. 2023). The five primary forest types, agro-ecosystem, dipterocarp, montane, mossy, and mossy-pygmy, exhibit clear altitudinal zonation similar to other Philippine and Southeast Asian mountain systems (Anas et al. 2021; Aureo et al. 2021; Ng et al. 2022). However, Mt. Hamiguitan is exceptional in the degree of endemic species integration across all zones, particularly within mid- and high-elevation forests (Amoroso et al. 2016; Amoroso et al. 2017). Dipterocarp forests (420–920 m asl) represent the tallest and most structurally complex formations, providing essential ecosystem services such as carbon sequestration, soil stabilization, and faunal habitat (Luo et al. 2022; Thüs et al. 2021). Montane forests function as transitional zones where diversity remains high but morphological constraints begin to shape tree stature and composition, while mossy and mossy-pygmy forests exhibit extreme dwarfism and the distinctive “bonsai forest” phenomenon unique to Mt. Hamiguitan (Manuel and Pascua; Decena et al. 2023).

Endemicity, isolation, and conservation value

The concentration of endemic and elevation-restricted species in montane, mossy, and mossy-pygmy forests underscores Mt. Hamiguitan’s role as a classic tropical “sky island,” where long-term isolation and environmental filtering promote speciation and high conservation value (Love et al. 2023; Verrier and Mulder 2024). Compared with other Philippine mountain systems, Mt. Hamiguitan supports higher levels of endemicity, species turnover, and vertical structural variation, reinforcing its global uniqueness (Amoroso et al. 2018; Bullong et al. 2024). Vertical stratification allows generalist and specialist taxa to coexist across elevation bands, a mechanism also observed in tropical mountain ecosystems worldwide (Vetaas 2021; Xing et al. 2023). However, this spatial partitioning increases vulnerability to climate change, as upslope migration may compress suitable habitat for summit-restricted species, raising extinction risk (Freeman et al. 2018; Brodie et al. 2025; Sękiewicz et al. 2024).

Human influence, slope, and buffer zone opportunities

Anthropogenic pressures are largely confined to lower elevations, particularly within agro-ecosystem zones characterized by gentler slopes and accessibility. Despite cultivation, the persistence of native dipterocarp species highlights substantial restoration potential rather than irreversible degradation (Amoroso et al. 2018). In contrast, steeper slopes at higher elevations naturally limit access and disturbance, reinforcing the integrity of core conservation zones (Liu and Tang 2024). These findings support slope- and elevation-sensitive management strategies that prioritize community-based reforestation, agroforestry using native species, and biodiversity corridor enhancement within buffer zones. Such approaches reduce pressure on high-elevation forests while supporting sustainable livelihoods, consistent with observed successes in Mt. Hamiguitan's community-based initiatives (Mendoza et al. 2024; Mendoza et al. 2020).

Policy relevance and implications for sustainable management

As a protected area governed under the Protected Area Management Board (PAMB), MHRWS serves as a model for science-based conservation planning. Data on forest structure, diversity patterns, endemicity, and slope distribution provide a strong empirical basis for identifying high-priority conservation zones, restoration sites, and climate-sensitive habitats. These findings directly inform slope-sensitive land-use planning, buffer zone enhancement, and long-term ecological monitoring (Celeste 2021; Calag et al.). Mt. Hamiguitan's UNESCO World Heritage status further amplifies its ecological, cultural, and economic significance. Sustainable development initiatives, such as regulated ecotourism, restoration of degraded lowlands, and inclusive management involving local communities and indigenous peoples, offer pathways to balance conservation objectives with socio-economic benefits. Strengthening governance frameworks, sustainable financing, and the integration of geospatial technologies can enhance enforcement, monitoring, and adaptive decision-making.

Contribution to conservation science

By integrating vegetation structure, elevation, slope, land cover, and endemicity, this study advances understanding of how physical and environmental constraints shape biodiversity in tropical montane systems. Mt. Hamiguitan emerges as a globally significant reference site for conserving entire elevational continua rather than isolated forest patches, demonstrating an effective model of integrated ecological and socio-economic stewardship.

CONCLUSION

This study quantitatively demonstrates that species richness and evenness decline with increasing elevation, while endemic and specialized species become more dominant in upper montane, mossy, and pygmy forest zones. By integrating plot-based biodiversity indices (Shannon–Wiener and Simpson) with GIS-derived spatial analysis, the research links field-measured floristic structure to remotely validated elevational zonation across Mt. Hamiguitan, providing the first sanctuary-wide assessment of vegetation composition, dominance patterns, and endemism along the gradient.The results confirm that vegetation transitions reflect both ecological processes and varying conservation value. Lower elevations exhibit higher diversity and mixed species assemblages, whereas higher zones are characterized by stunted, stress-tolerant vegetation and concentrations of endemic taxa associated with ultramafic soils. These findings reinforce mountain biodiversity stratification theory while supplying site-specific empirical evidence supporting Mt. Hamiguitan's global importance as a UNESCO World Heritage Site.

From a management perspective, the analysis identifies elevation-sensitive priorities for protected area zoning. Agro-ecosystems and lower dipterocarp forests, which show lower biodiversity sensitivity, may accommodate regulated ecotourism infrastructure and visitor activities. In contrast, mossy and pygmy forests, despite lower richness, contain highly specialized and vulnerable species and therefore require strict protection, controlled access, and strengthened monitoring to prevent degradation. The study supports the Protected Area Management Board and local governments in implementing science-based policies, including visitor carrying capacity limits, conservation buffers, and trail planning. Overall, the findings provide an integrated ecological basis for balancing biodiversity conservation, sustainable tourism, and community-inclusive protected area management in the Philippines, while guiding future biodiversity monitoring and adaptive management strategies nationwide.

ACKNOWLEDGMENT

The authors sincerely thank Davao Oriental State University, particularly the Faculty of Advanced and International Studies, for academic support; DENR–CENRO Mati for logistical assistance; Forester I Bobby C. Corpuz, Forester I Henry Benignos, and Forester II Jowanie F. Albarida for help in tree species identification; the PAMB and MHRWS staff for research access; and the field assistants, local guides, and community members for their valuable support during the surveys.

FUNDING SOURCE

This research was supported by Davao Oriental State University, Faculty of Advanced and International Studies, under institutional research grants for environmental and conservation studies. Additional logistical support was provided by the Department of Environment and Natural Resources (DENR)–CENRO Mati.

AUTHOR CONTRIBUTIONS

R.L.R: Conceptualized, methodology, coordinated fieldwork, data collection, vegetation surveys, GIS and remote sensing analysis. E.S.A and P.N.C: Data analysis, and interpretation of results. P.N.C: Drafted the manuscript. All authors reviewed, edited, and approved the final version for submission.

DECLARATION

Informed consent statement

Fieldwork and data collection were conducted in strict accordance with the guidelines set by the Mount Hamiguitan Range Wildlife Sanctuary Protected Area Management Board (PAMB) Resolution No. 2025-22. No plant specimens were collected to avoid disturbance in this protected area. All survey methods followed ethical practices for biodiversity research, ensuring minimal impact on vegetation, habitats, and local communities. Proper permits and authorizations were obtained from DENR–CENRO Mati and PAMB prior to research activities.

Conflict of interest

The authors declare no conflicts of interest regarding the publication of this study. All research activities were conducted independently, and there were no financial or personal relationships that could have influenced the outcomes.

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